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Technology for Improving Reliability of Oil-flooded Screw Compressors

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Several issues exist with large oil-flooded screw compressors used for high-pressure. The large force, acting on their rotors, induces impact vibration between the male and female rotors, causing a large force acting on their bearings. In addition, the compressed gas directly contacts the lubricant, decreasing the oil viscosity. The present paper introduces new technologies, developed to resolve these issues.

Introduction

Oil-flooded screw compressors are widely used in industry because of their features including high efficiency, a small footprint and capacity control. Kobe Steel makes world-class oil-flooded screw compressors with maximum discharge pressures up to 10 MPaG and maximum rotor sizes up to about 500mm.

Screw rotors for large, high-pressure screw compressors are subject to large load and torque variations. Thus, the designing of such a compressor unit requires new technologies, and so does the designing of its peripheral equipment.

To ensure compressor reliability under such harsh operating conditions, Kobe Steel has developed several unique technologies and has delivered many compressors around the world. This paper introduces three typical technologies developed for improving the reliability of screw compressors.

1. Technical issues associated with reliability improvement

The following describes the main technical issues associated with improving the reliability of oil-flooded screw compressors.

- Abnormal vibration of screw rotors

Large pressure variations in the rotor groove increase the fluctuating torque acting on the rotors, causing the rotors to vibrate abnormally. Such abnormal vibrations shake the compressor units, increasing their noise, and can cause the rotors to be damaged.

- The prediction of bearing performance

The bearings of screw rotors are critical parts since they support the force caused by gas pressure and acting on the rotors. Thus, bearing analysis techniques are essential for developing compressors, making the prediction of bearing performance indispensable.

- Drop in lubricant viscosity

An oil-flooded compressor uses oil, poured into compressed gas, for cooling the gas and to improve the sealing between the engaged rotor grooves. The oil is collected by an oil recovery tank provided at the compressor outlet and is supplied to the bearings. Hydrocarbons, if contained in the compressed gas, can dissolve into the lubricating oil, decreasing the oil's viscosity, which deteriorates the bearing lubrication and can cause damage to the bearings. This necessitates a prediction technology for the reduction of lubricant viscosity.

Kobe Steel has overcome these technical challenges and succeeded in improving the reliability of screw compressors. The following outlines the technologies used for the improvement.

2. Analysis of screw rotor vibration [1~3)]

2.1 Rotor behavior

Fig. 1 shows the rotor profiles of a pair of engaging screw rotors. The arrows indicate the respective directions of rotation. The male rotor drives the female rotor and the rotors contact each other on their driving sides. For rotors in abnormal vibration, however, the screw rotors make contact on both their driving sides and trailing sides, resulting in a motion as depicted in **Fig. 2**. In the figure, the vertical axis (x) is the actual rotor clearance, while the horizontal axis represents time. The screw rotors have a designed clearance, δ, and $x=0$ indicates a contact on the driving side, while $x=\delta$ indicates a contact on the trailing side. In other words, the vibration is caused

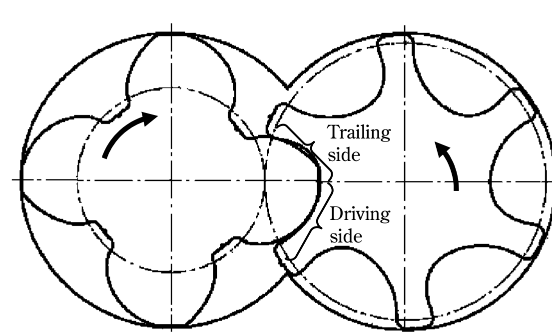


Fig. 1 Screw rotor profile

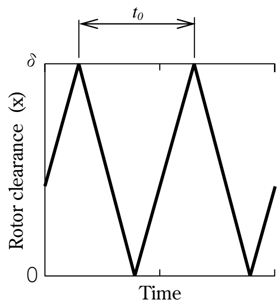


Fig. 2 Motion of rotors

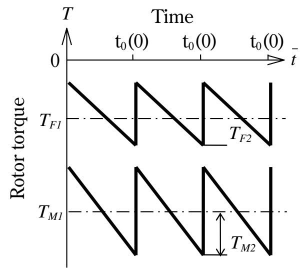


Fig. 3 Rotor torque

by periodic impacts on the driving side and trailing side, in which alternating collisions occur at a frequency of t_0.

The following summarizes the analysis of rotor behavior that causes impact vibration in a periodic manner as shown in Fig. 2.

2.2 Rotor motion equation

Fluctuating torque acts on the screw rotors as shown in **Fig. 3**, in which the horizontal axis represents time, $\bar{t}$. The time $\bar{t}=0$ is a time point at which the torque changes discontinuously, and t_0 represents the variation period of the torque. The time $\bar{t}=t_0$ ($t_0(0)$ in the figure) indicates the origin $\bar{t}=0$ of the next variation period of the torque. The torques acting on the female rotor and the male rotor are given by the following equations respectively:

$$T_F=T_{F1}+T_{F2}(1-2\bar{t}/t_0) \quad (0 \le \bar{t}/t_0) \quad \cdots\cdots(1)$$

$$T_M=T_{M1}+T_{M2}(1-2\bar{t}/t_0) \quad (0 \le \bar{t}/t_0) \quad \cdots\cdots(2)$$

The following describes the rotor behavior with the torques acting on the female and male rotors respectively, as shown in Fig. 3. By omitting negligible terms, the rotor motion equation is given as follows:

$$\frac{d^2x_F}{dt^2}=f_1+f_2(1-2t) \quad \cdots\cdots(3)$$

$$\mu\frac{d^2x_M}{dt^2}=-f_1+f_3(1-2t) \quad \cdots\cdots(4)$$

The respective variables and parameters are dimensionless quantities expressed as follows:

$t=\bar{t}/t_0$ $\quad$ $x_F=\theta_F/\xi$
$x_M=\theta_M/\xi$ $\quad$ $\mu=I_M/I_F/(N_M/N_F)^2$
$f_1=t_0^2T_{F1}/I_F/(N_M/N_F)/\xi$ $\quad$ $f_2=t_0^2T_{F2}/I_F/(N_M/N_F)/\xi$
$f_3=t_0^2T_{M2}/I_F/(N_M/N_F)^2/\xi$

wherein

I_M and I_F are the inertia moments of the male and female rotors respectively;
θ_M and θ_F are the rotation angles of the male and female rotors respectively; and
N_M and N_F are the number of teeth of the male and female rotors respectively.

The angle ζ is the rotation angle of the male rotor corresponding to the rotor clearance. Here, the rotors are assumed to collide against each other with a coefficient of restitution R.

Examples of periodic vibration, caused by impact between the rotors, are shown in **Fig. 4** (a) and (b). The horizontal axis represents time, and one tick corresponds to one period of external force. The vertical axis represents rotor position. The periodical vibration waveform is expressed as vibration (J, K, L, M). Here, J, K, L and M are either zero or a positive integer respectively having the following meaning. It is to be noted that the number of branches described below represents the number of different types of vibration waveforms.

J is the external force periodic number;
K is the number of times the tooth flanks impact on the driving side;
L is the number of times the tooth flanks impact on the trailing side; and
M is the number of branches for the periodic vibration.

The vibration that can lead to abnormal vibration is represented in Fig.4 (a), in which tooth flanks impact on the trailing side periodically. In the case of the vibration shown in Fig.4 (b), the tooth flanks do not make contact on the trailing side; however, it causes abnormal sound.

2.3 Stable regions for periodic vibration

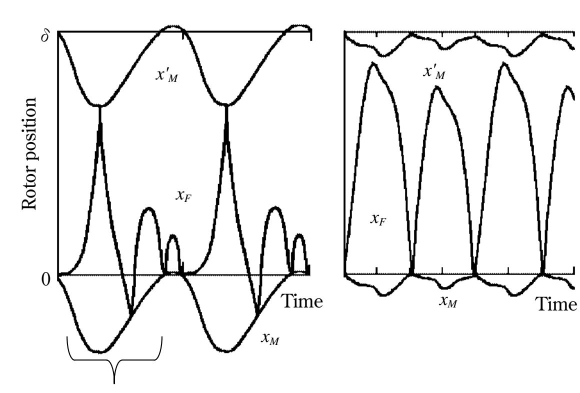
Periodic vibrations are calculated from the vibration waveforms shown in Fig. 4. The stable regions for the periodic vibrations are determined by a characteristic equation. The stable region for (J, 1, 0, 1) vibration is analytically calculated as follows:

$$0<\frac{f_2}{f_1}(1-2t_p)\left(1-\frac{f_3}{\mu f_2}\right)<\frac{1+\mu}{\mu}\left\{1+\left(\frac{1-R}{1+R}\right)^2\right\} \quad \cdots(5)$$

wherein

$$t_p=\frac{1}{2}\left\{1\pm\sqrt{\frac{1}{3}+2J\frac{(1+\mu)f_1}{f_3-\mu f_2}\left(1-\frac{2R}{1+R}\right)}\right\} \quad \cdots\cdots(6)$$

The stable region for (1, K, 1, M) vibration can not



(a) (1, K, 1, 1) Vibration (b) (2, 1, 0, 2) Vibration

Fig. 4 Periodic vibration

be obtained analytically and is determined by numerical calculation.

Fig. 5 shows the stable regions for a conventional rotor profile calculated from its periodic vibration. The areas surrounded by solid lines are stable regions for impact vibration caused by the tooth flanks impacting each other as shown in Fig. 4 (a). The area surrounded by a dashed-dotted line is the stable region for the impact vibration caused by the tooth flanks impacting on their driving sides only as shown in Fig. 4 (b). The horizontal axis represents f_2. The vertical axis is f_2/f_1 which corresponds to the rotor torque and is determined by the pressure condition of the compressors. The parameters f_2 and f_2/f_1 of the conventional rotor profile correspond to the solid circle (●) which falls in a stable region of periodic vibration. Thus the conventional rotor profile can exhibit abnormal vibration.

A rotor profile has been developed which prevents abnormal vibration. **Fig. 6** shows the stable region derived from the periodic vibration of the newly developed rotor profile. The newly developed

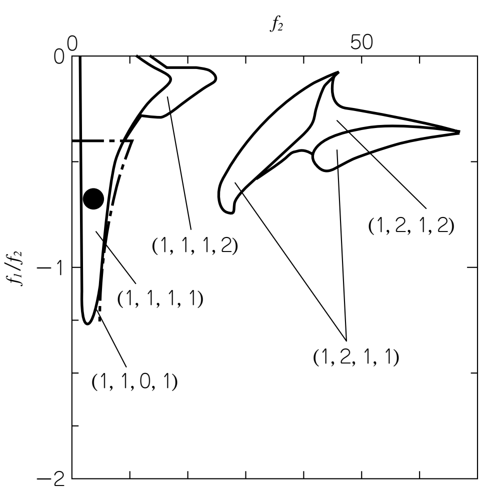


Fig. 5 Stable region of periodic vibration for conventional profile

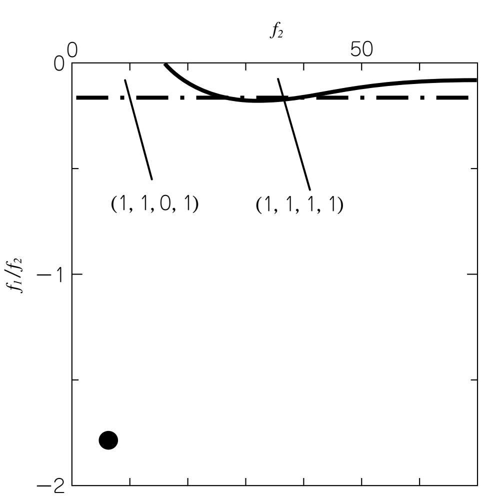


Fig. 6 Stable region of periodic vibration for new profile

rotor profile has a small stable region and its f_2 and f_2/f_1 fall on the black circle which is located away from the stable region, eliminating the possibility of abnormal vibration.

3. Bearing analysis technique

3.1 Bearing load

Gas pressure acts on a bearing via a screw rotor. The bearing loads, radial load (F_R) and thrust load (F_S), are approximated by the following equations respectively:

$$F_R = \alpha DL(P_D - P_S) \quad \cdots\cdots(7)$$

$$F_S = \beta D^2(P_D - P_S) \quad \cdots\cdots(8)$$

wherein D is rotor diameter, L is rotor length, P_D is discharge pressure and P_S is suction pressure. The α and β are coefficients determined from rotor profiles.

The bearing area depends on the bearing diameter, i.e., on the rotor diameter D. It should be noted that, as expressed by the equations (7), (8), the bearing load can increase to a level exceeding the allowable pressure and damage the bearing, regardless of the bearing size. Thus, it is essential to clarify the bearing characteristics.

3.2 Primitive equation for slide bearings

The bearing characteristics of a slide bearing are analyzed for bearing development. A slide bearing forms an oil film through the relative motion between the shaft and bearing surface. This oil film supports the bearing load. **Fig. 7** shows a schematic planer bearing having a varying clearance, in which the horizontal axis is x, and the vertical axis corresponds to the bearing clearance $h(x)$. The distribution pressure in the oil film is expressed as $p(x, z)$, in which z is the coordinate position in the thickness direction of Fig. 7. Assuming a bearing having a width of B, with the pressures at both ends of the bearing being at atmospheric pressure p_0, the pressure boundary condition is expressed by the following:

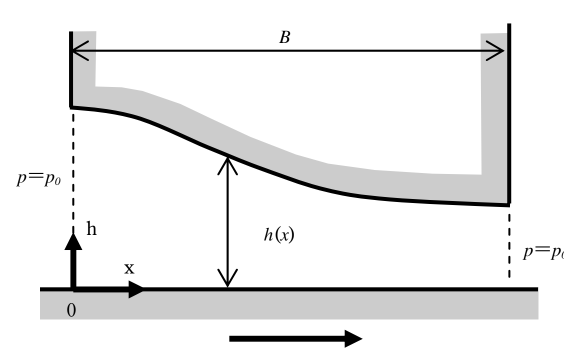


Fig. 7 Oil film bearing

$$p(0, z) = p_0,\ p(B, z) = p_0 \quad \cdots\cdots (9)$$

When the bearing surface (the bottom portion of Fig. 7) moves at a velocity of U, the relation between $h(x)$ and $p(x, z)$ is derived from the Reynolds equation as follows:

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right)=6U\frac{\partial h}{\partial x} \quad \cdots\cdots (10)$$

wherein η is the viscosity of the oil. Since the oil viscosity is significantly affected by temperature, the temperature distribution in the oil film should also be calculated. The temperature of an oil film is calculated from the heat generated by the shear and the transfer of oil, thermal conductance and the balance of heat transferred between the shaft and bearing.

The amount of heat Q_1 generated per unit area by shear is given by

$$Q_1 = U\left(-\frac{h}{2}\frac{\partial p}{\partial x}+\frac{\eta U}{h}\right) \quad \cdots\cdots (11).$$

While the amount of heat transferred Q_2, caused by the transfer and thermal conductance of an oil film, having a temperature of T is given by

$$Q_2 = \lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}\right)-C\gamma\left(u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}\right) \quad \cdots\cdots (12),$$

the amount of heat, Q_3, transferred to the shaft and bearing, is expressed as follows:

$$Q_3 = \alpha_A(T-T_A)+\alpha_B(T-T_B) \quad \cdots\cdots (13)$$

wherein

- λ is the thermal conductivity of the oil;
- C is the specific heat of the oil;
- γ is the specific gravity of the oil;
- α_A is the heat-transfer coefficient between the shaft and oil film;
- α_B is the heat-transfer coefficient between the bearing and oil film;
- u, w are the rate of the flow oil in the directions of x, z respectively; and
- T_A, T_B are the surface temperatures of the shaft and bearing respectively.

The following equation holds from the heat balance.

$$Q_1 = Q_2 + Q_3 \quad \cdots\cdots (14)$$

Furthermore, the relation between the oil temperature and viscosity is expressed as follows:

$$\eta = 10^{10^{(A-B\log(T))}} \quad \cdots\cdots (15)$$

wherein A and B are constants.

The oil pressure generated, $p(x, z)$, and oil film temperature are determined by solving the equations (10) - (15). Integrating $p(x, z)$ for the bearing surface yields the oil film force (i.e., bearing force). This force balances with the bearing load.

3.3 Simulation program for bearing characteristics

A simulation program for bearing characteristics has been developed, using the difference method, based on the equations (10) - (15) described in section 3.2. Equations (10) - (15) calculate the bearing force for predetermined bearing clearances. In reality, however, the bearing load is predetermined, and the bearing clearance is calculated iteratively, such that the predetermined bearing load matches the bearing force.

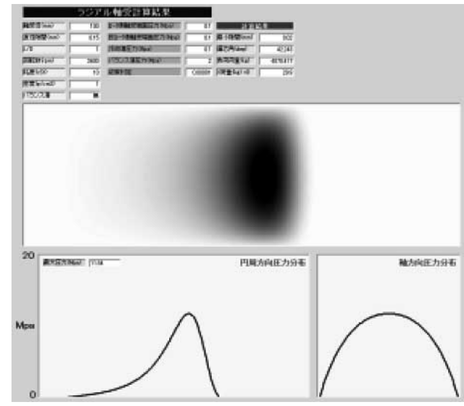


Fig. 8 Bearing simulation

Fig. 8 shows a sample result obtained by the simulation program for bearing characteristics. The diagram in the middle shows the pressure distribution calculated by the equation (10), with the horizontal axis indicating the circumferential direction and the vertical axis indicating the shaft direction of the bearing. In this diagram, a darker area depicts the part in which the oil pressure is higher. The graph at the lower left shows the oil pressure along the circumferential direction of the bearing, while the graph at the lower right shows the oil pressure along the shaft direction. The calculation yields the minimum oil-film thickness and bearing temperature; the values provide indication as to whether or not sufficient bearing clearance is secured. It should be noted that the heat-transfer coefficients are determined experimentally due to the difficulty of determining them theoretically.

4. Technique for predicting oil viscosity

4.1 Dissolution of gas into lubricant

Fig. 9 is a flow chart of fluid in an oil-flooded screw compressor consisting of a compression chamber, bearing and oil cooler. In this compressor, the oil, poured into the compression chamber and the bearing, is mixed with gas. An oil recovery tank at the compressor outlet separates the gas and oil. The separated oil goes through the cooler and is poured into the compression chamber and bearings again.

In many cases, gas contains a hydrocarbon (CmHn), which decreases oil viscosity during the

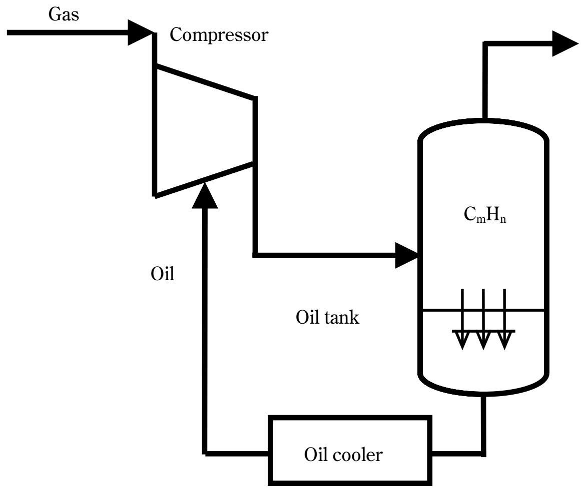


Fig. 9 Flow diagram of an oil-flooded screw compressor

compression process. Decreased oil viscosity may cause insufficient lubrication of the bearings. Thus, it is important to predict the decrease in oil viscosity and select more viscous oil.

4.2 Equation for predicting oil viscosity

Provided that the content of CmHn in the incoming gas is x% and the discharge pressure is P_D, the partial pressure of CmHn at the compressor outlet is expressed as follows:

$$P_X = \frac{x}{100} P_D \quad \cdots\cdots(16)$$

The amount G_X of CmHn dissolved into the oil in the oil recovery tank is calculated by ROULT's law as follows:

$$P_X = P_C \frac{G_X/M_C}{G_X/M_C + G_0/M_0} \quad \cdots\cdots(17)$$

wherein

P_C is the saturation vapor pressure of CmHn at the discharge temperature;
G_X is the mass of CmHn;
M_C is the molecular weight of CmHn;
G_0 is the mass of oil; and
M_0 is the molecular weight of the oil.

After passing the compressor, the oil is cooled and poured into the compressor again. Here, the viscosity at a feed temperature is calculated for the oil having a mass of G_0, with a mass, G_X, of CmHn dissolved in the oil. Provided that the viscosity of the oil at the feed temperature is μ_0 and the viscosity of CmHn is μ_c, the viscosity of the mixture, μ, is expressed as follows:

$$\log \mu = K_0 \log \mu_0 + K_c \log \mu_c \quad \cdots\cdots(18)$$

wherein

$$K_0 = \frac{W_0/A}{W_0/A + W_C/M_C}$$

$$K_C = \frac{W_C/M_C}{W_0/A + W_C/M_C}$$

$$W_0 = \frac{G_0}{G_0 + G_X}$$

$$W_C = \frac{G_X}{G_0 + G_X}$$

in which A is the constant determined by the type of lubricant. The equation (18) is the prediction equation for one component gas, CmHn. In reality, however, more than one component may dissolve into the gas. In addition, the decrease in viscosity depends on the type of CmHn. Thus, the comprehensive equation covering all cases becomes rather complex and is omitted here.

4.3 Verification of forecast equation by elemental experiment

The equations (16) and (17) are valid only for ideal conditions. The behaviors in reality do not follow the theoretical formula in many cases. In particular, CmHn has a molecular structure similar to that of oil and strongly interacts with oil. Thus a correction term must be calculated experimentally. **Fig. 10** compares the vapor pressures, theoretically predicted and experimentally measured, of CmHn mixed with mineral oil. The prediction well matches the experiment for benzene; however, there are slight discrepancies for toluene and xylene. Similar discrepancies are observed for other substances and, for that reason, the equation (17) must be used with corrections.

Fig. 11 compares the viscosities, theoretically predicted and experimentally measured, for a mixture of benzene and mineral oil. The value, A, of equation (18) is obtained by experiment and, if used

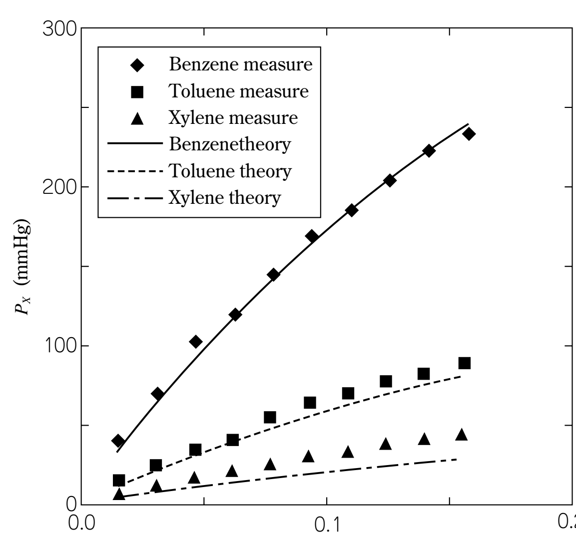


Fig.10 Vapor pressure of a mixture with oil and HmCn

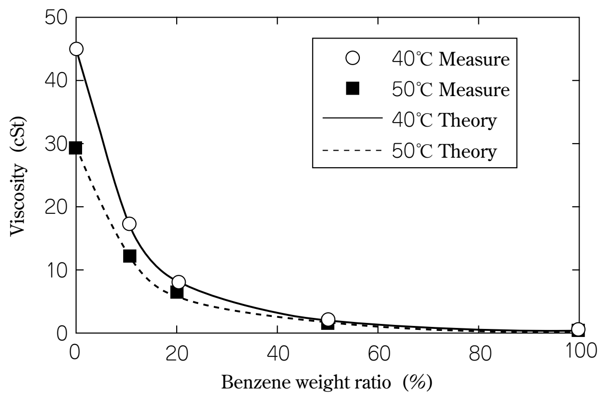


Fig.11 Viscosity of the mixture of oil and benzene

herein, results in a better match with the theoretical value.

Kobe Steel is now able to predict the oil viscosity, using theoretical formulae corrected by experimental data and is thus able to select the most appropriate types of oil.

Conclusion

The oil-flooded screw compressors of Kobe Steel have advanced features offered by carefully selected oil poured into compressed gas. The oil cools the gas and seals the compressor by forming a film. In addition, the compressors fully exploit their unique capacity control capability, offering advantages superior to those of other compressors. In the past, the oil caused various problems; however, Kobe Steel has successfully solved these problems and has developed compressors of larger sizes and with a high pressure capacities, which are unprecedented anywhere else in the world. Kobe Steel will strive to develop compressors for new applications based on those technologies.

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High-pressure 100 barG Oil-flooded Screw Compressor

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Kobe Steel has developed a series of oil-flooded screw compressors for high-pressure. The company's original rotor technology, along with larger bearings and special mechanical seals, has enabled discharge pressures up to 100 barG. The compressors, with their high performance and reliability, are suitable for fuel gas boosting and, in particular, for high-efficiency gas turbines. They are finding an increasing number of applications, such as the desulfurization of fuels, and further increases are anticipated.

Introduction

Screw compressors are positive displacement compressors, but also have characteristics of rotary compressors. Screw compressors are widely used across the industry for their characteristics of high efficiency, a small footprint and long-lasting features. Oil-flooded screw compressors, in which oil is poured into the gas being compressed, can achieve high discharge pressures in one stage with high pressure ratios. The oil-flooded compressors are finding increasing applications, as their technology is improved for higher pressures, larger gas volumes, better lubrication and advanced oil separation.

Kobe Steel has developed a series of oil-flooded screw compressors, the "EH series", which are applicable to discharge pressures up to 100 barG. **Fig. 1** is a range chart for the oil-flooded screw compressors, including the conventional series, developed by Kobe Steel. **Table 1** summarizes their specifications.

This paper introduces an oil-flooded screw compressor with a maximum discharge pressure of 100 barG. Also included are the examples of applications using the newly developed compressors and their future applications, which are expected to increase in number [1)-3)].

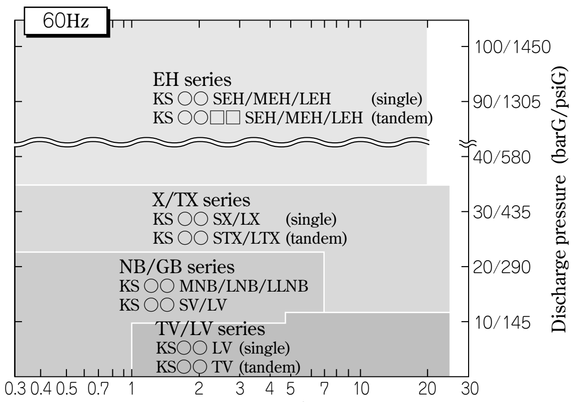

Fig. 1 Range chart for KOBELCO EH series

Table 1 Basic specifications of 100 barG oil-flooded screw compressor

Max. working discharge pressure (barG)	100
Max. working suction pressure (barG)	100
Casing design pressure (barG)	115
Capacity range (m^3/h)	200〜20,000
Rotor material	Forged steel
Casing material	Cast steel
Mechanical seal	SiC+SiC
Bearings : Radial	Babbittes sleeve type
Thrust	Tilting pad type
Capacity Control	Step less 100〜15%

1. Construction and features of 100 barG oil-flooded screw compressor

Fig. 2 is a cut-away view of an oil-flooded screw compressor having a discharge pressure of 100 barG. Gas is introduced into a suction nozzle, compressed by a pair of male and female rotors engaging each other and discharged from an outlet. Each rotor has radial bearings on both of the sides along the shaft and a thrust bearing installed on the discharge side of the radial bearing away from the rotor. A mechanical seal, disposed at the portion of the male rotor passing through the casing, prevents the compressed gas from leaking outside.

1.1 Rotor tooth profile

The most important feature of Kobe Steel's screw compressors is their tooth profiles, which have been continually developed and adapted for various applications. The following conditions must be met in order to achieve high volume efficiency:
- shortening the seal line between the rotors for each unit of displacement volume,
- minimizing the size of the passage way called "blow-whole" created by the male/ female rotors and the casing,

and
- optimizing the rotor wrap angles for minimizing the pressure ratio in each of the grooves.

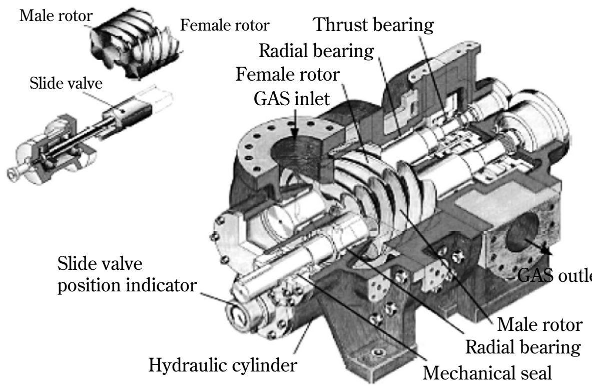

Fig. 2 Construction of 100 barG oil-flooded screw compressor

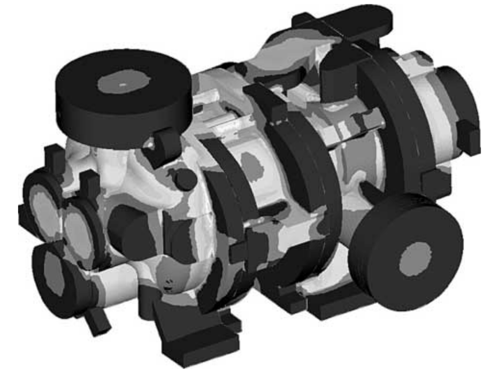

Fig. 3 FEM analysis of casing stress

These conditions, however, cannot easily be met simultaneously. To this end, Kobe Steel has developed a simulation program based on a unique theory on tooth profiles. The simulation program allows the designing of the most suitable tooth profiles for various applications. The tooth profile of the 100 barG oil-flooded screw compressor was designed using this program. The program includes bearing load simulation and performance simulation based on gas pressure and other parameters, including the number of teeth and rotor lengths. The simulations lead to a rotor combination, most suitable for a high load, consisting of a male rotor having five teeth and a female rotor having seven teeth (5 + 7 tooth profile).

1.2 Bearings

The compressor adopts sleeve-type radial bearings and thrust bearings of the tilting pad type. The high discharge pressure is supported by the bearings, which are selected to be large enough to bear the load. Adopting the "5 + 7 tooth profile" has enabled the radial bearings to have large enough bearing surfaces. The standard material for the bearings is white metal, with an alternative use of aluminum for the bearings exposed to corrosive gas.

1.3 Mechanical seal

The mechanical seal of a compressor is single-type, double-type or tandem-type, depending on the customer's needs.

The pressure inside the box of a mechanical seal becomes almost equal to the suction pressure during the run. This means the mechanical seal strongly affects the maximum suction pressure of an oil-flooded screw compressor.

All the seal components are made of silicon carbide (SiC) which endures high suction pressure and assures durability.

1.4 Casing

An FEM stress analysis was conducted to optimize the casing for high discharge pressure. Included in the analysis were wall thickness and rib shapes. **Fig. 3** shows the result of the casing stress analysis.

A casing was designed, based on the above analysis, and was tested for its mechanical strength. A compressor using the casing was test-run to ensure operation at the discharge pressure of 100 barG. The performance measurement was conducted using a testing apparatus built in-house. In addition, the gas discharged at the pressure of 100 barG was analyzed for its oil content to verify the effectiveness of oil separation.

2. Applications of the oil-flooded screw compressor with 100 barG discharge pressure

Fig. 4 is a schematic diagram of a typical oil-flooded screw compressor. After passing a suction filter and check valve, gas is compressed to a high pressure. The oil-flooded screw compressor uses a large amount of oil for lubricating the rotors and bearings and for removing compression heat. The oil has to be separated and removed from the compressed gas to an acceptable level. The oil is recovered in a first separator and then fed into the compressor via an oil-cooler. The oil remaining in the compressed gas is removed further by high-order separators employing a special filter made of fine fibers.

The following describes the practical applications which can fully exploit the features oil-flooded screw compressors having discharge pressures up to 100 barG.

<Petroleum refining>
- Compressors for desulfurization
- Net-gas booster compressors
- Off-gas compressors

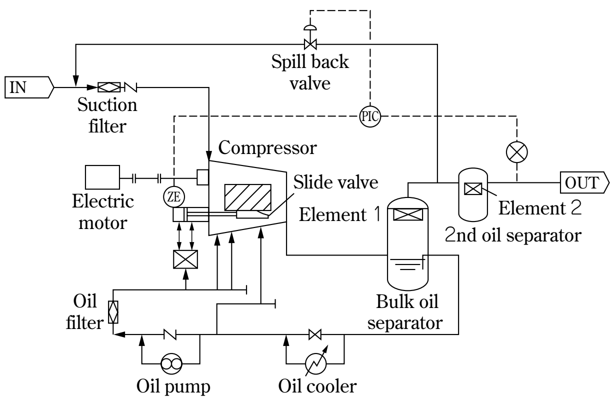

Fig. 4 Schematic diagram of oil-flooded screw compressor

<Petrochemical>
- Hydrogen compressors
- Carbon dioxide compressors

<Energy>
- Fuel gas compressors for gas turbine

<Oil & Gas>
- Gas-lifting compressors for offshore rigging
- Booster compressors for LNG pipelines

Conventionally either reciprocal compressors or centrifugal compressors have been used for those applications; however, an increasing number of oil-flooded screw compressors are being used for pressure ranges up to 60 barG. This is because the oil-flooded screw compressors have the advantages of positive displacement compressors which are highly reliable and unaffected by the type of gas. The following section introduces typical applications that can employ oil-flooded screw compressors.

2.1 Compressors for desulfurization

Sulfur in gasoline and diesel fuels is a global environmental concern, and reducing the sulfur content poses challenges to petroleum companies around the world. Desulfurization is a process for removing sulfur from fuel using hydrogen and requires a hydrogen compressor, commonly known as a "recycled gas compressor". The gas consists mainly of hydrogen, but also contains a small amount of hydrogen sulfide, which is corrosive. Occasionally, the gas also contains heavy hydrocarbons, such as methane, propane and butane, which can dissolve into the lubricant and lower the oil's viscosity. Nitrogen may be used during the start-up of a plant. The gas content can be affected by the desulfuration process. Thus, the compressors must be able to respond to various gas and operation patterns. In addition, the compressors are required to achieve high reliability and to run continuously for extended periods.

As described above, the lubricating oil poured into the interior of an oil-flooded screw compressor may have a viscosity decreased by the dissolved gas i.a., heavy hydrocarbons. This can deplete the oil film in the bearings and mechanical seals, causing the parts to wear. This limits the use of oil-flooded screw compressors for those applications; however, a newly developed synthetic oil, polyalkyl glycol (PAG), which has resistance to heavy hydrocarbon, enables the use of the compressors for hydrocarbon containing gases.

Fig. 5 shows a typical compressor used for desulfurization. The compressor is being used as a net-gas booster, a major apparatus for desulfurization, which requires even higher reliability. Going forward, the compressor is expected to be used for desulfurizing diesel fuel, which requires a discharge pressure at the 100 barG level.

2.2 Hydrogen compressor

Hydrogen is widely used in the petroleum refining and petrochemical fields and is purified by various methods, including pressure swing adsorption (PSA), membrane separation and electrolysis. Hydrogen is usually produced at a low pressure (near atmospheric pressure) and, usually, is sucked into a compressor at that low-pressure. Compressing hydrogen from a state of such low pressure to the high pressure specified by each application requires a compressor with a high pressure ratio. However, hydrogen, with its small molecular mass, is prone to leak, making it difficult to boost the gas with a high pressure ratio. Thus, hydrogen is conventionally compressed in more than one stage. **Fig. 6** shows a hydrogen compressor.

The lubricating oil poured into the rotor chamber of an oil-flooded screw compressor during the run decreases the gas leakage from the rotors and suppresses the temperature rise caused by gas compression. This enables single stage compression with a high pressure ratio. In addition, Kobe Steel's

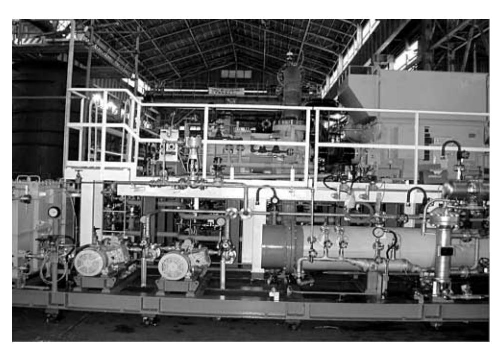

Fig. 5 Screw compressor for desulfurization process

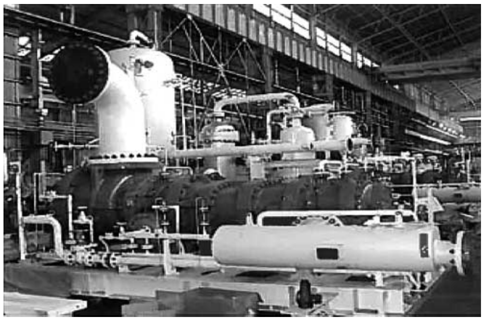

Fig. 6 Screw compressor for hydrogen process

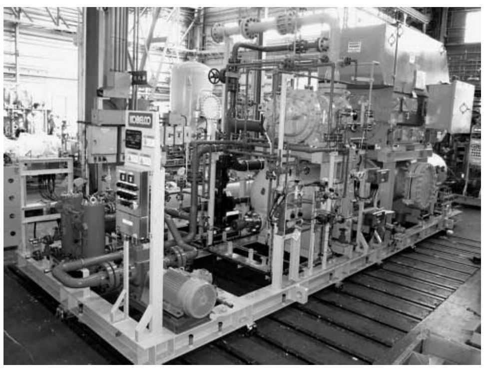

Fig. 7 Screw compressor for gas turbine fuel gas

original tandem arrangement enables dual stage compression in a single casing using neither connecting piping, nor an intermediate gas cooler. The new arrangement simplifies the entire compressor, improves the reliability, eliminates the need for reserve machines and decreases the footprint.

The newly developed oil separation technology using a coalesce filter does not affect the downstream of the compressors and enables oil purification by activated carbon adsorption up to a 50 ppb level if required.

2.3 Screw compressor for gas turbine fuel gas

Another example of an application taking the advantages of the oil-flooded screw compressors is fuel gas compressors for gas turbines. Recent fuel gas compressors require high discharge pressure to improve turbine efficiency. The series of oil-flooded screw compressors made by Kobe Steel, including the newly developed compressor with 100 barG discharge pressure, achieve the gas volumes and pressures required by almost all the modern gas turbines. **Fig. 7** shows the appearance of a fuel gas compressor unit.

A fuel gas compressor for gas turbines must be able to maintain a constant discharge pressure regardless of the variations in the turbine load and supply pressure (suction pressure). Kobe Steel exploits the combined features of two valves, slide valves and spill-back valves, for controlling the gas volume and pressure. Slide valves decrease power consumption during partial loading, while spill-back valves have improved stability and load following capability.

Now, an increasing number of oil-flooded screw compressors are being used for gas compression for gas turbines.

3. Advantages of oil-flooded screw compressors

3.1 Pressure fluctuation and capacity control

Fig. 8 shows the typical load characteristics of an oil-flooded compressor running at a constant discharge pressure with fluctuating suction pressure. In an oil-flooded screw compressor running at a low pressure ratio, increased suction pressure decreases power and increases the gas volume processed. The compressor type is usually selected based on the minimum suction pressure. In reality, however, the compressors run with higher suction pressures and at lower capacities than the designed conditions (100%).

Kobe Steel's oil-flooded screw compressors, with their volume control capability using the slide valves, save energy during operations.

3.2 Energy-saving

Under the conditions where the suction pressure fluctuates significantly, as in the case of the source pressure of gas pipeline, compressors often operate with higher suction pressures and with lower pressure ratios than the designed points. In addition, the source pressure may vary greatly and may exceed the discharge pressure of a compressor. Oil-flooded screw compressors consume less power in such situations where the pressure conditions vary significantly.

Fig. 9 shows an example of a system employing

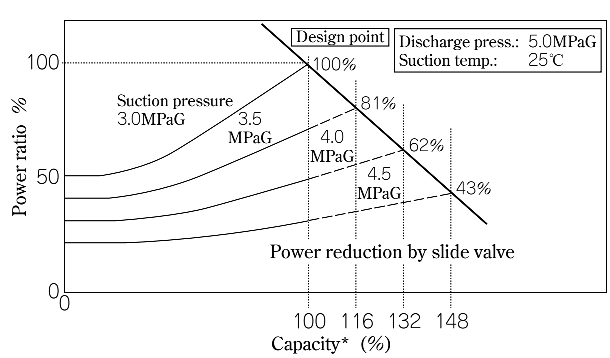

Fig. 8 Typical load characteristics of an oil-flooded compressor

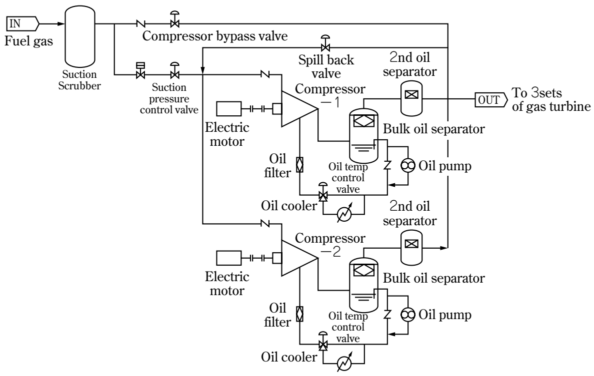

Fig. 9 Oil-flooded screw compressor system (case 1)

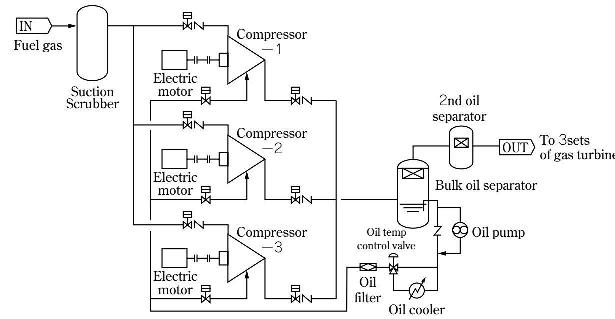

Fig.10 Oil-flooded screw compressor system (case 2)

more than one compressor. The depicted system employs two compressors supplying fuel gas to three gas turbines. A bypass line allows the fuel gas to be fed direct, without passing through the compressors, when the source pressure becomes high. The system integrates a suction pressure control valve with a spill-back valve to achieve a small footprint. The unified pipeline, connecting the two compressors and the three gas turbines, simplifies the site installation work.

3.3 Cost-saving

Fig. 10 shows a system having three compressors for supplying fuel gas to three gas turbines, one of which is for reserve. Thus the three compressors share apparatuses, such as an oil recovery tank, separator and lubricant pump, designed for the gas volume for two turbines. This construction decreases the system cost, as well as the footprint.

3.4 Adding values to the process gas

Coke oven gas (COG) is a by-product of the coking process and is commonly used, for example, for hydrogen Pressure Swing Adsorption (PSA), gas cutting and fuel. COG contains a considerable amount of impurities, e.g., tar, naphthalene, BTX (benzene, toluene and xylene) and hydrogen sulfide, which must be removed before use. Kobe Steel's oil-flooded screw compressor has been adopted in this COG application, which has attracted attention because this has not been done anywhere else in the world.

The lubricating oil, flooded into the rotor chamber of the screw compressor, serves to clean the tar and dust in the COG being compressed. The oil separator and lubricant filter on the discharge side remove the dust and pass the cleaned gas to the downstream.

Injecting the lubricant into the compressed gas not only cools, but also cleans the gas and thus adds value to it. This application is an exemplary case, exploiting the features of oil-flooded screw compressors, and indicative of the future.

Conclusion

Kobe Steel will continue to expand the applications by further improving the intrinsic features of oil-flooded screw compressors, as well as their applicability to high discharge pressures. Furthermore, Kobe Steel will strive to develop new applications exploiting their features and thus contribute to the industry.

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World's Largest Capacity Oil-free Screw Compressor, MODEL KS80

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Large capacity oil-free screw compressors are mainly used in petrochemical plants such as styrene monomer and linear alkyl benzene plants, where suction and discharge pressures are relatively low and a large capacity is needed. Recently, these plants have tended to become larger and the capacity required of the compressor has also tended to increase. To satisfy such a market needs Kobe Steel has developed the world's largest capacity oil-free screw compressor, MODEL KS80, using the design technology and manufacturing technique of the large screw compressor. In this paper, the design concepts and features of MODEL KS80 are introduced.

Introduction

Kobe Steel's oil-free screw compressors are widely used for process gases in various industrial fields, such as petrochemistry, general chemistry, petroleum refining and the gas industry. Large capacity oil-free screw compressors, which work at low pressures, are used in petrochemical plants. Examples are found in the production of styrene monomer and linear alkylbenzene. The former is used as the raw material for, e.g., polyester resin, synthetic rubber and styrene resins, while the latter is used as synthetic lubricant and as the raw material for detergents. Kobe Steel has delivered many oil-free screw compressors, including EX-series compressors, which have large capacities and are designed for the low pressure required by those applications.

Recently, as styrene monomer plants have become larger, the required flow rate in the process stream has increased. In response to market needs, Kobe Steel has developed an oil-free screw compressor for process gas, MODEL KS80, which has the world's largest volume capacity. This paper introduces the design concepts and features of the newly developed MODEL KS80.

1. Applications

The following are the typical applications of large oil-free screw compressors:

- off-gas compressors for styrene monomer plants
- recycle gas compressors for linear alkylbenzene plants.

These applications may involve

1) large capacity
2) low discharge pressure
3) gas containing foreign matter
4) the possible polymerization of the monomer during compression and
5) water injection into the compressor chambers for suppressing the temperature rise caused by gas compression and for removing foreign matter from the gas.

The MODEL KS80 compressors are designed to satisfy these requirements.

2. Design specification

Table 1 compares the displacement volume of KS80LZ, the standard type of MODEL KS80 compressor, to that of KS63EX, the largest machine among the Kobe Steel's EX-SERIES compressors. KS80LZ has a pair of rotors, the size of the world's largest class, and achieves a displacement volume 20% above that of the KS63EX for a given rotor circumferential velocity.

The following describes the features of MODEL KS80.

2.1 Nozzle arrangement

As shown in **Fig. 1**, MODEL KS80 has suction and discharge nozzles, both directed downward. The advantages of this arrangement are as follows:

1) It enables to simplify the arrangement of a large silencer and piping in the same direction;
2) It does not require dismounting of the silencer and the associated piping from the compressor when compressor needs to be dismantled, which improves the workability for maintenance and other jobs; and
3) The discharge nozzle, directed downward, promotes the drainage of water injected inside the rotor chamber, as well as the discharge of

Table 1 Comparison of theoretical displacement volume at same tip speed

Specification	KS80LZ	KS63EX
Male rotor speed (rpm)	3,675	4,570
Theoretical displacement volume (m^3/h)	96,000	80,000

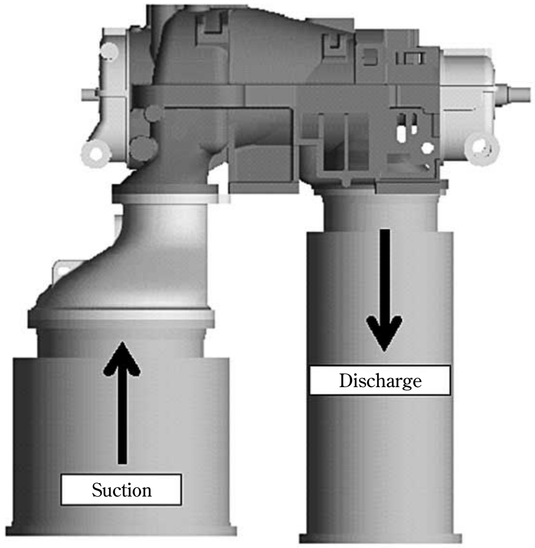

Fig. 1 Compressor nozzle layout of MODEL KS80

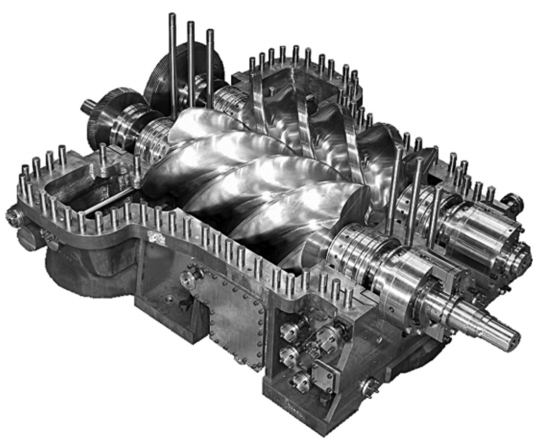

Fig. 2 Horizontally split compressor casing

solvent and foreign matter. Furthermore, the downward configuration protects the rotor from being damaged by solid matter, such as polymer, which might otherwise fall on the rotors.

2.2 Casing

Kobe Steel's large compressors adopt horizontally split casings, as shown in **Fig. 2**. This casing simplifies the assembly and disassembly of the compressor and facilitates the maintenance work.

The standard casing is cast from carbon steel. An option is available for protecting the interior surfaces of the rotor chamber from corrosion. In this alternative, austenitic stainless steel layers several millimeters thick are formed by clad welding. This is a suitable alternative for applications, for example, those in which water is injected. This clad welding is a technology put to practical use by Kobe Steel after years of trial and error. It should be noted that the clad structure, which also has excellent erosion resistance, is now used by many off-gas applications for styrene monomer. The clad structure also has the advantages of lower cost and better material availability compared with cast stainless steel.

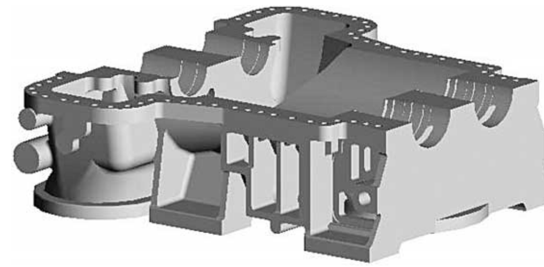

Fig. 3 3-D model of compressor casing

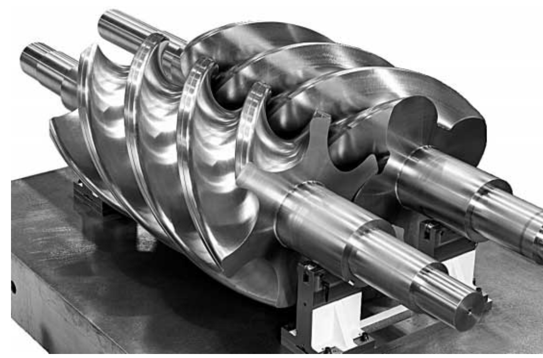

Fig. 4 Stainless steel rotor

Because the oil-free screw compressor has a complex casing structure, a 3D-CAD model, as shown in **Fig. 3**, is used to analyze the cast casing and the thermal deformation caused by temperature distribution. In addition, solidification simulation is adapted to prevent casting defects by predicting the defect positions before casting such a casing.

2.3 Rotors

The rotors are made of either forged carbon steel or of forged stainless steel, depending on their applications. Stainless steel rotors (**Fig. 4**), having high erosion resistance, are used for applications which involves, for example, water injection.

The rotors for MODEL KS80, as well as other EX-SERIES compressors, adopt the construction of non cooling by oil. The fabrication of such a rotor does not involve any welding step, thus reducing the cost and shortening the lead time. In an application where the suction and discharge pressures are low, the gas load acting on the rotors becomes small enough for the rotor shaft and bearing to secure enough rigidity with small diameters. This enables smaller sized bearings and shaft seals to be used, downsizing the compressor.

2.4 Shaft seals

Shaft sealing is one of the most important technologies for process gas compressors. Kobe Steel offers several options for the shaft seals of oil-free screw compressors, so that the users can select the type of shaft seal that best suits the specifications required by their applications. The following three types of shaft seal are commonly used in large compressors for petrochemical applications:

1) carbon ring seal with seal gas;
2) bearing oil film seal; and
3) dry gas seal (hydrostatic type).

MODEL KS80 compressors allow the use of any one of these shaft seals. Conventionally, a Kobe Steel large compressor has been built such that a hydrostatic-type dry gas seal is mounted/dismounted in the axial direction after the upper and lower bodies of the split casing are fastened together. MODEL KS80 compressors, on the other hand, are designed such that the hydrostatic-type dry gas seal can be mounted/dismounted in the horizontal direction before the upper and lower bodies of the split casing are fastened together. This construction facilitates the assembly and disassembly of the compressors and improves the maintenance workability.

2.5 Timing gear

The timing gears of Kobe Steel oil-free screw compressors have split construction, as shown in **Fig. 5**, to enable the backlash adjustment of gears. A gear backlash adjusted smaller than the rotor backlash prevents the rotors from contacting each other in the event of an emergency stop and improves the reliability of the compressors.

A high strength material is selected for the timing gears of MODEL KS80 compressors to ensure sufficient strength without increasing the gear size along the shaft direction. This minimizes the weight increase of the gears and improves the rotor stability.

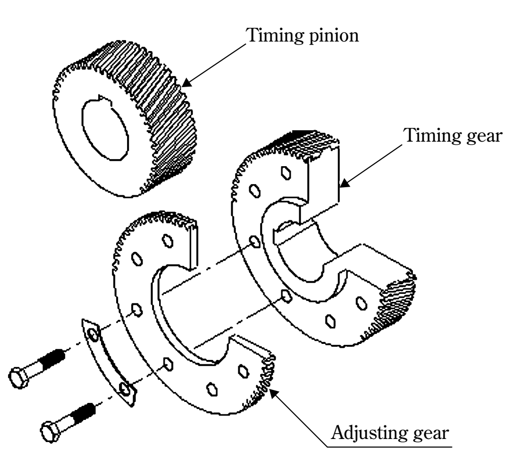

Fig. 5 Split piece timing gear

2.6 Water injection system

Water injection requires a nozzle designed for spraying water such that the water can easily vaporize. To ensure the uniform distribution of the sprayed water in the process gas, water is injected in the direction opposite to the gas flow. This minimizes the amount of erosion caused to casings and rotors by the injected water.

2.7 Silencers

To reduce the acoustic energy in the process gas pipes, each oil-free screw compressor made by Kobe Steel has silencers on both its suction and discharge nozzles. Generally, pulsation at the discharge side is greater than that at the suction side. Thus, the key is to reduce the acoustic energy at the discharge side effectively.

The rotational speeds of large screw compressors are relatively slow, and thus the frequencies of their discharge pulsation are low. Therefore, the low frequency pulse must be reduced to decrease the acoustic energy inside the discharge piping effectively. A wider range of pulses must be reduced for some applications, such as the off-gas application for styrene monomer, where a steam turbine is used for variable speed operation.

Kobe Steel owns the technology for designing silencers that are best suited for the respective gas and required acoustic characteristics. Thus, MODEL KS80 compressors can use a silencer designed to meet customer's needs.

2.8 Piping layout

Kobe Steel uses a 3D-CAD for piping layouts when designing compressor units (**Fig. 6**). The 3D-CAD allows advance checking of the piping interference and workability.

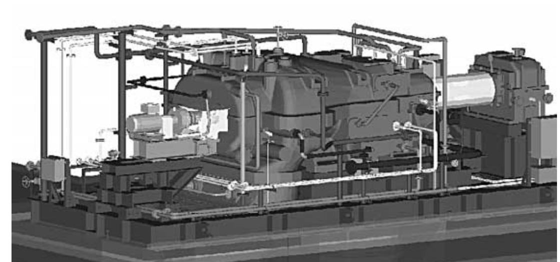

Fig. 6 3-D model of compressor unit

3. Build verification test

Kobe Steel conducts in-house test runs before shipping to verify the designed performance and stable operation. Furthermore, the tests on MODEL KS80 compressors include measuring the acoustic pressure inside the silencers, as described in Section 2.7, to confirm that the acoustic energy inside the piping is reduced as designed.

4. Future prospects

Fig. 7 shows a KS80LZ compressor delivered to a styrene monomer plant. The sales of MODEL KS80 compressors for such low-pressure, large-capacity applications are expected to expand. In addition, Kobe Steel will continue striving to satisfy market demands.

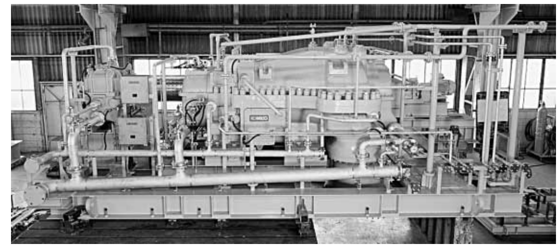

Fig. 7 World's largest capacity oil-free screw gas compressor for styrene monomer plant

Conclusions

Kobe Steel has been developing, designing, manufacturing and delivering many oil-free screw compressors for over fifty years. Kobe Steel will strive to expand the applications of oil-free screw compressors by developing new models and upgrading the existing models to meet market needs, making use of the company's technology and know-how.

Micro Steam Energy Generator

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Small steam plants are commonly found in various industries. Saving energy in such a plant is difficult, because the steam may have changes in flow, a small volume, or low-pressure. To resolve the issue, Kobe Steel has developed a series of small screw generators, called "micro steam energy generators." These generators enable the effective use of steam in small plants, saving more energy and reducing CO_2 emissions. They have an improved power output in the range between 132kW and 160kW. Two types of these generators are available: one is for a large pressure difference and the other is for a small pressure difference. The generators improve the efficiency by 58 to 74% compared with 132 to 160kW class steam turbines. This paper reports the test results for the newly developed generators.

Introduction

Global warming is an unavoidable issue worldwide. Japan has passed laws and created legislation, such as the "Law Concerning the Promotion of Measures to Cope with Global Warming" and the "Law Concerning the Rational Use of Energy". With these laws, Japanese industry has become even more environmentally conscious. In many industries, steam is used as a source of thermal energy for heating, desiccating, concentrating and sterilizing; however, it has not been effectively used. This is because

- the amount of steam varies depending on the running status of a plant;
- low-pressure steam (less than 1 MPaG) is difficult to utilize; and
- steam generated in a small amount (several tons per hour) is also difficult to utilize.

Large plants have stable supplies of steam in large quantities. In such plants, axial flow turbines and radial turbines are typically used to convert steam energy into kinetic energy and electric power. Large axial flow turbines have high efficiency; however, the turbines have difficulty in producing kinetic energy and electric power from steam with a small volume and low-pressure.

With this background, Kobe Steel has developed small screw generators, the "STEAMSTAR (TM)" series with an output power of 100kW. The generators effectively utilize steam having a small flow, low pressure and varying volume. By utilizing such steam, which is prevalent in industries, the screw generators save energy and reduce CO_2 emissions.

This paper describes the construction and operating principle of a new STEAMSTAR generator developed for higher power output than that of the previously developed machines. Also described are the test results of the newly developed generator using steam in a small plant.

1. Surplus steam in a factory process

In a typical steam plant, as shown in **Fig. 1**, a boiler generates steam, and a reducing valve decreases the pressure of the steam to a predetermined level. This steam with decreased pressure is supplied to thermal processes, such as heating and desiccation. The steam may be sufficient in volume when supplied for these processes; however, it does not necessarily produce pressure differences large enough to allow conversion into kinetic energy.

In another steam plant, as shown in **Fig. 2**, the amount of steam generated by the boiler may exceed the amount consumed by the processes. In such cases, the surplus steam is released into the atmosphere.

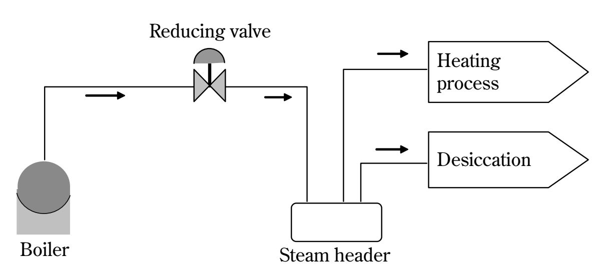

Fig. 1 General process flow in small-sized steam plant

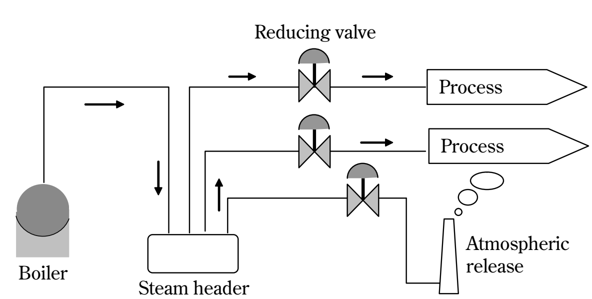

Fig. 2 Process flow in small-sized steam plant with excess steam

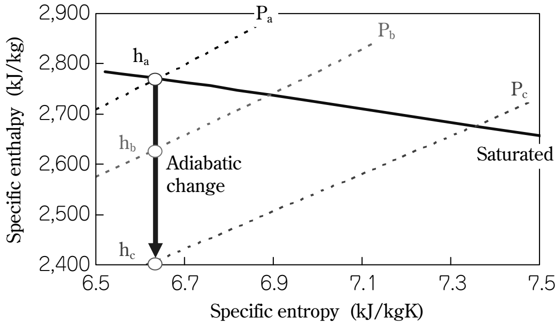

Fig. 3 State quantity of steam

Now, a comparison is made of the states of steam as shown in Fig. 1 and Fig. 2. **Fig. 3** is an enthalpy - entropy (h-s) diagram that shows the state quantities per unit mass of steam. Here, the vertical axis is enthalpy and the horizontal axis is entropy. In this figure, P_a is the steam pressure at the supply side of a STEAMSTAR generator; P_b is the process pressure on the secondary side of the reducing valve as shown in Fig. 1; and P_c is the atmospheric pressure for a case in which the steam is released into the atmosphere as shown in Fig. 2. The isobars for pressures P_a, P_b and P_c intersect with a saturated steam line linking the saturated steam points at each pressure. The adiabatic changes caused by the adiabatic expansion of steam are h_a-h_b for the case shown in Fig. 1, and h_a-h_c for the case shown in Fig. 2. A smaller amount of a unit volume of the steam used for the process shown in Fig. 1 compared with that recovered in the case shown in Fig. 2, where the steam is released into the atmosphere. The case shown in Fig. 1 requires a larger amount of steam to generate a given amount of kinetic energy and/or electric power than does the case shown in Fig. 2. A generator is needed to achieve high efficiency under the following two conditions:

1) large pressure difference and low flow rate
2) small pressure difference and high flow rate

2. Construction and principle

2.1 Construction and principle of screw expanders

Fig. 4 schematically shows the expansion stroke of a screw expander, the major component of STEAMSTAR. A screw expander has spaces (hereinafter referred to as "actuation spaces") formed by a male rotor, female rotor, and casing. Each actuation space has a pressure different from that of the others. Each rotor has surfaces, each of which receives pressure caused by the pressure difference between the high-pressure side and the low-pressure side after the expansion. The differential pressures cause rotation torques to act on the respective rotors, causing them to rotate in opposite directions. The rotations of the rotors isolate the actuation spaces from the air supply port. The actuation spaces increase in volume as they proceed toward the exhaust side, expand the steam inside the enclosed spaces and provide rotational energy to the rotors. The screw expander thus generates kinetic energy through this continuous sequence of actions[1).]

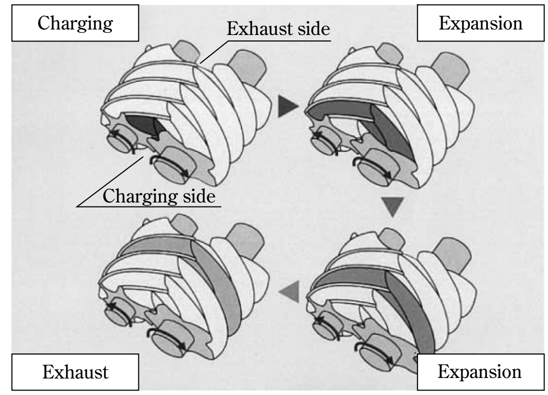

Fig. 4 Expansion stroke of screw expander

2.2 Construction of STEAMSTAR

Fig. 5 shows the construction of a STEAMSTAR generator and **Fig. 6** shows its appearance. As shown in Fig. 5, a timing gear is provided at the shaft end for synchronizing the male and female rotors. The rotors, not contacting each other, maintain spaces between them while rotating. In a conventional machine, the rotational forces of screw rotors are transmitted to generators via reducers. On the other hand, the newly developed machine uses gear couplings that directly connect the rotor shafts to a permanent magnet generator. The permanent magnet generator is oil cooled and has a high efficiency. Combining the newly developed machine with the generator achieves higher output. In addition, the newly developed machine rotates the rotors at a higher circumferential velocity to drive the high-speed generator.

As shown in Fig. 6, a STEAMSTAR generator is constructed as an all-in-one system, consisting of all the necessary units in a package in order to reduce its footprint and installation cost.

2.3 Characteristics of screw expanders

The hatched area, surrounded by an indicator diagram in **Fig. 7**, represents the amount of work generated by an ideal screw expander experiencing neither leakage nor loss. The vertical axis represents the pressure, while the horizontal axis represents the displacement volume. In the figure, the charging,

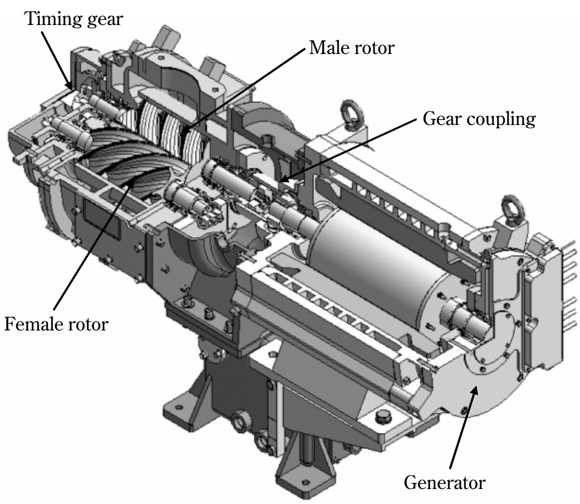

Fig. 5 Main structure of micro steam energy generator

Fig. 6 External view of micro steam energy generator

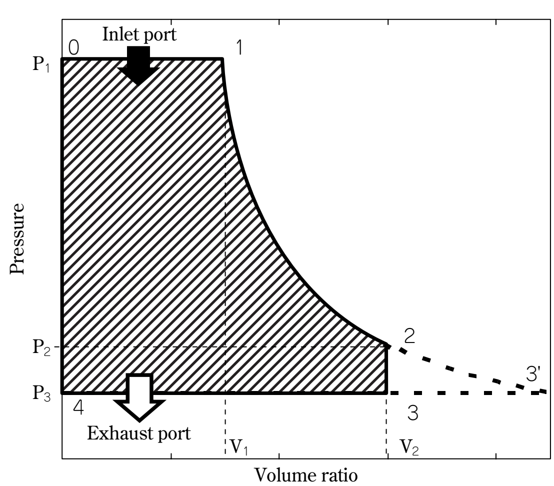

Fig. 7 Indicator diagram

expanding and discharging strokes of the expander are represented respectively by (0 to 1), (1 to 2 to 3) and (3 to 4)[2].

According to the definition of work, $W=\int Vdp$, the work done by the screw expander is given by integrating from P_1 to P_3. Here, P_1, P_2 and P_3 represent the supply pressure, internal exhaust pressure and exhaust pressure, respectively. In the figure, V_1 represents the specific volume of the suction port and V_2 represents the specific volume of the exhaust port. The steam flowing into the screw expander does the work by adiabatically expanding during the process from 1 to 2 and further expanding during the process from 2 to 3. It should be noted that Fig. 7 applies only to a case in which the exhaust pressure is lower than the internal exhaust pressure of the screw expander ($P_2 > P_3$).

Assuming the steam to be a perfect gas having a specific heat ratio of k, the technical work, Lth, which corresponds to the hatched area in Fig. 7 of an ideal screw expander, is given by the following[3].

$$Lth=\frac{1}{k-1}(P_1V_1-P_2V_2)+P_1V_1-P_3V_2 \quad \cdots\cdots\cdots\cdots\cdots(1)$$

Assuming that the process from 1 to 2 occurs as a polytropic change as in the case of real gas, the equation (1) is rewritten as follows, using a polytropic index, n:

$$Lth=\frac{1}{n-1}(P_1V_1-P_2V_2)+P_1V_1-P_3V_2 \quad \cdots\cdots\cdots\cdots\cdots(2)$$

By using the equation (2) and the state quantity of steam, $h_i = u_i + P_iV_i$, the technical work, Lth, done by an ideal screw expander is

$$Lth=(h_1-h_2)+(P_2-P_3)V_2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(3),$$

where u is internal energy.

Fig. 8 is an enthalpy-entropy (h-s) diagram showing the change in the state quantity of steam passing through an ideal screw expander. The steam isentropically expands from state 1 at the inlet to state 2 at the internal exhaust pressure and reaches state 3 at the exhaust pressure. State 3' is reached by an isentropic expansion to the exhaust pressure. The expansion gradually transforms the steam in a saturated state (state 1) into wet steam. After the isentropic expansion, the steam further expands inside the screw expander from the internal exhaust pressure to exhaust pressure, increasing the heat drop of the steam from h_1-h_2 to h_1-h_3. In other words, the kinetic energy recoverable from a unit mass of steam increases to h_1-h_3.

This means that the work generated by an ideal screw expander can be expressed as follows:

$$Lth=(h_1-h_3)G_{th}=(h_1-h_2)+(P_2-P_3)V_2 \quad \cdots\cdots\cdots(4)$$

where G_{th} represents the theoretical amount of steam passing through the ideal screw expander.

When the steam has a small pressure difference, as in the case of Fig. 1, the difference between h_1 and $h_{3'}$ in Fig. 8 decreases, and the amount of kinetic energy that can be recovered from a unit mass of steam decreases. In this case therefore, the mass flow

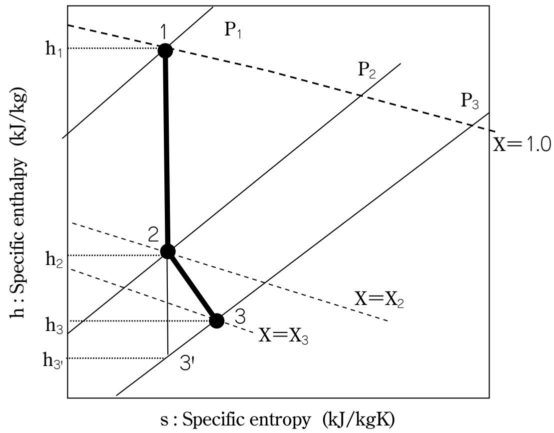

Fig. 8 h−s diagram of screw expander

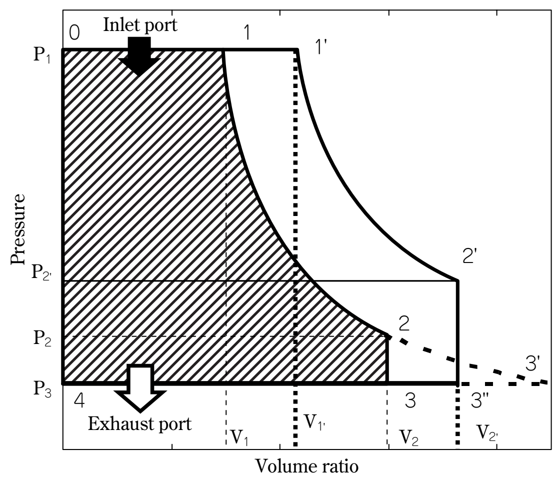

Fig. 9 Indicator diagram-1

G_{th} of steam must be increased in order for the screw expander to generate a high power. This is shown in the indicator diagram in **Fig. 9**. The area surrounded by 0 1' 2' 3'' 4 in Fig. 9 represents the work done by the screw expander. The figure shows that the increase in the amount of supplied steam from V_1 to $V_{1'}$ increases the amount of kinetic energy generated by the screw expander. However, the area, represented by the second term on the right side of equation (3), increases relative to the amount of work generated. This, as a result, decreases the amount of kinetic energy that can be recovered from a unit mass of steam.

When the steam has a large pressure difference, as in the case of Fig. 2, the difference between h_1 and $h_{3'}$ increases, and the amount of kinetic energy that can be recovered from a unit mass of steam increases. In addition, the increased pressure difference inside the screw expander decreases the difference between the internal exhaust pressure P_2 and exhaust pressure P_3. The area, represented by the second term on the right side of equation (3), decreases relative to the area surrounded by 0 1 2' 3'' 4 in **Fig. 10**, the area representing the amount of work done by the screw

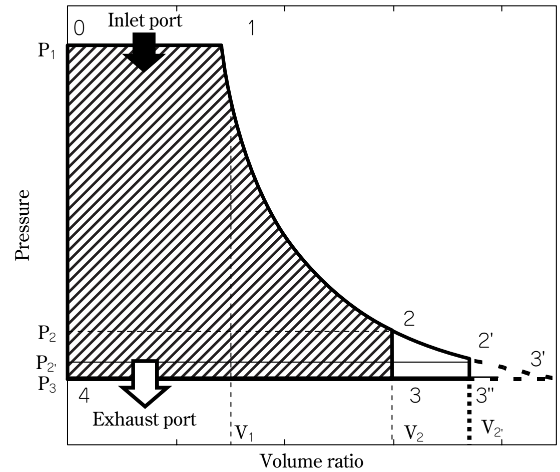

Fig.10 Indicator diagram-2

expander. The kinetic energy is nearly adiabatic.

Here, the volumetric efficiency, η_V, is defined as follows[4] :

$$\eta_V = G_{th}/G_r \quad \cdots\cdots(5),$$

where G_r is a supply flow reflecting the steam leakage that occurs in actual screw expanders and G_{th} is an ideal supply flow without the leakage.

Counting the mechanical loss, radiation loss, fluid friction loss and electrical loss that occur before the power is output, the electric power L_e generated by a unit mass of steam is expressed as follows:

$$L_e = \eta_G \eta_m Lth = \eta_G \eta_m \eta_V L_{ad} \quad \cdots\cdots(6),$$

where, η_m is mechanical efficiency, η_G is the efficiency of the electrical apparatus, and L_{ad} is the adiabatic kinetic energy of steam flowing into the screw expander.

Assuming η to be the ratio of the electric power L_e per unit amount of steam divided by the heat drop, $h_1 - h_{3'}$, of steam as shown in Fig. 8, L_e is given by the following:

$$L_e = \eta (h_1 - h_{3'}) = \eta L_{ad} \quad \cdots\cdots(7),$$

where η represents the power generation efficiency of the STEAMSTAR generator.

3. Test facility for power generator

Table 1 summarizes the standard specifications of the STEAMSTAR generators. The two generators are designed for a maximum output of 132kW to 160kW respectively. One is adapted for high differential pressure and low steam flow and the other is adapted for low differential pressure and high steam flow. To adapt for different steam conditions, the low differential pressure type, advantageous for energy recovery from a small pressure difference, is designed for the allowable differential pressure of 0.65MPa. The high differential pressure type, advantageous for energy recovery from large pressure difference, is designed for the

Table 1 Standard specification of STEAMSTAR®

ITEM \ MODEL			M.S.E.G. 132L	M.S.E.G. 160L
Supply condition	Pres.	(MPaG)	0.2～0.95	
	Max temp	(℃)	210	
Exhaust pressure		(MPaG)	0～0.5	
Max differencial pressure		(MPa)	0.6 or 0.75	
Steam flow		(t/h)	1～5	
Output of power generation		(kW)	8～132	8～160
Power voltage		(V)	400/440	
Control method			Pressure control by a inverter	
Power generator			IPM synchronous generator	
Dimensions		(mm)	2,604×1,335×2,005	
Weight		(kg)	2,880	

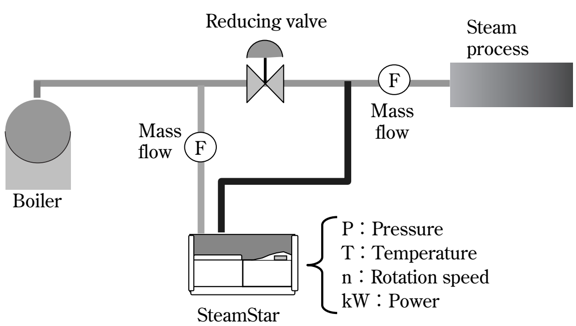

Fig.11 Flow chart of test facility

allowable differential pressure of 0.75MPa.

Fig. 11 is the flow diagram of a test facility for STEAMSTAR generators. The test facility comprises a boiler, a steam process, a reducing valve disposed between the boiler and the steam process, and a STEAMSTAR generator placed parallel to the reducing valve. This is a typical construction in which STEAMSTAR generator are used. The facility supplies steam to the process via the reducing valve when the amount of steam consumed in the process is significantly small. The reducing valve also operates when the steam exceeds the amount allowed by the STEAMSTAR generator. The state quantity of the steam and the power generation data are monitored by a steam flow meter, a pressure gauge, a thermometer and an electric power meter. The steam flow meter is disposed on the steam supply plumbing, while the pressure gauge, thermometer and electric power meter are placed in the STEAMSTAR unit.

4. Test results

The power output of a STEAMSTAR generator depends on the ratio between the supply pressure and exhaust pressure of the steam. It also depends on the flow rate of steam. **Fig. 12** shows the power output of the high differential pressure type, the 160kW generator for varying steam flow. The vertical axis represents the power output and the horizontal

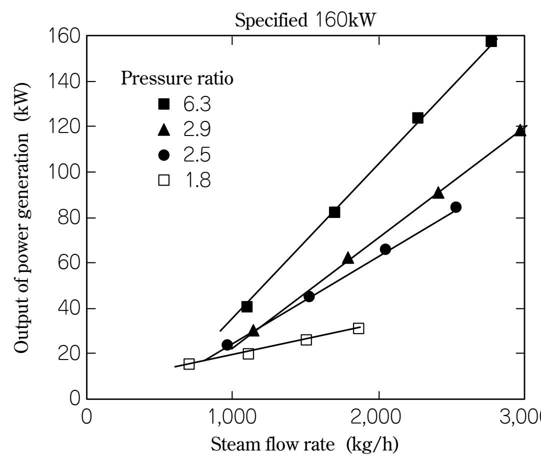

Fig.12 Relationship between output of power generation and steam flow rate for high pressure difference type expander

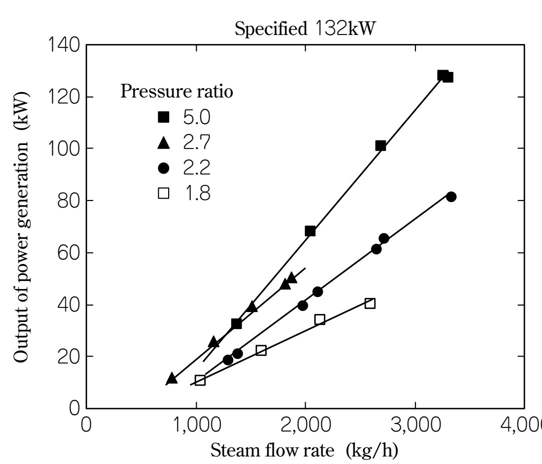

Fig.13 Relationship between output of power generation and steam flow rate for low pressure difference type expander

axis represents the amount of steam supply. As shown, a power output of 15 to 157kW is obtained for the amount of 700 to 3,000kg/h of steam. **Fig. 13** shows the power output of the low differential pressure type, 132kW, the generator for varying steam flow. Again, the vertical axis represents the power output and the horizontal axis represents the amount of the steam supply. As shown, a

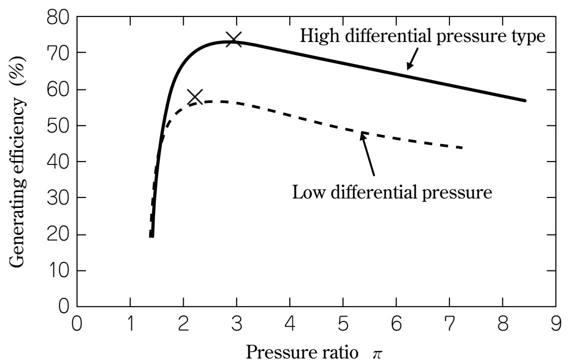

Fig.14 Relationship between pressure ratio and generating efficiency

power output of 12 to 128kW is obtained for an amount of 780 to 3,300kg/h of steam.

In either case, the output power increases proportionally to the supply of steam. A screw expander can adjust the amount of steam passing through it by adjusting its rotation. Thus the steam flow and power output become proportional to the rotation for a given pressure condition.

In both cases, a higher pressure ratio results in a larger power output for a given flow. For a given operating pressure ratio (e.g., 1.8) and a given steam flow, the high differential pressure type generator generates greater power than the low differential pressure type. Conversely, for a given steam flow, the low differential pressure type generates greater power than the high differential pressure type. In other words, to compare the two, the high differential pressure type generates greater power for a smaller steam flow while the low differential pressure type generates greater power for a larger steam flow.

Fig. 14 shows the relationship between pressure ratio and generating efficiency. In the figure, the solid line represents the generating efficiency expected for a high differential pressure type screw expander when the exhaust pressure varies from 0.5 to 0.0MPaG at the supply pressure of 0.75MPaG. The dashed line represents the generating efficiency expected for a low differential pressure type screw expander when the exhaust pressure varies from 0.5 to 0.0MPaG at a supply pressure of 0.65MPaG. It should be noted that the expected generating efficiency values in Fig. 14 are calculated from the test results, taking into account the mechanical loss and electrical loss of the testing apparatus. The "×" marks in the figure are measured values for the high differential pressure type and low differential pressure type respectively.

For both types of generators, the generating efficiency peaks around the internal pressure ratios of the screw expanders. The efficiency decreases drastically when the operating pressure ratio falls below the internal ratio. On the other hand, the generating efficiency gradually decreases with an increasing pressure ratio in the region in which the operating pressure ratio exceeds the internal pressure ratio.

As shown in Fig. 14, the maximum generating efficiency for the high differential pressure type is 78%, while that for the low differential pressure type is 58%. The overall generating efficiency is lower for the low differential pressure type. This is considered to be due to the fact that the low differential pressure type has a supply efficiency lower than that for the high differential pressure type. In addition, the low differential pressure type is subject to more leakage inside its expander than is the high differential pressure type.

Conclusions

Small steam generators (STEAMSTAR) using screw expanders have been introduced along with their constructions and operating principles. Experiments were conducted with two types of STEAMSTAR generators, namely, the high differential pressure type and the low differential pressure type. The generators were subjected to different steam conditions. The following summarizes the experimental results.

(1) The high differential pressure type STEAMSTAR for 160kW generates an output of 15 to 157kW for a steam flow of 700 to 3,000kg/h.
(2) The low differential pressure type STEAMSTAR for 132kW generates an output of 12 to 128kW for a steam flow of 780 to 3,300kg/h.
(3) For a given operating pressure ratio, the low differential pressure type generates greater power from a larger amount of steam than does the high differential pressure type.
(4) For a given operating pressure ratio, the high differential pressure type generates greater power from a small amount of steam than does the low differential pressure type.
(5) The maximum generating efficiency is 74% for the high differential pressure type and 58% for the low differential pressure type. In both cases, the maximum efficiency is reached at approximately the machines' own internal pressure ratios.

STEAMSTAR generators feature the capability of generating power from a small amount of steam with a varying flow. The two STEAMSTAR generators introduced in this paper have been developed to effectively use the surplus steam at the individual customer's site. The generators have been demonstrated to achieve high generating efficiency and high output ratio.

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High Performance Large Class Oil-free Screw Compressor

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High-performance, energy-saving equipment is much needed to address the growing concern for the environment. To meet such needs, Kobe Steel has developed high-performance, large class, oil-free screw compressors, the Emeraude-ALE series. This paper introduces the newly developed compressors, which combine the features of high efficiency, economic performance and high reliability.

Introduction

The electric power consumed by air compressors occupies 5% of the total energy consumed in Japan and 20 to 30% of the energy consumed by the manufacturing industry of the country (**Fig. 1**) [1]. Large air compressors rated 90kW or greater occupy only 1% in the total number of compressors shipped. However, due to their high power consumption those large compressors consume 20 to 25% of the total energy consumed by all the types of air compressors (**Fig. 2** [1] and **Fig. 3** [1]).

Most users of large air compressors are the designated energy management factories specified by the "Law Concerning the Rational Use of Energy" and are conscious about energy-saving. Thus, an increasing number of oil-free screw compressors are used in applications where ratings greater than 90kW are required. This is also the result of an increasing awareness of environmental issues. Among the large machines, the super-large air compressors rated greater than 300kW are used as the base-load machines for industrial plants. Typically, a super-large compressor is either a two-stage screw compressor or a turbo compressor. For base-load compressors, full-load performance is a more important factor in energy-saving.

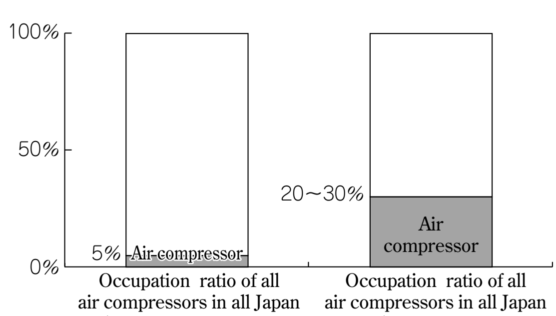


Fig. 1 Electricity consumption ratio of compressor [1]

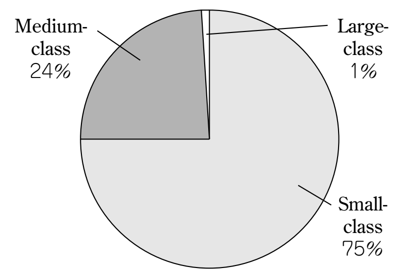


Fig. 2 Shipment ratio of compressor [1]

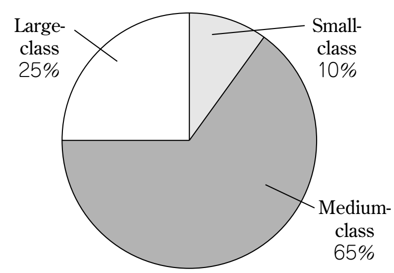


Fig. 3 Electricity consumption ratio of compressor [1]

In addition to full-load performance, screw compressors also have excellent partial-load performance. Because of this, they are used not only for base-load machines, but also for capacity controllers. In response to such needs, Kobe Steel has developed large oil-free screw compressors with high-performance and excellent energy-saving features.

1. Large oil-free screw compressor, Emeraude® ALE® series

Kobe Steel has a product line-up of oil-free screw compressors for general purposes, namely, the Emeraude FE series rated from 15 to 55kW and the Emeraude ALE series rated from 45 to 290kW. In addition to the existing product line-up, the company has newly developed the large Emeraude ALE series rated from 305 to 400kW. This is in response to the growing need for a large oil-free screw compressor that can be used in both ways as a base-load machine and as a capacity controller. **Table 1** summarizes their specifications and **Fig. 4** shows the appearance of a newly developed compressor.

Table 1 Specifications

TYPE		ALE305W	ALE340W	ALE370W	ALE370WE	ALE400WE
Frequency		50/60				
Motor output	kW	305	340	370	370	400
Discharge pressure	MPa	0.69			0.93	
Discharge air volume	m^3/min	56.9/56.9	63.5/63.6	69.0/69.1	56.8/56.8	63.4/63.5
Shaft power	kW	304.1/304.4	338.8/339.0	367.8/368.4	357.7/357.4	396.3/397.1
Dimensions (W×D×H)	mm	3,500×2,000×2,400				
Weight (3000V type)	kg	7,700	7,900	8,200	8,200	8,500

Fig. 4 New large class oil free compressor Emeraude-ALE

Fig. 5 Plate fin type gas cooler

2. Features of large Emeraude ALE

2.1 Improved full-load performance

Because the air compressors of the 300kW class are frequently used as base-load machines, Kobe Steel placed priority on the full-load performance. Firstly, a two-stage compressor unit was adapted for improved performance. More specifically, the newly developed unit employs a screw rotor larger than the conventional one and rotates it at a low revolution to reduce mechanical loss. Optimized intermediate pressure has reduced the power loss caused by insufficient or excessive compression. This new arrangement has improved the performance by approximately 3%.

Secondly, the newly developed air compressor uses plate fin coolers (**Fig. 5**) to its intercooler and aftercooler. In a plate fin cooler, water passes through a pipe whose outer surface is exposed to air. The plate fin cooler slows down the airflow and reduces pressure loss. Its large heat-transfer surfaces on the air side allow relatively compact design. The plate fin cooler exhibits an air pressure loss of 0.005MPa or less, while a conventional shell-and-tube cooler exhibits a pressure loss of about 0.01MPa or greater. Thus, the plate fin coolers reduce pressure loss and save power. The saved power is utilized for compression work, which improves performance by approximately 4%.

The above improvements have realized a performance improvement of approximately 7% in compound total compared with Kobe Steel's conventional series. The newly developed large compressors perform at the world's highest level, unrivaled by any other large machines (**Fig. 6**).

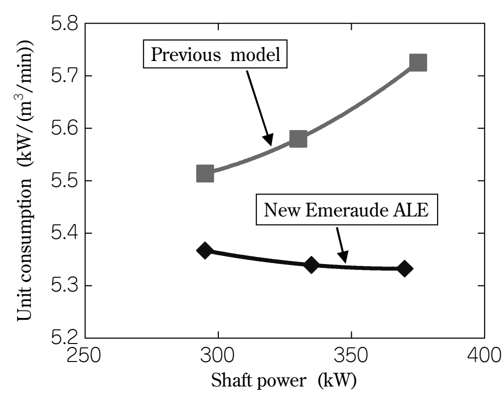


Fig. 6 Performance comparison

2.2 Improved partial load performance

In general, the larger the air compressors the more often they are used as base-load machines. In the case of screw compressors, however, the machines are also used for capacity control on many occasions. This requires the further improvement of partial-load performance, an intrinsic feature of a screw compressor.

Conventionally, a pressure differential of 0.1MPa has been applied to the pressure control. The newly developed compressors have a pressure differential controllable to a minimum of 0.05MPa with their

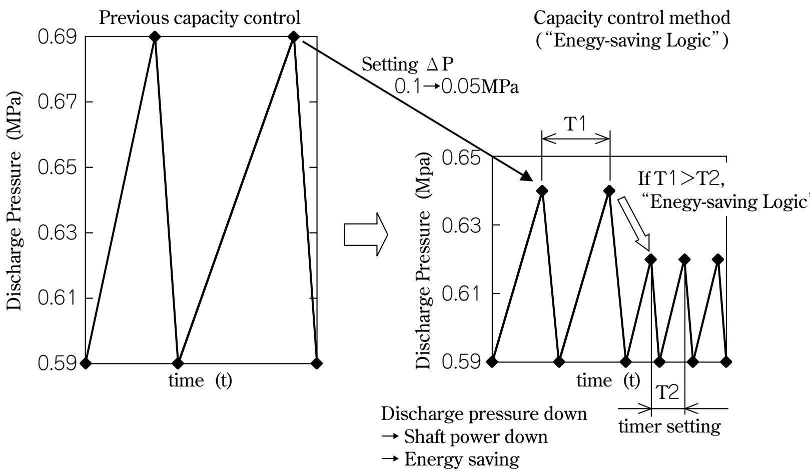


Fig. 7 Capacity control method

robust mechanism for capacity control, including a new capacity control valve. This eliminates the redundant pressure boosting, with a 3% conservation of energy for a given load pressure, compared with the conventional series.

In order to save energy in a load/unload control scheme, the starting pressure for unload operation must be as low as possible while keeping the downstream pressure at the required level. In a conventional oil-free screw compressor, the pressure differential of the control is fixed at the initial setting. As a result, increasing air consumption during the load operation decreases the rate of pressure rise. The decreased rate of pressure rise prolongs the duration in which the machine runs at a high discharge pressure, resulting in an increased consumption of power.

To resolve this issue, each newly developed compressor includes an internal timer. The timer forces the operation to switch from load to unload, depending on the status, such that the pressure differential of the control is kept to the minimum level. The compressors are also equipped with an energy-saving logic which enables operation in an energy saving mode. The internal timer and energy-saving logic are among the standard features of the new compressors. The new features forcibly switch load operation, extending over a certain period, to unload operation, regardless of whether or not the downstream pressure reaches the starting pressure for the unload operation. **Fig. 7** compares the pressure profile of the newly developed capacity control with that of a conventional capacity control. The newly designed capacity control valve decreases the pressure differential of the control from the conventional differential of 0.1MPa to 0.05MPa. This is because the valve can halve the cycle period between the load and unload. In the second cycle and thereafter, the timer switches the load operation to the unload operation even before the starting pressure of the unload operation is reached. This allows the pressure to be maintained at a level above the lower limit, without being increased more than necessary and, thus, saves power.

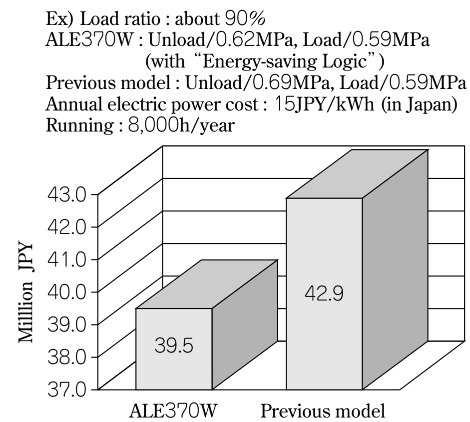
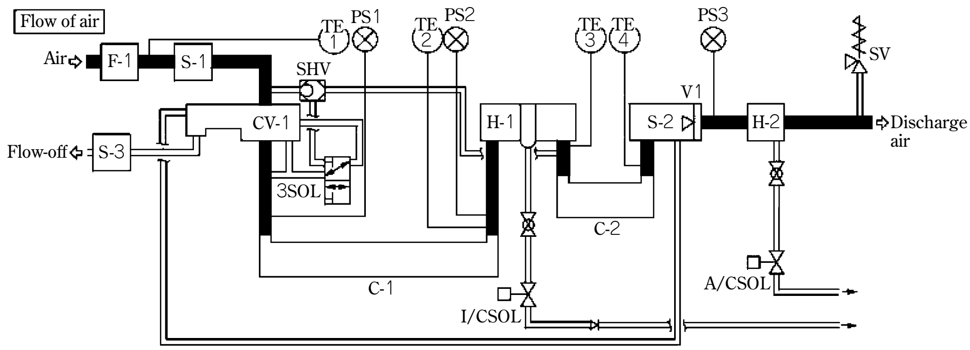


Fig. 8 Power cost comparison

Fig. 8 compares the electric cost of a large Emeraude ALE compressor with the energy-saving logic and that of a conventional machine, both under standard operating conditions. As shown in Fig. 8, the newly developed compressor saves about 9% of electric power, which corresponds to the saving of 3.4 million yen per year, assuming 8,000 hours/year of operation and 15 yen/kW of electric unit cost. This equates to a power reduction of about 230,000kWh and an emission reduction of about 125 tonne of CO_2/year. The emission reduction is based on the default value, 0.000555t-CO_2/kWh, according to the 2006 ordinance by the Ministry of Economy, Trade and Industry (METI) and Ministry of the Environment (MOE).

Also included in the standard features are an auto start-stop function and a weekly timer. The former feature automatically stops the motor after an extended unload operation and starts the motor



Symbol	Name	H-2	After-cooler	A/C SOL	Solenoid valve for after-cooler drain	TE1	Themocouple for 1st stage suction air temperature
C-1	1st stage compressor	F-1	Suction filter	V1	2nd stage discharge air check valve	TE2	Themocouple for 1st stage discharge air temperature
C-2	2nd stage compressor	SV	Safety valve				
CV-1	Volumetric regulator valve	SHV	Shuttle valve	PS1	1st stage suction air pressure sensor	TE3	Themocouple for 2nd stage suction air temperature
S-1	Suction silencer	3SOL	Three-way solenoid valve for volumetric regulator valve				
S-2	Discharge silencer			PS2	1st stage discharge air pressure sensor	TE4	Themocouple for 2nd stage discharge air temperature
S-3	Blow-off silencer	I/C SOL	Solenoid valve for inter-cooler drain	PS3	2nd stage discharge air pressure sensor		
H-1	Inter-cooler						

Fig. 9 Diagram of large class oil-free compressor

when the pressure is decreased to a preset level. The latter feature allows seven patterns to be set for starts and stops. Yet another feature, also standard, allows two of the compressors to be operated alternately without an additional control panel. These features contribute to further energy-saving.

2.3 Improved durability

The compressor units have improved durability and reliability realized by enhanced filtration to clean the lubricant oil poured into the bearings of the units.

The capacity control valves are six times more durable than conventional ones, in term of the number of times of actuation. The conventional valves are less durable because they employ dish-shaped diaphragms in their moving parts. Such a diaphragm has a large pressure-bearing surface which exerts a large force on the fixed parts, lowering the valve's durability. The newly employed capacity control valve uses a rolling diaphragm with a smaller pressure-bearing surface which decreases the force exerted on the fixed parts. With these measures, the newly developed compressors have improved durability, enabling them to operate between load and unload states with half the cycle of the conventional machines. In addition, the maintenance cycle has been extended to three years, as opposed to the one year cycle for the conventional compressors.

Conventional shell-and-tube coolers are made such that water flows outside their pipes. Because of this, the conventional coolers suffer from water scale which can deposit where the water flow stagnates. The plate fin coolers used for the newly developed compressors pass water inside their pipes, which makes the water chamber less susceptible to the water scale compared with the shell and tube coolers and facilitates the maintenance work.

As a result, only lubricant and filters are changed during annual maintenance. The total maintenance costs have been reduced by extending the maintenance cycles of various other parts.

2.4 Enhanced monitoring

An extensive network of sensors (**Fig. 9**) sends information to an intelligent total control system (ITCS) where the information is consolidated. Thus, daily management information (e.g., pressure, temperature and hours of operation) is obtained simply by monitoring this system. The operational status of each unit is constantly monitored, which prevents troubles and unexpected shut-off. For example, a low oil-supply pressure triggers an alarm before emergency shut-off. Emergency shut-off is then avoided by taking appropriate measures, such as raising the pressure and/or changing the lubricant filters, during this alarm stage.

An operational history is recorded including data and alarms, such as for pressure and temperature; this record is logged every hour of the last twenty four hours and every five seconds of the last fifteen minutes, allowing the confirmation of the operational history.

The ITCS monitor displays required maintenance work such as lubricant and/or filter changes. Periodic maintenance ensures long-lasting operation with high reliability.

Optionally, a remote monitoring unit and a communication output (MODBUS) are available to meet the recent needs for central monitoring and laborsaving.

Conclusions

The large Emeraude series consist of oil-free screw compressors that have been developed and modified based on user needs. They also proactively address environmental issues. Kobe Steel will strive to develop compressors which meet future needs for energy-saving.

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Inverter-motor Driven, Water-injected, Oil-free Screw Air Compressor, EmerauDe-Aqua® Series

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Kobe Steel has developed a series, EmerauDe-Aqua, of oil-free screw air compressors which use water injected during compression for sealing and cooling their parts. Each compressor employs Kobe Steel's original noncontact screw rotors, driven by an interior permanent magnet (IPM) high-speed motor controlled by an inverter. The motor is directly connected with the screw rotors, to assure high performance for a wide range of flow volume.

Introduction

In Japan, air compressors as a whole consume about 50 billion kWh/year of energy. This equates to 5% of the total power consumed in the country and 20 to 30% of the power consumed by the country's manufacturing industry. Japanese businesses have been incorporating various energy-saving measures to comply with the Energy Saving Act and to protect the global environment. This includes the effective use of air compressors with high energy performance. Air compressors driven by inverter motors are widely recognized as energy-saving alternatives, and many businesses are converting their compressors to this type. As a matter of fact, Kobe Steel has been delivering an increasing number of oil-flooded air compressors driven by inverter motors since 2000. In 2007, their shipment volume exceeded 50% of the total volume of compressors shipped (**Fig. 1**). This trend extends to oil-free air compressors which discharge oil-free air.

In response to the need, Kobe Steel developed a series of oil-free screw air compressors driven by inverter motors, the EmerauDe-Aqua series (EA400AD-VS and EA650AD-VS), which went on the market in March, 2008. The new series of compressors features water-injection, which is more suitable for inverter motor drives. Their development combines the company's own technologies, namely the technology for oil-free dry screw compressors with noncontact units and the technology for oil-flooded screw compressors driven by inverter motors. Each of the oil-flooded screw compressors comprises a main unit and a high-speed, interior permanent magnet (IPM) motor connected directly to the main unit, a form of construction termed "overhang direct connection". This paper introduces the EmerauDe-Aqua series[1)-4)].

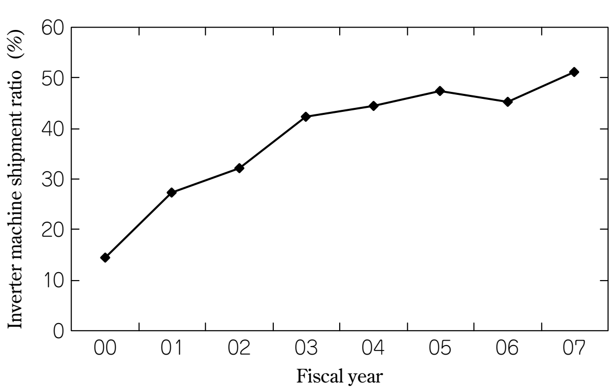

Fig. 1 Inverter machine shipment ratio in our medium-class oil-injected screw compressor

1. Product concept

The EmerauDe-Aqua series compressors were developed by combining the Kobe Steel's proprietary technologies for oil-free screw compressors and oil-flooded inverter driven screw compressors. The new concept aims at a highly efficient, energy-saving compressor for abating global warming. **Fig. 2** shows the appearance of an EmerauDe-Aqua compressor, while **Table 1** summarizes the specifications of the series of compressors.

Fig. 2 Outside view of EA650AD-VS

Table 1 Specifications

Type	EA400AD-VS	EA650AD-VS
Free air delivery (m^3/min)	3.7～4.0	6.2～6.5
Discharge pressure (MPa)	0.69～0.59	0.69～0.59
Rated motor power output (kW)	22.7	37.7
Noise level (dBA)	62	65

2. Features of EmerauDe-Aqua series

2.1 Non-contact unit directly driven by IPM motor

Fig. 3 is a cutaway view of the main unit of an EmerauDe-Aqua series compressor. The machine has a compression chamber into which water is injected, which significantly improves its performance as compared with conventional dry oil-free screw compressors. The water injected into the chamber during compression stroke improves compression efficiency by

- cooling the discharged air and
- fluidly sealing the clearances created by the male rotor, female rotor and casing to reduce the leakage of air.

Oil is injected into the compression chambers of oil-flooded compressors in a similar manner to improve performance. In an oil-flooded compressor, the male rotor directly contacts and drives the female rotor, using the oil as lubricant. In water-injected compressors, however, such direct contact and drive result in the seizure and wear of their metallic rotors because water has much less lubricity than oil. To avoid this issue, other companies use resin rotors adapted for water injection.

Each EmerauDe-Aqua compressor employs a timing gear for driving the male and female rotors, both metallic, in a noncontact state with a minute clearance between them. The timing gear is the same type as that used in dry oil-free compressors. Water is injected only during the compression, being used only for cooling and sealing during that process. This construction prevents performance deterioration due to wear when the male and female rotors contact each other in water. Metallic rotors achieve higher compression efficiency than resin rotors because metallic rotors, with their small thermal expansion, are less susceptible to dimensional change. In addition, they can be machined with high precision such that the clearances between the rotors and between the rotors and casing are kept minimal.

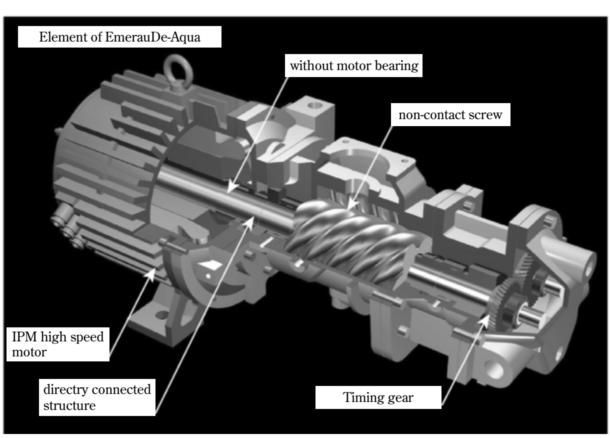

Fig. 3 Cross sectional view of EmerauDe-Aqua

The oil bath in an oil chamber lubricates the timing gears and bearings, which assures high reliability. Mechanical loss caused by the timing gears and bearings raises the temperature of the lubricant oil. The oil is cooled by water passing through the pipe provided in the oil chamber. This eliminates the need for oil recirculation and an oil cooler, which would be costly.

The shaft seal consists of a water seal, an oil seal, a hole vented to atmosphere and a drain hole. Both the vent and drain holes are provided between the seals. This arrangement prevents the water and oil from mixing. Oil leakage is prevented by an exhaust cleaner having an extremely small pressure loss. The exhaust cleaner, the same type as that used by Kobe Steel's dry oil-free screw compressors, vents the oil chamber to the atmospheric pressure.

The newly developed compressors adopt the same type of drive as that used for the inverter-driven oil-flooded screw compressors namely, an "overhang direct connection". In this type of drive, the shaft of the male rotor is directly coupled with the rotor of the electric motor in the screw compressor unit. This construction has eliminated the bearings for the electric motors. Also adopted is an IPM high-speed motor, which is excellent in overall efficiency and in performance for a wide range of partial load. As a result, the newly developed compressors have been significantly downsized and their weights reduced.

2.2 First class energy-saving performance

The EmerauDe-Aqua series compressors have achieved the largest discharge gas volumes in their class. This has been enabled by the newly developed compressor units of the water-injection type. The newly developed compressors, as well as the Kobe Steel's inverter-driven oil-flooded screw compressors, have the following three features.

- Wide range control: The power consumption of a compressor depends heavily on its discharge pressure. A low discharge pressure creates a margin in the power of the electric motor. The newly developed compressors monitor their discharge pressures such that the power margin created by lowered pressure can be used for increasing the revolutions. The increased revolution widens the control range (15 to 105% for EA650AD-VS) and increases the air volume. **Fig. 4** schematically shows how the wide range control increases the air volume.
- Start up using residual pressure: The newly

developed compressors can start up immediately after shut down, when air is needed.

- Inverter driven cooling fan: The cooling capacity required for a fan depends on the operating conditions and ambient temperature. A newly developed compressor controls the revolution of the fan by its inverter. Electric power is saved by reducing the fan revolution during low load operation or when the ambient temperature is low. **Fig. 5** shows the relation between the discharge temperature and the electric power consumed by the fan.

These features have made possible the discharge air volume that is the largest for any load condition, when compared with other compressors of the same class, as shown in **Fig. 6**.

Fig. 4 Concept of air volume increase

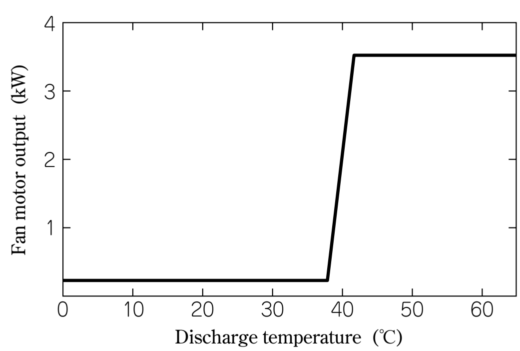

Fig. 5 Cooling fan output by inverter

2.3 Water quality management and corrosion resistance

The EmerauDe-Aqua series compressors have resolved the issue of water quality management associated with water-injection type compressors. This has been achieved by adopting a dryer drain recirculation.

Fig. 7 is a system diagram of an EmerauDe-Aqua series compressor. When initially poured into a compressor, water contains corrosive chloride ions. It also contains silica and calcium, both of which can form water scale. These can cause trouble if accumulated in the compressor in the long run.

The water drained from dryers, on the other hand, has a quality comparable to that of pure water. The newly developed compressors recover and re-circulate the drain water such that the detrimental constituents are diluted. This new feature has

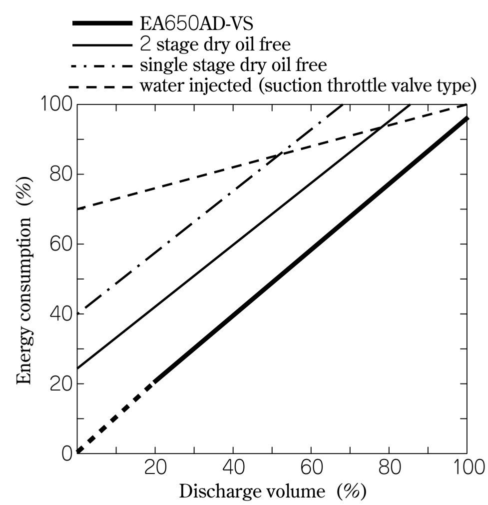

Fig. 6 Performance comparison (37kW class oil-free compressor)

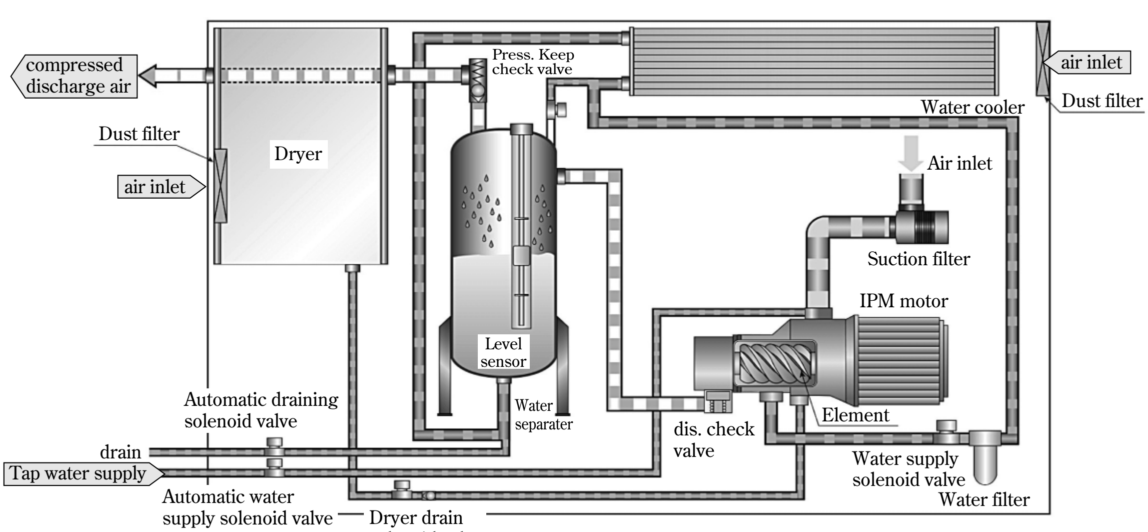

Fig. 7 System diagram

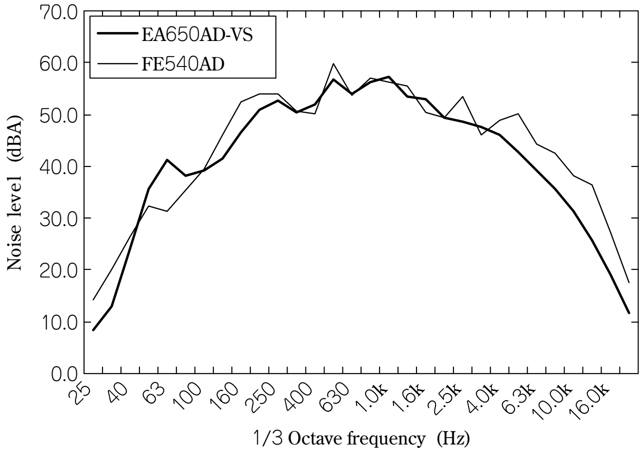

Fig. 8 Noise comparison

eliminated the water deionizing unit which has been required by conventional compressors of the water-injection type. All the water-contacting surfaces are made either of stainless steel, copper alloys, resin or rubber. Both of the measures described above assure corrosion resistance.

2.4 Most quiet of its class

The EmerauDe-Aqua series compressors are provided with measures against noise. A noise simulation technology originally developed by Kobe Steel for the noise control of railroads, construction machinery and highways was adapted for these compressors. **Fig. 8** compares the noise level of the EmerauDe-Aqua, EA650AD-VS, with that of a 2-stage oil-free dry screw compressor, FE540AD, also a product of Kobe Steel and having the same power as the former. Compared with the FE540AD, the EA650AD-VS has an improved sound quality with suppressed sound pressure levels in the high-tone range from 1.0 to 6.3kHz, which is dissonant to our ears. During full load operation, the EA650AD-VS exhibits the lowest noise level of all the machines in the same class. When operation load and/or ambient temperature are/is low, the revolution of the fan is reduced by the inverter control, further reducing the noise level.

Conclusions

The EmerauDe-Aqua series compressors accommodate today's most important environmental issues with their features of oil-fee and low-noise operations, and energy saving over a wide flow range. Kobe Steel will continue to strive to develop energy-saving air compressors and contribute to the abatement of global warming and the reduction of CO_2 emissions.

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Gas Energy Recovery Radial Turbine Generator System

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Gas energy recovery systems generate power from the pressure difference of gas. The systems are eco-friendly with reduced CO_2 emissions. An increasing number of them are being used around the world, Kobe Steel's radial turbines playing a key role. This paper introduces the energy recovery system based on the company's unique turbine technology. Also included are the company's activities aimed at the future expansion.

Introduction

In autumn 2008, Keiyo Gas Co., Ltd. introduced a system for recovering gas energy to generate electric power. The system employs a generator with a radial turbine developed by Kobe Steel. The turbine effectively utilizes the energy of adiabatic expansion, an unprecedented exploitation of energy, as a cold source to generate power without combustion.

This paper introduces Kobe Steel's radial turbine which plays a key role in the power generation system. Also included in this paper are the company's activities aimed at the future expansion.

1. Gas energy recovery system for power generation

City gas in Japan mainly consists of liquefied natural gas (LNG). The natural gas is mined and liquefied at gas fields overseas before being imported in dedicated tankers. The imported LNG is temporarily stored in the tanks of LNG terminals located in the country's coastal areas. This stored LNG is vaporized using a heat transfer fluid, such as seawater, adjusted for its calorific value and mixed with odorant before being supplied as city gas to consumers. To deliver the city gas over a wide area, each gas company supplies the gas through high-pressure [note)] pipelines to regional governor stations. Each governor station reduces the gas pressure to an intermediate pressure [note)] and stores it in a spherical gasholder (**Fig. 1**). The gas is then delivered through a network of intermediate pressure pipelines to local governors, where the pressure is adjusted to a level required by consumers.

A gas energy recovery system utilizes the energy released during this pressure reduction, the energy of adiabatic expansion, for rotating an expander turbine to generate electric power. **Fig. 2** depicts the flow of the power generation system. As shown, the expander turbine can be configured in two patterns. In the first pattern, the expander turbine is placed between a high-pressure line and an intermediate pressure line A (i.e., in the upstream of the spherical gasholder). In the second pattern, the turbine is placed between intermediate pressure line A and another intermediate pressure line B (i.e., in the downstream of the spherical gasholder). This system has a simple construction compared with other systems used, for example, for thermal power generation. In addition, the system generates power without combustion, emits much less CO_2 and is more environmentally friendly.

When recovering pressure energy using an expander turbine, however, a significant temperature drop occurs at the turbine outlet. The temperature

[note)] The term "high pressure" refers to the pressures of 1.0MPaG or higher. The term "interediate pressure A" refers to pressures of 0.3MPaG or higher and lower than 1.0MPaG. The term "intermediate pressure B" refers to pressures between 0.1MPaG and than 0.3MPaG. The term "low pressure" indicates gas pressure lower than 0.1MPaG. Gas is supplied to typical users, such as households, at a low pressure, while it may be supplied at an intermediate pressure, A or B, to commercial-scale utility customers.

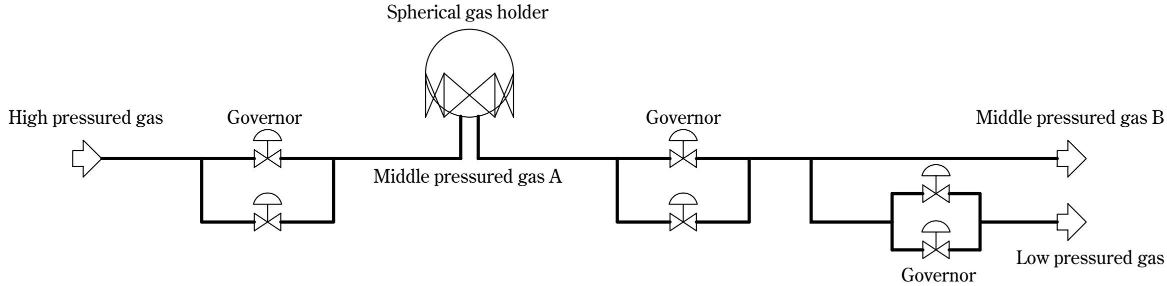

Fig. 1 General flow of gas supply

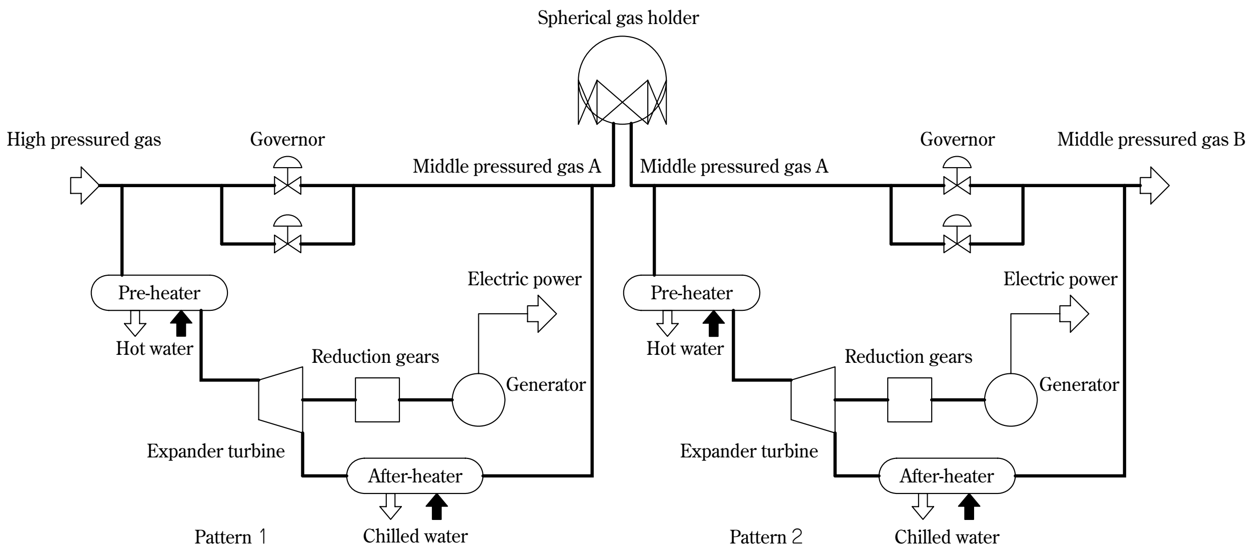

Fig. 2 System flow of gas energy recovery system

drop is partly attributable to the Joule-Thompson effect, which occurs any time when the pressure is reduced from high to low. An expander turbine, however, decreases the temperature more significantly with its characteristically large energy drop. On the other hand, the law stipulates the temperature of city gas must be higher than 0℃ when supplied to end users. Thus the gas must be heated during the energy recovery. As shown in Fig. 2, two methods are available for heating the gas namely,

(A) a preheater method in which, for example, a hot-water boiler heats the gas before it enters the turbine and

(B) an afterheater method in which an afterheater controls gas temperature using cold heat recovery at the turbine outlet or low temperature heat exhausted from neighboring facilities.

Most conventional governor stations, without any expander turbine, use similar heaters before and after the pressure reduction to compensate for the energy drop caused by the adiabatic expansion. These heaters can be the source of CO_2 emissions. In this respect, the new system emits slightly more CO_2 due to the additional amount of fuel consumed to compensate for its characteristic energy drop. But this emission is regarded as negligibly small considering the amount of power generated. It is to be noted that the pressure adjustment from intermediate pressure A to intermediate pressure B may not require any heater.

A terminal or station can employ either or both of the two methods, depending on user needs. The new gas energy recovery system offers various alternatives for the effective use of energy. This versatility of options is one of the features of the system.

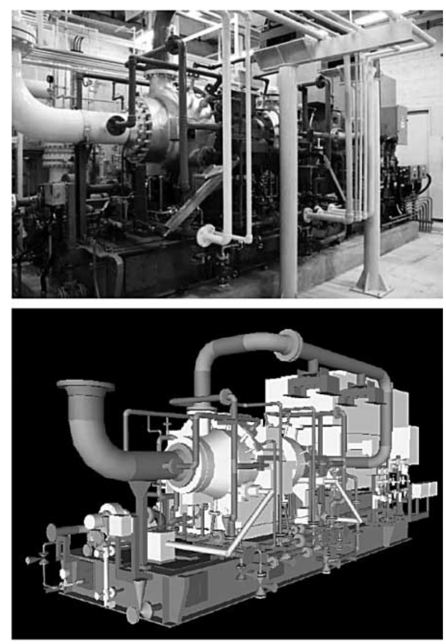

Fig. 3 Photo of gas energy recovery turbine unit and 3D-CAD drawing

1.1 Features of system delivered to Keiyo Gas Co., Ltd.

In 2008, Kobe Steel delivered a radial turbine generator to Keiyo Gas Co., Ltd. **Fig. 3** shows a near view and a 3D-CAD image of the generator, and **Fig. 4** depicts its system flow. **Table 1** summarizes the specifications of the generator. The generator delivered to Keiyo Gas Co., Ltd. has an expander turbine on the bypass line of the governor that adjusts the high pressure to intermediate pressure A. This is an example of the aforementioned first pattern. According to local news [1], the system is to

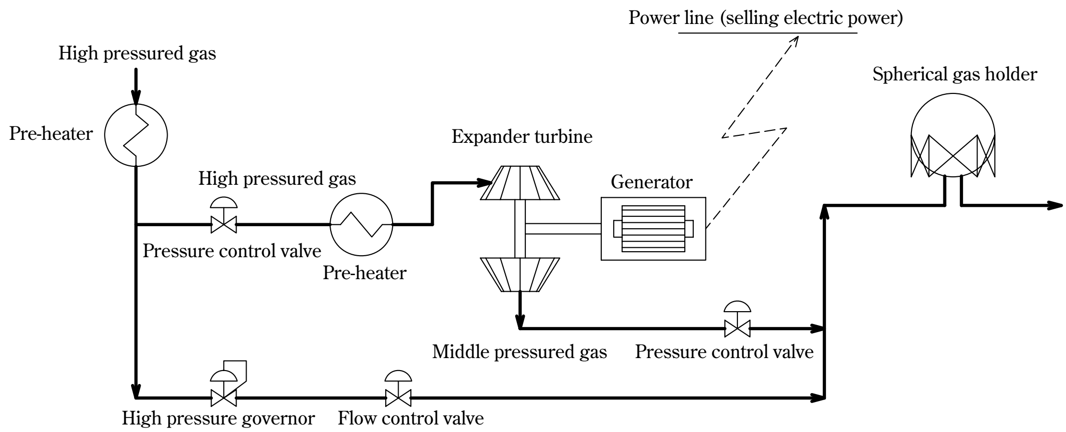

Fig. 4 Flow of gas power generating system for Keiyo Gas Co., Ltd.

Table 1 Specifications of gas energy recovery turbine unit for Keiyo Gas

Item	Spec.	Note
Stage	2	GRT250+GRT310
Gas flow (Nm^3/h)	30,000	10,000～30,000 variable operation
Turbine inlet		
Pressure (MPaG)	3.9	
Temperature (℃)	83	
Size	150A(6B)	
Turbine outlet		
Pressure (MPaG)	0.9	
Temperature (℃)	6	
Size	250A(10B)	
Rated power (kW)	830	@Terminal
Unit size (m)	6.5×2.6×2.2	Seal gas unit is separately installed
Unit Weight (kg)	25,200	Seal gas unit is not included

generate a peak power of 830kW and an annual power of 4.4 million kWh. This amount of electricity is sufficient to support about one thousand households for a year. The generator reduces the CO_2 emissions by 1,500 tonnes/year compared with a case in which the electricity would have been purchased. The system adopts the aforementioned preheater because the governor station where the generator is installed has neither a user of cold heat, nor a supplier of surplus heat in the neighborhood. According to certain announcements [2), 3)], the electricity generated at each governor station is sold to power producers and suppliers (PPS), in addition to being consumed in-house. In general, in-house consumption is the most economical way of using the generated power, as it decreases the bill to power companies by the amount that would have been paid without the self-generated power. However, there is no user for the self-generated power in many cases.

Until recently, Japanese gas companies had introduced fewer energy recovery systems than foreign companies. One reason is that regulations prevented the gas companies from using self-generated power other than for their in-house consumption. Thus, energy recovery was feasible only for large gas terminals that consume large amounts of electricity.

The recent deregulation of the Electricity Business Act has enabled entities to sell their self-generated power to power product suppliers (PPSs) and other power companies in addition to consuming it in-house. As a result, a governor station with a small in-house consumption can afford to introduce a gas energy recovery system for self-generation. In addition, government now provides certain subsidies for newly installed equipment that utilizes unused energy and reduces CO_2 emissions. The bounty system is expected to promote the introduction of the energy recovery system described in this paper.

1.2 Features of Kobe Steel's expander turbine

1.2.1 High efficiency

In general, turbines are either the axial flow type or radial flow type. Kobe Steel employs a radial turbine based on the impeller technology developed for the company's centrifugal compressors. The major advantage of the turbine is a high efficiency in converting pressure energy into external power [4) - 6)].

1.2.2 Excellent partial load performance

City gas companies control the supply of gas in accordance with the consumption. This affects the amount of gas passing through the turbines. Average households, major consumers of gas, consume a larger amount of gas in the morning and evening of each day for activities such as cooking, air-conditioning and bathing. Less Gas is consumed early in the morning and late in the evening. More gas is consumed during the winter months than during the summer months each year. Thus, the gas flow is constantly subject to change during the day and throughout the year. This requires turbines for gas energy recovery to have wide operation ranges and superb partial-load efficiency.

Turbine efficiency depends on the gas flow rate and declines significantly when the flow rate falls lower than the design point. This is because decreased gas flow changes the rate and angle of the flow from the turbine nozzle into the turbine runner, making it difficult to keep the flow optimized at the design point. A variable nozzle resolves this issue by adjusting nozzle angle in accordance with the change of flow from the nozzle into the runner. The nozzle can adjust the rate and angle of the gas flow in a wide range and keep it in the most suitable condition.

The system delivered to Keiyo Gas Co., Ltd. accommodates a gas flow ranging from 10,000 to 30,000Nm^3/h. This wide operation range and high efficiency are important for encouraging the use of the generator system.

1.2.3 High reliability

Kobe Steel developed a turbine-generator for cold power generation in the late 1970s. This was the beginning of the company's history of special turbine-generators recovering pressure energy from city gas and LNG. Cold power generation systems generate electricity from the cold heat of LNG. Such a system vaporizes LNG by a heat exchanger using seawater for example and recovers the pressure energy associated with the volume expansion using a turbine. This has led to the development of the pressure energy recovery system described previously. The newly delivered system also ensures high safety and reliability using the Kobe Steel's shaft-seal technology to prevent the flammable and explosive fluid from leaking from the rotary feedthrough. Kobe Steel acquired this shaft-seal technology over years of developing centrifugal compressors.

1.2.4 High durability

A prior art example of the gas energy recovery system is found in the cold power generator at the Senboku No. 2 plant of Osaka Gas Co., Ltd. The company put Kobe Steel's first machine into service in 1979 and its second machine in 1982. The Himeji terminal of Osaka Gas Co., Ltd. inaugurated a Kobe Steel machine in 1987. Remarkably, the first machine has been in service for around thirty years, demonstrating its durability.

2. Future activities

The gas energy recovery system meets the market need for power generation utilizing unused energy. The generation system is being widely used, as the electric power business has been deregulated and more effort is being made to reduce CO_2 emissions and prevent global warming.

The following section describes the technical challenges and Kobe Steel's recent efforts.

2.1 Technical challenges

2.1.1 Operation with small gas flow

As described above, the generator at Keiyo Gas Co., Ltd. operates at 10,000 to 30,000Nm^3/h. The generators, such as the one installed at Keiyo Gas Co., Ltd., may be feasible only in heavily populated urban areas where enough gas flows can be secured. However, conditions as favorable as those found at Keiyo Gas Co., Ltd. are rare in this country, and there are terminals with gas flows of less than 10,000Nm^3/h. Now many small to medium sized gas companies plan to introduce gas energy recovery systems as a part of their climate change mitigation programs. A small or medium-sized city gas company may generate less electricity and needs a system adapted for small-scale operations. Such a generator must balance the saved energy that would have been bought, the energy used by the preheater for heating, and the cold and/or waste energy utilized by the afterheater. In addition, a smaller system tends to have an increased equipment cost per unit output. This requires a less capital-intensive system with less costly components such as turbines.

When the gas flow becomes extremely small, a turbine starts to work as an electric motor, consuming, instead of generating, power. This actuates a reverse power relay and shuts off the turbine generator.

Thus a continuously running system that works cooperatively with the mains power must be considered. Such a continuous system is disconnected from the mains power and keeps its turbine in idle when the system cannot generate enough power. The system is connected back to the mains power when the gas flow is recovered.

2.1.2 Shaft seal system

Kobe Steel's standard specification calls for nitrogen for the shaft seal of the turbines; however, most governor stations do not have nitrogen equipment. The shaft seal may alternatively employ a large amount of air; however, governor stations are likely to have compressors that lack the capacities or air quality (dew point) needed. This often necessitates the addition or upgrade replacement of compressors and decreases the advantage of the generator system.

Therefore, it is desirable to develop a new shaft seal that consumes less nitrogen or air, while securing the high performance of the current design.

2.2 Kobe Steel's effort to promote widespread use

The following are required to promote the widespread use of the generator system.

- Reduced running cost

A new technology is required for reducing utility consumption, particularly the consumptions of nitrogen and/or air for the shaft seal, as well as the initial cost of the turbine generator.

- Control technology for stable operation with a small gas flow.

The newly adopted variable nozzle has improved partial load performance; however, control technologies remain to be improved. This includes preventing reverse power for small gas flow and achieving continuous operation regardless of whether the generator is connected to the mains power or not.

Conclusions

There are about one thousand governor stations and spherical gasholders dotted around the country. They are of various sizes and are connected, for example, to high pressure pipelines or to natural gas pipelines. These stations and gasholders provide a potential market for the gas energy recovery system. The market will increase with the expanding network of city gas pipelines and the addition of governor stations and spherical gasholders. A huge market may exist in overseas pipeline stations. Kobe Steel's radial turbines have been well recognized in the market for their high performance.

Kobe Steel will keep ahead in resolving technical issues, such as downsizing, cost reduction and performance improvement, to establish a competitive position. The company will strive to continue development and make a positive contribution to reducing global warming.

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Cycle Gas Compressor for Polyolefin, DH series

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To meet the growing demands for polyethylene (PE) and polypropylene (PP), many plants have been and are being built. In addition, plant capacities are being increased year by year to achieve high plant performance. Kobe steel has developed and improved compressors to meet their needs. This paper reports on a cycle gas compressor, one of the most important apparatuses for polyolefin plants, focusing on its special features and the outlook for the future.

Introduction

Worldwide plastic production exceeded 260 million tonnes in 2007[1]. Production decreased in 2008 due to the world recession, but steady growth is expected, primarily in developing nations. In the long run, demand will continue strong for the general-purpose polyolefin resins, e.g., polyethylene (PE) and polypropylene (PP). This demand is driven by increasing consumption in the BRIC and other developing countries that are achieving significant economic growth. The demand is also expected to recover in Europe and North America, which have been major consumers for some time. In response, large PE/PP manufacturing plants are being built one after another in the BRIC countries and oil producing countries, especially in the Middle East. In 2009, many plants either started or were planning to start production.

Kobe Steel manufactures and sells to these PE/PP manufacturing plants a series of cycle gas compressors (DH series), as well as kneading mixers and pelletizers. The mixers and pelletizers are used for making pellets, a primary product, from granular polymer produced by gas phase polymerization in a reactor. The cycle gas compressors are used for the gas phase polymerization (hereinafter referred to as "polyolefin applications"). In recent years, Kobe Steel has delivered over 70% of the compressors imported by the People's Republic of China and has achieved significant sales also in Southeast Asia and the Middle East (**Table 1**).

This paper introduces the features of the DH series compressors used in polyolefin plants (**Fig. 1**) and describes the outlook for the future.

Table 1 Reference list of model DH for polyolefin plant

Delivery	Area	Plant	Model	Driver rating (kW)
2006	Russia	PE	DH9M	3560
2006	Germany	PP	DH9M	1650
2006	Germany	PP	DH7JM	1500
2007	Korea	PP	DH7JM	3450
2007	Korea	PP	DH7JM	1100
2007	China	PE	DH9M	5100
2007	Korea	PP	DH7JM	1300
2008	Thailand	PE	DH9M	4550
2008	Austria	PP	DH7JM	930
2008	China	PE	DH9M	5000
2008	Thailand	PP	DH7JM	1200
2008	Thailand	PP	DH7JM	4000
2008	Saudi Arabia	PP	DH7JM	1400
2009	UAE	PE	DH9M	4400
2009	UAE	PP	DH7JM	3250
2009	UAE	PP	DH9M	2800
2009	China	PE	DH9M	4900
2009	China	PE	DH9M	5510
2009	China	PE	DH9M	4900
2009	China	PP	DH9M	6000
2009	China	PP	DH9M	1750
2009	China	PP	DH9M	1380
2010	China	PE	DH9M	4900
2010	China	PP	DH9M	1550
2010	China	PP	DH7JM	2950

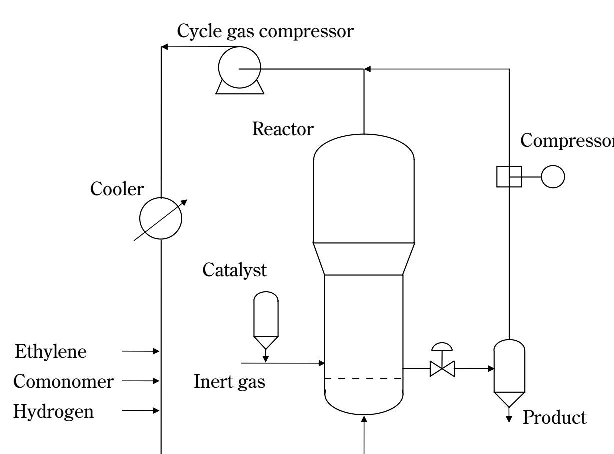

Fig. 1 Typical polyolefin plant process [2]

1. Features of the body structure

Polyolefin plants typically employ single-stage compressors because such an application requires a compressor with a low pressure ratio. They also adopt compressor units having cylindrical casings (a barrel type) because they require medium pressures. **Table 2** summarizes the specifications of Model DH9M, which represents typical compressors made by Kobe Steel. The compressor unit consists essentially of a compressor and an electric motor that drives the compressor via a coupling.

Fig. 2 shows the external appearance of the compressor. This compressor meets the requirements of API STANDARD 617, Chapter 2, American Petroleum Institute. **Fig. 3** is a cross-sectional view of a DH series compressor used for polyolefin applications. The compressor includes an impeller, a thrust bearing and a rotor shaft. The impeller is attached to an end of the rotor shaft such that the impeller overhangs at the shaft end beyond the bearing. The shaft-seal consists of a tandem dry gas seal disposed on the bearing side of the impeller so as to prevent the process gas from leaking outside. The overhung single-stage structure requires only one seal, facilitating maintenance work better than a single axial compressor with an inboard rotor would. The impeller, however, produces a large thrust force, so the thrust bearing must be carefully selected. The bearing is housed in a bearing box and is attached to the casing of the compressor. The compressor also includes an inlet guide vane as a standard feature. The guide vane enables an efficient adjustment of the compressor's capacity by varying the circumferential velocity component at the impeller inlet to change the impeller characteristics.

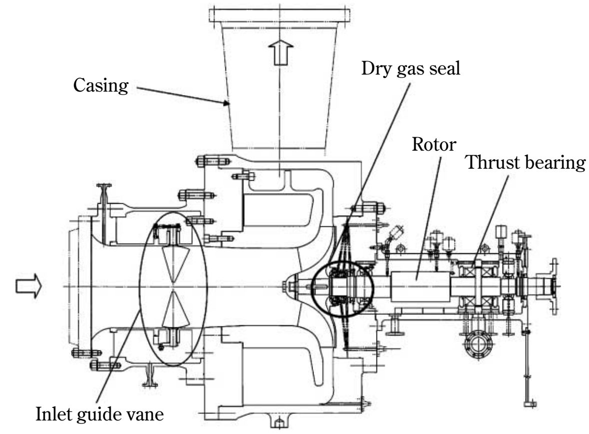

Fig. 3 Construction of model DH

Table 2 Typical specification of compressor

Model		DH9M (Single stage barrel casing type)
GAS		Hydrocarbon, Hydrogen, Nitrogen
Suction volume	(m^3/h)	57,290
Suction pressure	(MPaA)	2.50
Suction temperature	(℃)	85.00
Discharge pressure	(MPaA)	2.67
Rated speed	(rpm)	2,977
Driver type		Induction motor
Driver rated output	(kW)	5,100
Shaft seal		Tandem dry gas seal
Capacity control method		Inlet guide vane device


Fig. 2 Example of model DH

2. Impeller

In polyolefin applications, compressors are used to circulate gas through the polymerization process. Such an application requires a compressor with a large capacity and low pressure ratio. For high mechanical reliability, the compressor typically uses an electric motor for direct drive via a coupling without gears.

To satisfy the requirements, Kobe Steel's compressors adopt impellers of a high specific speed type that is suitable for large capacity. In addition, conventional impellers are prone to surging caused by a small pressure variation because of their small pressure margins between the design points and the surging points. Therefore, Kobe Steel has developed an impeller with a sufficient pressure margin particularly for polyolefin applications.

3. Measures against polymer dust

3.1 Countermeasure against polymer dust in impellers

In most polyolefin applications, the compressors must handle process gas containing polymer dust.

Conventional impellers for gas applications are of a covered type, each consisting of a hub, blades and a cover, which are assembled to form a gas passage. The compressors for polyolefin applications used to have impellers of this type. Such a covered impeller, if used for the polyolefin process, often suffers from vibration caused by the imbalance of the rotor. The imbalance is a result of the dust of PE/PP contained in the process gas, accumulating on the portions where the gas flow becomes stagnant. Such portions include the labyrinth seal between the casing and the inlet cover disk of the impeller. The accumulated dust can also block the gas passage, which deteriorates compressor performance. Thus, such compressors require frequent maintenance which disrupts operation.

To resolve the issue, Kobe Steel developed a unique open-type impeller in 1999. The covered type impellers that had been delivered to the customers were replaced with this open type with the cooperation of the customers. The developed impellers have been used for similar applications after demonstrating their performance. The development involved a three-dimensional viscous flow analysis. **Fig. 4** shows examples of flow analyses conducted on a covered impeller and an open impeller. The figures represent relative Mach numbers measured in the vicinity of the shroud of the gas passage between the impeller blades. In comparison with the covered impeller, the open impeller, as shown, maintains a higher speed particularly at the impeller inlet, suppressing the low speed region. The results show that the open impeller effectively prevents dust from accumulating at the portion where the gas flow becomes stagnant, a condition found in the inlet portion of the covered impeller. The back surface of the impeller is profiled to control the buffer gas in such a way that the process gas does not flow in reverse along the back surface.

More than twenty machines, including the ones converted from the covered type to open type, are currently in service, demonstrating their effectiveness against dust-containing gas.

3.2 Inlet guide vane

Inlet guide vanes are provided at the suction port of a compressor for controlling the compressor capacity. The gas flow becomes stagnant at the feedthrough inside the duct where the vanes are attached. This part requires modification to prevent the dust from accumulating. Kobe Steel developed a dual structure in which an extra chamber is provided outside the gas passage of the inlet guide vane. The same gas as that used as the buffer gas for dry seal is fed through in such a way that a small amount of gas seeps into the process. This eliminates the stagnant zone and prevents the accumulation of dust. Similarly, nitrogen gas may be introduced into the outer chamber to prevent dust accumulation.

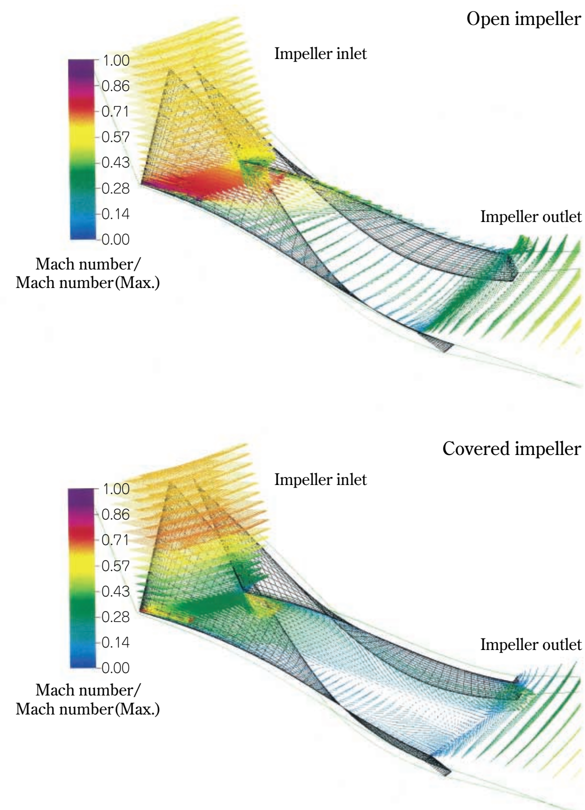

Fig. 4 Example of flow analysis of impeller

3.3 Gas seal system

To seal the shaft, the developed compressor employs a tandem dry gas seal, the seal commonly used for centrifugal gas compressors. In general, the seal uses buffer gas which is discharged from the compressor, filtered and fed into the primary seal to maintain a narrow gap in the seal. In the polyolefin applications, however, the discharge gas cannot be used for the buffer gas, since it contains dust. Thus, the buffer gas consists of, for example, ethylene or propylene, a gas which is inert even if mixed in the process.

A labyrinth seal is provided between the primary seal and secondary seal. The nitrogen supplied into the labyrinth seal escapes into a flare line; so does a small amount of the buffer gas. The anomaly of the dry gas seal is detected by a flow/pressure sensor provided in the flare line. For further protection, a separation seal is provided on the atmosphere side of the secondary seal. The nitrogen supplied into the separation seal prevents the lubricant from seeping into the shaft-seal from the bearing.

4. Ease of maintenance

The developed compressor is of a large size for processing a large volume. Kobe Steel constructed the compressor in such a way that its rotor assembly, including the impeller and shaft-seal, can be disassembled on the side opposite to the suction port. This facilitates the inspection of the impeller, bearing and shaft-seal. The construction allows the inspection of the rotor assembly without disassembling the heavy main body and attracts favorable comment from customers. **Fig. 5** and **Fig. 6** show examples of the rotor assembly being dismantled.

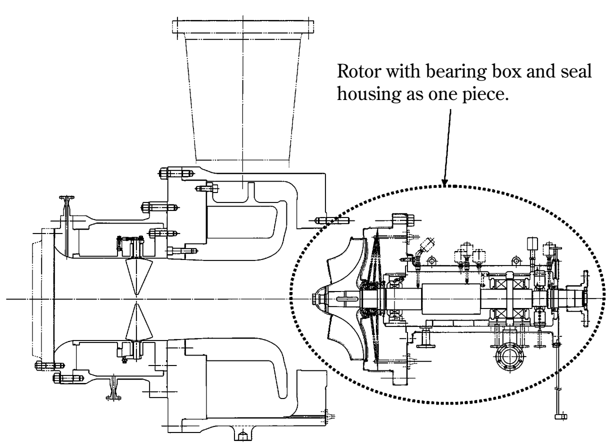

Fig. 5 Dismantling of rotor assembly from compressor casing

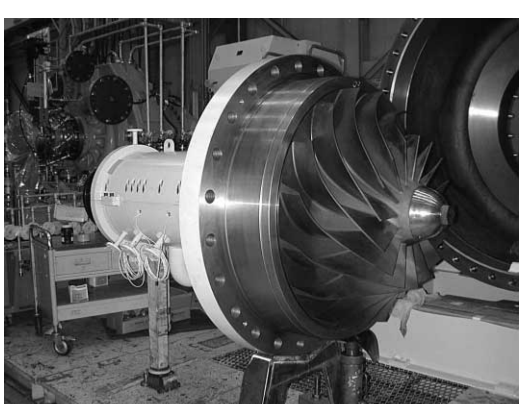

Fig. 6 Example of dismantling of rotor assembly

5. Response to special requirements

5.1 Measures against high load caused by piping

PE and PP plants require pipes with large diameters for handling large capacities. In addition, such a plant consists of a small number of mechanical components, making the piping fairly simple. This leaves only a little room for absorbing the elongation of the pipes caused by, for example, thermal expansion. Thus, some plants require nozzle loads and moments almost three times higher than those specified by API. Kobe Steel responds to the requirements by elaborating the base structures to reduce the piping load and moment, as well as increasing nozzle strength.

5.2 Measures against plant shut down

In a plant that polymerizes polyolefin, an emergency shut down results in a large amount of polymerized powder being left inside the reactor. The residual powder must be removed when restarting the plant, which takes a lot of time and effort.

Many customers strongly desire to continue operation as long as possible without shutting down their compressors. Kobe Steel has developed a system that restarts immediately after instantaneous power failures. Kobe Steel's compressor systems meet various customer needs. On of them includes a system that keeps the compressor running when the motor shuts down, using a turbine that utilizes the energy of process gas and stops the polymerization reaction gradually.

6. Future outlook

6.1 Upsizing of plants

Fig. 7 shows the capacities of compressors delivered by Kobe Steel each year. As seen from the figure, the plans are becoming larger and larger with the background of increasing demand and the need for higher productivity. New demand is emerging for compressors larger than any that have ever been delivered. In response to such needs, Kobe Steel will continue developing a new series of compressors with larger capacities and modifying the existing series to have improved impellers with higher specific speed.

6.2 Controlling starting current of motors

As the compressors have become larger, their

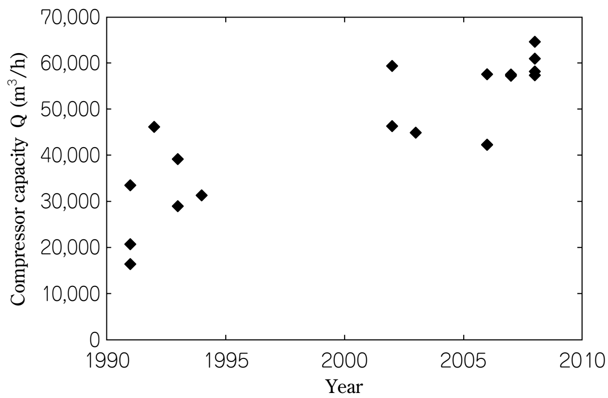

Fig. 7 Transition of compressor capacity

electric motors have required a greater output. Thus, the starting current of the motors must be restricted even more tightly to meet the specifications of the power facilities of the plants. A similar problem exists for conventional systems; however, the current restriction is much tighter for larger plants and is becoming an important factor in plant design.

Conclusions

The cycle gas compressors used for gas phase polymerization of PE/PP processes have simple structures. Such a compressor requires high reliability for stable operation, particularly because it is used for gas containing dust. Kobe Steel, one of the few manufacturers with broad experience in various processes, is striving to develop products to meet the customer need for larger compressors.

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Integrally Geared Centrifugal Compressors for High-pressure Process Gas Services

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An integrally geared centrifugal compressor, the High Pressure SUPER TURBO, has been developed for high pressure process gas services. The compressor has a modified design to ensure maximum stability of the rotor for high pressure application, and the analysis results met the requirements of the API standards. A full load running test was performed over 80Bar discharge pressure, which confirmed sufficient rotor stability by verifying low rotor vibration and low temperature rise in the bearing pads. This result has expanded the high pressure application coverage of integrally geared centrifugal compressors. The compressors could be applied to the main market of process gas services.

Introduction

Kobe Steel's integrally geared centrifugal compressors, hereafter simply referred to as compressor(s), are widely recognized for their energy-saving performance and small footprint. Kobe Steel has delivered many of these compressors with discharge pressures up to about 50Bar. In recent years, their range of application has been expanding to both larger and smaller sizes, as well as to higher pressures.

In response to this trend, Kobe Steel has developed a compressor, the High Pressure SUPER TURBO, to cultivate the new market. This compressor matches market needs with its high discharge pressure of up to 80Bar. Kobe Steel has conducted an operational demonstration for the specified pressure, using a test machine. This paper outlines the demonstration test and its results.

Kobe Steel has chosen the name Super Turbo, which has wide market recognition, for a series of geared centrifugal compressors for process gas services.

1. Brief description of test compressor

Fig. 1 shows the outside view of the test compressor, while **Table 1** summarizes its specifications. An integrally geared centrifugal compressor generally includes a gear-up unit with a pinion shaft. At least one impeller is attached to and overhangs at one or both ends of the pinion shaft, configuring a rotor. The rotor design is the most important factor in securing the mechanical stability against destabilizing fluid force, a force which increases as the required pressure increases.

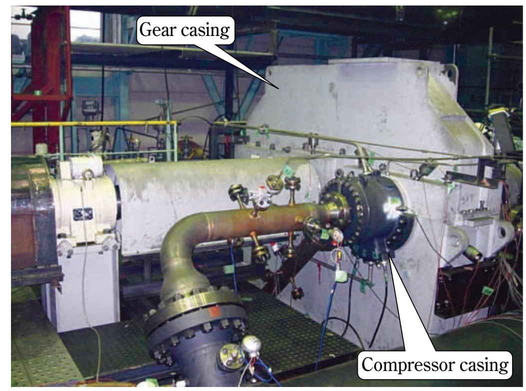

Fig. 1 Outside view of test machine

Table 1 Specifications of test machine

Type	Integrally geared centrifugal compressor (Model : VGP150H)
Application	Dry air booster
Gas	Dry air (MW=28.96)
Number of stage	2
Suc. pres.	LP: 28.1 / HP: 52.1 (barA)
Dis. pres.	LP: 52.2 / HP: 81.0 (barA)
Suc. temp.	40/40 (℃)
Speed	27,900 (rpm)
Motor output	2,900 (kW)
Shaft seal	Tandem dry gas seal

LP : Low pressure stage, HP : High pressure stage

The test machine has a rotor that has been designed for ideal stability. **Fig. 2** compares the rotor profile of a conventional machine (upper) to that of the test compressor (lower). The new design, in which the clearance has been revised, keeps the overhang at a minimum length for improved stiffness. To decrease the mass, the newly developed rotor adopts a pair of impellers made of titanium alloy. A pair of reference impellers made of stainless steel was also prepared. Load tests were performed on both the impellers.

The test machine is designed to use a tandem dry gas seal for sealing its shaft. This seal requires a longer overhang length, which renders the shaft less stable. However, the shaft designed and verified for the tandem dry gas seal can adopt any type of compressor seal. A newly developed casing allows the mounting of the shaft seal.

The bearings significantly affect rotor stability

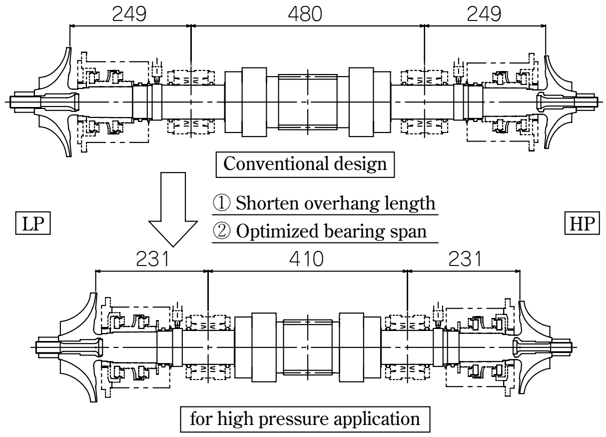

Fig. 2 Comparison of rotor design

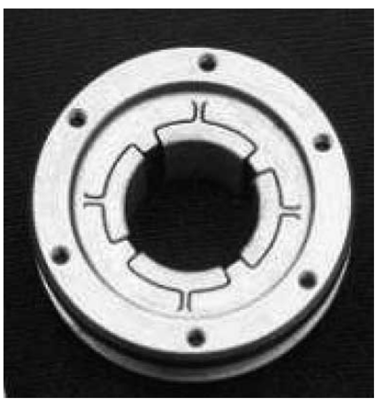
Fig. 3 Tilting pad journal bearing

and high performance is required of them in order to endure high revolutions under high load. With this in mind, two bearings were prepared for the load test, namely,

- a tilting pad journal bearing (**Fig. 3**), and
- a tilting pad journal bearing with a squeeze film damper (SFD).

Bearing specifications (common)

Bearing diameter: ϕ70 (mm)

Revolutions: 27,900 (rpm) [465(Hz)]

Circumferential velocity at the bearing surface: 102 (m/s)

Bearing projection pressure: 213 (N/cm^2)

After careful consideration, it was concluded that conventional gear and casing designs could be adapted to the newly developed machine. Since the compressor is intended to be used for a high pressure, another test was conducted to quantitatively analyze the gas thrust force to meet the high pressure requirement.

2. Rotor stability analysis

The American Petroleum Institute (API) standard [1], which is most widely known and highly esteemed, defines the anticipated destabilizing fluid force as the cross couple spring stiffness, Q_A, working on the impellers as follows.

$$Q_A = \frac{HP \times B_c \times C}{D_c \times H_c \times N} \times \frac{\rho_d}{\rho_s} \text{ (kN/mm)} \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where

HP : gas power (N·m/s = W)

B_c = 3

C = 9.55

D_c : impeller outer diameter (mm)

H_c : impeller outlet width (mm)

N : rotational speed (rpm)

ρ_d : discharge gas density (kg/m^3)

ρ_s : suction gas density (kg/m^3)

To judge the stability of an impeller, an analysis should be conducted assuming the destabilizing force expressed by Equation (1). If the result does not satisfy any of the conditions i), ii), or iii), then the impeller is regarded as stable. If it satisfies any one of them, a more detailed Level Ⅱ analysis is required.

i) $Q_0/Q_A < 2.0$

ii) $\delta_A < 0.1$

iii) $2.0 < Q_0/Q_A < 10$ and the critical speed ratio (CSR) falls in region B of **Fig. 4**,

where

Q_0 is the destabilization spring constant which yields zero logarithmic decrement, δ ,

δ_A is the logarithmic decrement rate with assumed destabilization spring constant of Q_A, and

CSR is the maximum continuous speed/first undamped critical speed on rigid support.

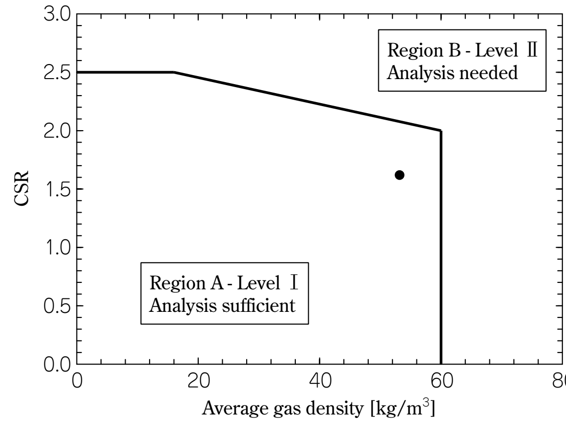

Fig. 4 Screening criteria

Fig. 5 shows the results of the stability analysis conducted on the present test machine. The destabilization spring constant and the logarithmic decrement are given as follows and satisfy neither of the conditions i) nor ii).

- Q_0/Q_A= 2.8 (>2.0)
- δ_A= 0.28 (>0.1)

As indicated by the dot in Fig. 4, the relation between the CSR value, an indicator of rotor stiffness, and the average gas density falls in region A and

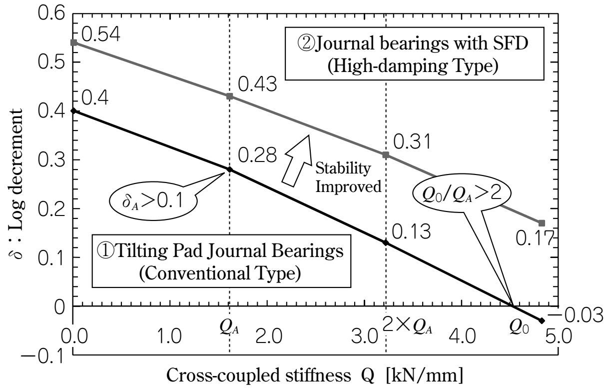

Fig. 5 Rotor stability analysis

Table 2 Rotor hammering test

	Eigenvalue (Hz) (free-free)	
	Measured value	Calculated value
1st mode	343	333 (97.1%)
2nd mode	690	692 (100.3%)
3rd mode	1,339	1,343 (100.3%)

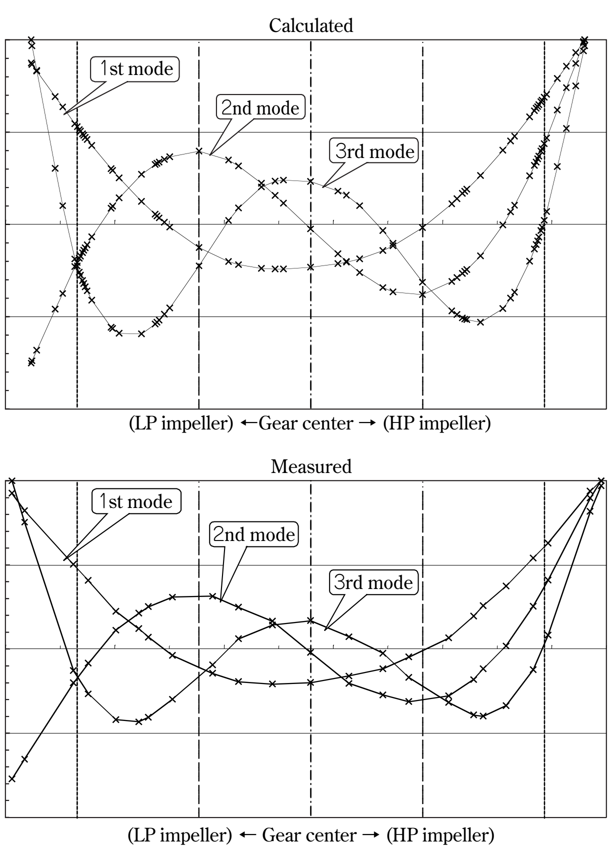

Fig. 6 Comparison of mode shape

does not satisfy condition iii).

Thus, the rotor of the test machine does not satisfy any one of the conditions i) through iii), demonstrating sufficient stability under the API standard. The analysis results show that the machine with the squeeze film damper performs better than the one with only the tilting pad journal bearing.

A rotor hammering test was conducted in free-free mode to verify the appropriateness of the rotor model used for the analysis. As shown in **Table 2**, all the results from the first to the third mode indicate that the differences between the calculated values and measured values are within 3%, verifying sufficient prediction accuracy. As shown in **Fig. 6**, the calculated characteristic vibration modes match well with the measured values, verifying the appropriateness of the calculation model.

3. Actual load running test

A closed loop actual load test was conducted on the compressor using a test bench made by Kobe Steel. Nitrogen, pressurized up to about 80Bar, was used as the test gas. Measured items include shaft vibration and the temperature of the bearing pad (**Table 3**).

The API standard specifies the allowance for shaft vibration during in-house mechanical running to be about 17μm. The test run results were mostly within this allowance even at full load. **Fig. 7** is the result of the Fast Fourier Transform (FFT) analysis of the shaft vibration. As shown in the figure, the predominant vibration appears at 465Hz, the primary frequency component of the rotational speed. No significant asynchronous vibration, characteristic of rotor destabilization, was observed. Thus it is confirmed

Table 3 Records of running test

Item	Unit	① Rated	② Near surge	③ Middle point	④ Max. flow
Motor input	(kW)	2852.8	2387.7	2619.5	3077.6
Shaft vibration LP-H	(μ)	13.4	10.8	11.7	16.7
Shaft vibration LP-V	(μ)	12.5	10.2	11.0	13.9
Shaft vibration HP-H	(μ)	15.8	16.8	15.9	16.0
Shaft vibration HP-V	(μ)	14.2	15.3	14.1	14.2
Supply oil temp. at comp	(℃)	41.6	41.5	41.5	41.5
J-bearing temp. LP	(℃)	63.2	62.5	62.8	63.2
J-bearing temp. HP	(℃)	68.7	65.9	67.3	69.9
LP stage suct. press.	(MPa)	2.883	2.690	2.747	3.016
LP stage disch. press.	(MPa)	5.400	5.211	5.277	5.459
HP stage suct. press.	(MPa)	5.379	5.199	5.262	5.432
HP stage disch. press.	(MPa)	8.010	8.081	8.055	7.790

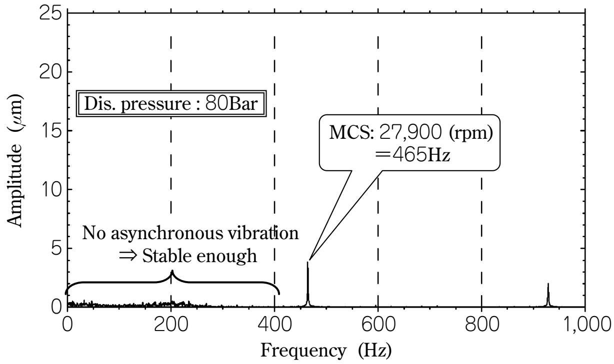

Fig. 7 FFT analysis of shaft vibration

that the test compressor can safely be run at the specified pressure.

In addition, temperatures were measured for the entire journal bearing pad. The measured maximum of 70℃ is well within the standard values of Kobe Steel.

4. Rotor destabilization test

To define the limit at which the rotor destabilizes, a test was conducted to determine the vibration behavior under decreased rotor stability and increased destabilizating fluid force. An impeller made of stainless steel was adopted to increase the added mass. A load test was conducted using argon

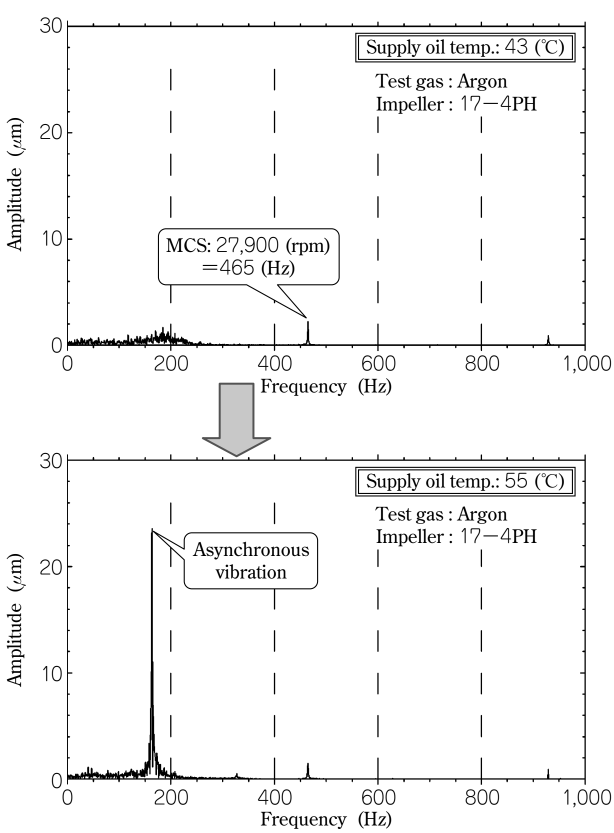

Fig. 8 Results of destabilization test

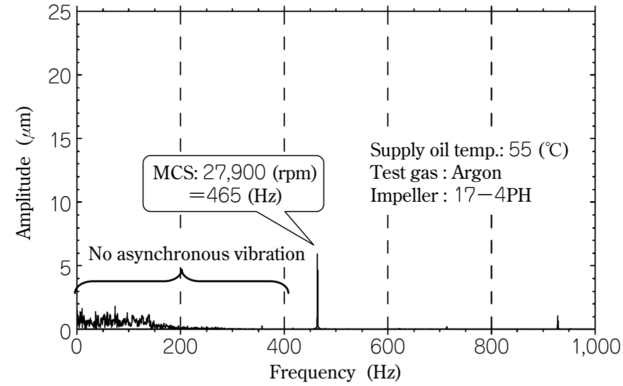

Fig. 9 Test result of SFD bearing

(molecular mass = 39.948) for the test gas and the vibration behavior was observed. The evaluated destabilizing fluid force at 80Bar of discharge pressure using argon gas corresponds to an approximately 13% increase in destabilizing force as against the same discharge pressure predicted by Equation (1) (a 15% average increase in gas density) when the original gas (nitrogen) was used.

The frequency analysis of shaft vibration revealed no significant asynchronous vibration at a supply oil temperature of 43℃(design temperature) and no impairment of rotor stability. Raising the supply oil temperature to 55℃, however, causes an asynchronous vibration as shown in **Fig. 8**.

On the other hand, the substitution of an SFD for the bearing caused no significant asynchronous vibration even in the case where the bearing caused an asynchronous vibration (**Fig. 9**), verifying the improvement in stability due to the SFD.

5. Measuring the gas thrust force

The gas thrust force was measured during the load test to collect the data useful for high load design. The force was measured by the load cells embedded behind the four pads of the thrust surfaces on the loaded side and unloaded side of the thrust bearing for the low-speed shaft. The force is transmitted from the pinion shaft to the low-speed shaft via a rider ring (thrust collar). Verification tests were conducted before the actual load test. The thrust force was evaluated by taking the average of the values measured at the four points. **Fig. 10** shows the bearing and load cells used for the test.

Table 4 summarizes the average values of the measured loads on the four pads which represent the trust force at 80Bar which is in the vicinity of the maximum load. The measured values fall within 10% of the thrust force (17.1kN) calculated on the basis of Kobe Steel's design method. The results verify the appropriateness of the calculated value.

Fig. 10 Thrust bearing with load cell (for measurement of gas thrust force)

Table 4 Measurement of gas thrust force

	Measured value (kN)	Differential (*)
1st trial	17.4	+2.2%
2nd trial	18.0	+5.5%
3rd trial	17.8	+4.2%

(*) Caluculated thrust force : 17.1 (kN)

Conclusions

This development has established a method for designing an integrally geared compressor which can handle up to about 80Bar of process gas. The new design has expanded the applicability of integrally geared compressors characterized by a small footprint and energy saving.

Kobe Steel will continue to develop technologies for further expanding the applications of integrally geared compressors, with an eye to the upsizing and high pressure applications such as carbon dioxide capture and storage.

References

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Overview of Market for Direct Reduced Iron

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Unlike the blast furnace process, which utilizes coking coal, the direct reduction process utilizes natural gas and non-coking coal as a reductant. The worldwide production of direct reduced iron (DRI) has rapidly increased. This paper outlines the history and prospects of the market for direct reduced iron.

Direct reduction iron-making is a method for producing iron without using a blast furnace. Direct reduction iron-making was first industrialized in the 1960s, and various plants started to be built on the commercial and semi-commercial scales. Direct reduction iron-making processes roughly fall into two classes, natural gas base and coal base, depending on the reductant used. The former includes the MIDREX® process and the HYL/ENERGIRON process, while the latter includes the SL/RN process, the FASTMET® process, the FASTMELT® process and the ITmk3® process.

The production volume of direct-reduced iron has increased steadily. As shown in **Fig. 1**, between 1970 and 2008, the volume increased by a factor of more than 80 from about 800 thousand tonnes to approximately 68 million tonnes.

Kobe Steel has built many direct reduction iron-making plants over the world since the company first delivered a direct reduction iron-making plant to the Qatar Steel Company; this plant began operation in 1978, based on the MIDREX process. In 1983, MIDREX Technologies, Inc. became a wholly-owned subsidiary of Kobe Steel. Currently, about 58% of the direct reduced iron produced in the world is made by the MIDREX process (**Fig. 2**).

Direct reduction iron-making plants are much less capital intensive than blast furnace based plants and do not require coke either. Because of this, developing countries, particularly natural gas producing countries, have built direct reduction iron-making plants for their own ironworks.

As-reduced iron is known to have pores which are left after oxygen has been removed. These pores, if filled with water, for example, can cause the iron to re-oxidize, generate heat and occasionally ignite a fire. This makes the marine transport of reduced iron difficult, and ironworks must consume it in-house.

To resolve this issue, Kobe Steel introduced a technology for agglomerating the reduced iron into hot briquette iron (HBI) to prevent re-oxidation. This technology has facilitated the marine transport of reduced iron, making it an iron source for the global market.

With this background, several countries, such as Venezuela, have built direct reduction iron-making plants with HBI technology and are specializing in exporting the HBI.

As shown in **Fig. 3**, the demand for crude steel has increased rapidly since the beginning of this century, supported by strong demand in the BRIC countries.

Year	Total	Year	Total	Year	Total	Year	Total
1970	0.79	'80	7.14	'90	17.68	'00	43.78
'71	0.95	'81	7.92	'91	19.32	'01	40.32
'72	1.39	'82	7.28	'92	20.51	'02	45.08
'73	1.90	'83	7.90	'93	23.65	'03	49.45
'74	2.72	'84	9.34	'94	27.37	'04	54.60
'75	2.81	'85	11.17	'95	30.67	'05	56.99
'76	3.02	'86	12.53	'96	33.30	'06	59.79
'77	3.52	'87	13.52	'97	36.19	'07	67.22
'78	5.00	'88	14.09	'98	36.96	'08	68.45
'79	6.64	'89	15.63	'99	38.60		

Source : Midrex Technologies, Inc.

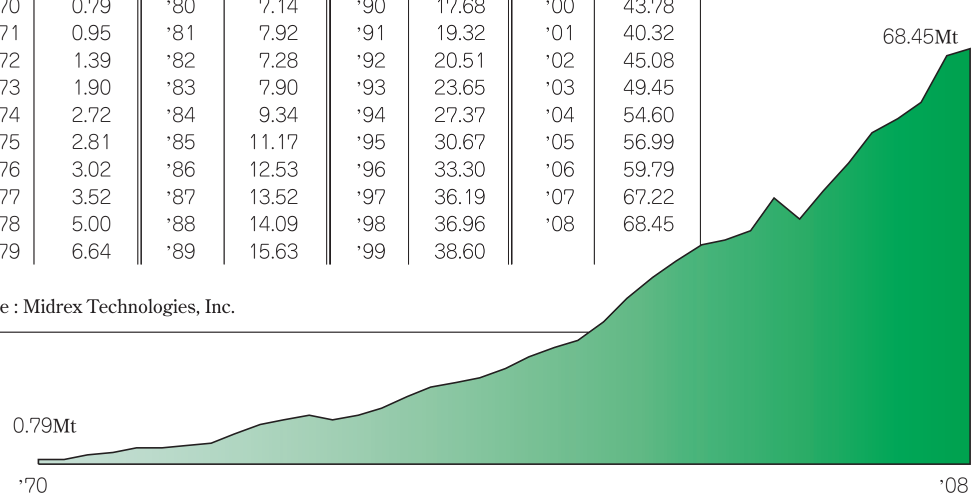


Fig. 1 World-wide direct reduced iron production by year

It remains strong, although the growth rate has slowed since the latter half of 2008 due to the financial crisis triggered by defaults on sub-prime mortgage loans in the United States.

The demand for the construction of direct reduction iron-making plants has increased in response to the increasing demand for crude steel. Many plants based on the MIDREX process were built one after another between 2005 and 2008. In addition, strengthened environmental controls promoted the use of the FASTMET process for separating constituents such as zinc from iron-making dust to produce/recycle reduced iron.

Fig. 4 shows the plants currently in operation based on the MIDREX and FASTMET processes.

The top three regions producing reduced iron are Asia/Oceania, Middle East/North Africa and Latin America. In the Asia/Oceania region, India has significantly increased its production volume in recent years. It produces reduced iron mainly by the SL/RN process using coal as a reductant. On the other hand, in the Middle East, North Africa and Latin America, regions rich in natural gas, produce reduced iron using their natural gas as a reductant (**Fig. 5**).

As the BRIC countries continue to industrialize, the global competition for natural resources has become increasingly severe. As a result, high-quality resources such as high-grade ore and coal are becoming depleted, and the leaving resources that are inferior in quality. In addition, environmental regulations such as CO_2 restrictions are becoming more stringent with global awareness of environmental protection.

Direct reduction iron-making helps to address the resource issue, as it allows the use of low grade iron ore and non-coking coal. There are high expectations for the direct reduction process for ironmaking, with its low environmental burden, including small CO_2 emissions.

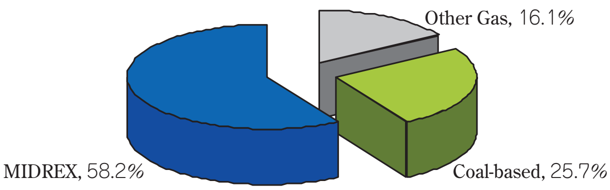


Fig. 2 World-wide direct reduced iron production process in 2008

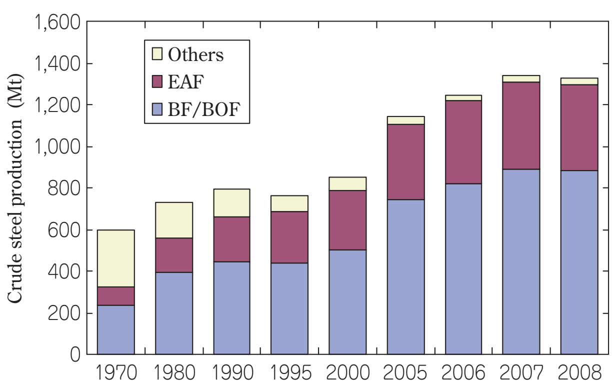


Fig. 3 World-wide crude steel production

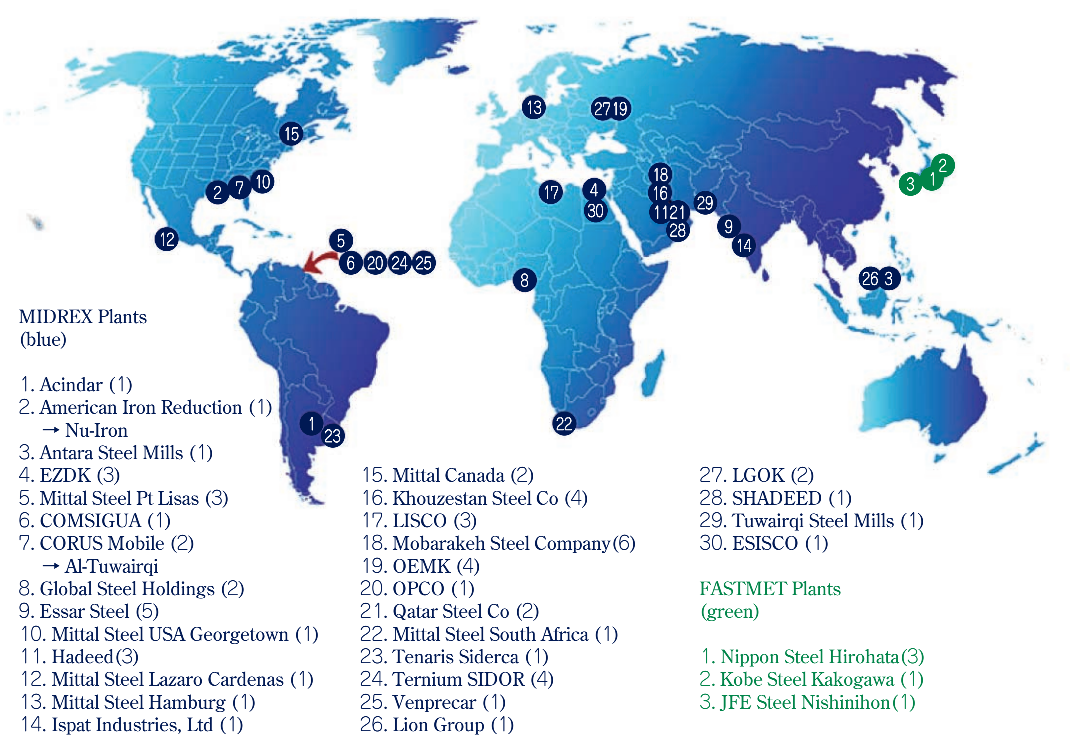
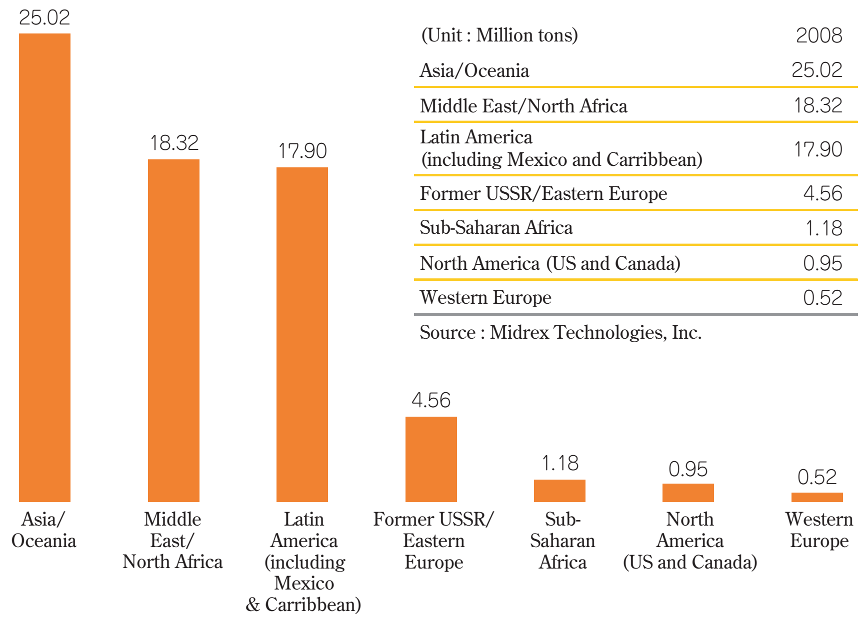


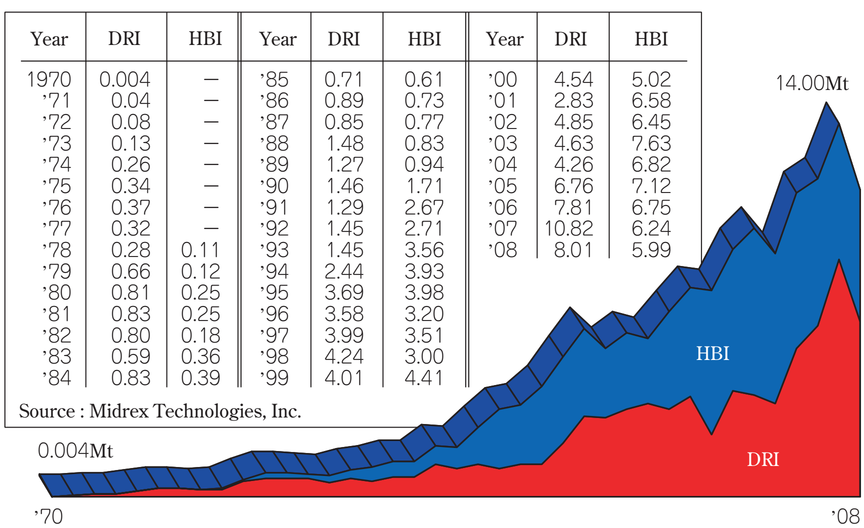
Fig. 4 MIDREX/FASTMET plant in the world



(Unit : Million tons)	2008
Asia/Oceania	25.02
Middle East/North Africa	18.32
Latin America (including Mexico and Carribbean)	17.90
Former USSR/Eastern Europe	4.56
Sub-Saharan Africa	1.18
North America (US and Canada)	0.95
Western Europe	0.52

Source : Midrex Technologies, Inc.

Fig. 5 World-wide direct reduced iron production by region in 2008



Year	DRI	HBI	Year	DRI	HBI	Year	DRI	HBI
1970	0.004	–	'85	0.71	0.61	'00	4.54	5.02
'71	0.04	–	'86	0.89	0.73	'01	2.83	6.58
'72	0.08	–	'87	0.85	0.77	'02	4.85	6.45
'73	0.13	–	'88	1.48	0.83	'03	4.63	7.63
'74	0.26	–	'89	1.27	0.94	'04	4.26	6.82
'75	0.34	–	'90	1.46	1.71	'05	6.76	7.12
'76	0.37	–	'91	1.29	2.67	'06	7.81	6.75
'77	0.32	–	'92	1.45	2.71	'07	10.82	6.24
'78	0.28	0.11	'93	1.45	3.56	'08	8.01	5.99
'79	0.66	0.12	'94	2.44	3.93			
'80	0.81	0.25	'95	3.69	3.98			
'81	0.83	0.25	'96	3.58	3.20			
'82	0.80	0.18	'97	3.99	3.51			
'83	0.59	0.36	'98	4.24	3.00			
'84	0.83	0.39	'99	4.01	4.41			

Source : Midrex Technologies, Inc.

Fig. 6 World-wide direct reduced iron shipment by year

Even in advanced countries such as the USA, the demand for reduced iron as an alternative source of clean iron is increasing and the volume of reduced iron shipment is also on the rise (**Fig. 6**). Steelmaking in electric arc furnaces (EAFs) has been expanding (**Fig. 7**), and this factor too will increase the demand for reduced iron.

Plants based on the FASTMET, FASTMELT and ITmk3 processes use coal as a reductant. They are more flexible in their site location than the plants based on the MIDREX process, which requires natural gas. Thus, the demand for FASTMET, FASTMELT and ITmk3 plants is expected to grow, as well as the demand for the MIDREX plants.

The Kobe Steel group owns various promising direct reduction processes for iron-making and will continue to contribute to iron and steel production world-wide.

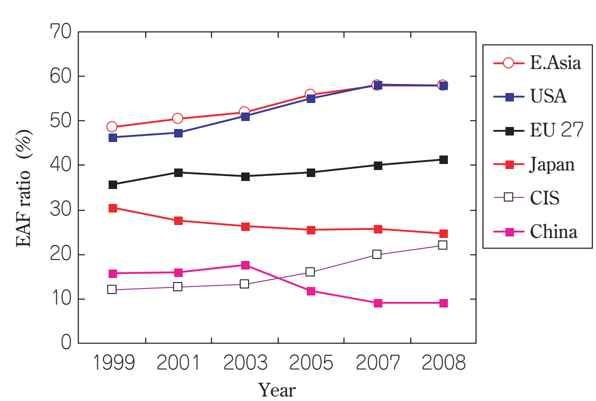


Fig. 7 EAF ratio of crude steel production

MIDREX® Processes

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Since 1978, when a plant based on the MIDREX process was built in Qatar for producing direct reduced iron, Kobe Steel and MIDREX Technologies, Inc., have collaborated to make many technical improvements in the process. The largest MIDREX module, having an annual production capacity of 1.8 million tones, began operation in 2007. The MIDREX module, together with a melt shop, now has a production capacity comparable to that of a blast furnace. This paper presents an overview of the history of the technical developments in these processes, as well as the latest developments in this field.

Introduction

MIDREX direct reduction ironmaking (hereinafter referred to as the "MIDREX process") reduces iron ore using natural gas. The original process was developed by the Midland-Ross Co., which later became MIDREX Technologies, Inc. (hereinafter referred to as "MIDREX Technologies"), a wholly owned subsidary of Kobe Steel. A pilot plant was built in Toledo, Ohio in 1967. The first commercial plant, having a production capacity of 150 thousand tonnes/year, was built in Portland, Oregon, in 1969.

The process was immature in 1978, when Kobe Steel began the construction of a plant with a production capacity of 400 thousand tonnes/year in the State of Qatar. Kobe Steel significantly modified the design, exploiting the company's technologies developed through blast furnace operation, and stabilized the then new process. On the other hand, MIDREX Technologies also carried out various improvements to the plants they built in various countries. These were all integrated in the early 1980s, making the process nearly complete [1].

The maximum production capacity in 1984, when Kobe Steel became affiliated with MIDREX Technologies, was 600 thousand tonnes/year. Later improvements, made by Kobe Steel in collaboration with MIDREX Technologies, have dramatically increased the production capacity. In 2007, the scale reached 1.8 million tonnes/year, which is comparable to that of a small blast furnace.

1. Characteristics of reduced iron

The MIDREX process produces direct reduced iron (hereinafter referred to as "DRI"). The process reduces iron ore using a reforming gas made from natural gas. The DRI is used mainly as the raw material for electric arc furnaces (EAFs), as a clean iron source substitute for scrap iron.

Pores are left behind in the DRI after oxygen has been removed. These pores, if filled with water, for example, can cause the iron to reoxidize with ambient oxygen, generate heat and occasionally ignite a fire. This makes it difficult to transport the product by ship or to store it in the open air over an extended period of time. To resolve this issue, Kobe Steel developed a technology for compacting DRI into briquette iron at a temperature of around 700℃. DRI has an apparent density of 3.4 to 3.6t/m^3, while the briquette iron has an apparent density of 5.0 to 5.5t/m^3.

The reoxidation issue had restricted DRI manufacturing sites to the vicinity of steelmaking plants. The hot briquette technology has eliminated this site restriction, making it possible to build a reduced ironmaking plant where resources such as natural gas, iron ore and power are less costly. The product, hot briquette iron (hereinafter referred to as "HBI"), can be exported by sea to steelmaking plants and rolling mills in other countries. This has expanded the number of potential sites for MIDREX plants all over the world [1].

Table 1 compares the chemical and physical properties of DRI and HBI, while **Fig. 1** shows the appearance of DRI and HBI.

The global production of DRI increased dramatically from 790 thousand tonnes/year in 1970 to 68.45 million tonnes in 2008. DRI made by the

Table 1 Specification of DRI and HBI

	DRI	HBI
Fe total (%)	90～94	←
Fe metallic (%)	83～89	←
Metallization (%)	92～95	←
Carbon (%)	1.0～3.5	←
P* (%)	0.005～0.09	←
S* (%)	0.001～0.03	←
Gang* (%)	2.8～6.0	←
Mn, Cu, Ni, Mo, Sn Pb and Zn (%)	trace	←
Bulk density (t/m^3)	1.6～1.9	←
Apparent density (t/m^3)	3.4～3.6	5.0～5.5
Discharge temperature (℃)	40	80

* depends on components of iron ore

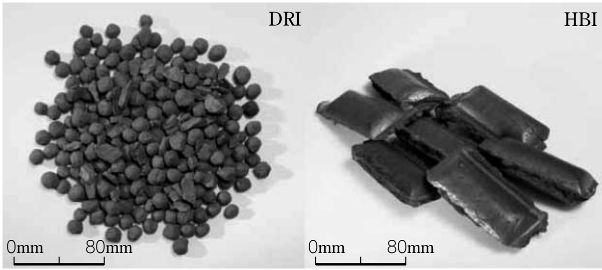

Fig. 1 Appearance of DRI and HBI

58 modules operating & 4 modules under construction in 19 countries.
Total capacity of MIDREX Process=48.4 million ton/y

Fig. 2 World's MIDREX plants

MIDREX process accounts for about 60% of global production.

Fig. 2 shows the worldwide locations of MIDREX plants.

2. MIDREX process

Fig. 3 is a flow chart for the MIDREX process. Either lump ore, or pellets prepared for direct reduction ironmaking, are charged as raw material from the top of a shaft furnace. The ore is reduced inside the furnace and the reduced iron is discharged from the bottom of the furnace. Reductant gas blown in from about the middle of the shaft furnace reduces the raw material above the nozzle and escapes from the top of the furnace. The cooling gas, which circulates in the lower portion of the furnace, cools the DRI. Both the charging and discharging ports are dynamically sealed by a sealing gas, allowing the continuous charging of raw material and discharging of DRI.

The reaction occurring in the shaft furnace is the well-known reduction reaction of iron, described as follows:

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$

The exhaust gas (top gas) emitted from the top of the shaft furnace is cleaned and cooled by a wet scrubber (top gas scrubber) and recirculated for reuse. The top gas containing CO_2 and H_2O is pressurized by a compressor, mixed with natural gas, preheated and fed into a reformer furnace. The reformer furnace is provided with several hundreds

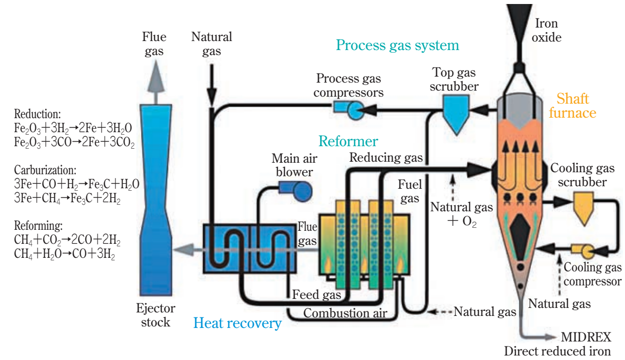

Fig. 3 MIDREX process flow sheet

of reformer tubes filled with nickel catalyst. Passing through these tubes, the mixture of top gas and natural gas is reformed to produce reductant gas consisting of carbon monoxide and hydrogen. The reaction that occurs in the reformer tubes is as follows:

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$
$CH_4 + H_2O \rightarrow CO + 3H_2$
$2CH_4 + O_2 \rightarrow 2CO + 4H_2$
$CO + H_2O \rightarrow CO_2 + H_2$
$CH_4 \rightarrow C(S) + 2H_2$

3. History of the development of the MIDREX process

3.1 Operation of MEGAMOD® shaft furnace: Raw material coating (1990 -)

There was an urgent need to upsize the shaft furnace in response to the market need for an increased production capacity. To achieve this, Kobe Steel and MIDREX Technologies began development by

- conducting analyses using the three-dimensional finite element method,
- conducting two-dimensional model experiments for verification and
- improving raw material characteristics on the basis of reduction/pulverization tests.

As a result, the shaft diameter was increased to 5.5m and then to 6.5m (MEGAMOD shaft furnace). This has increased the production capacity from the previous maximum of less than 400 thousand tonnes/year, first to 800 thousand tonnes/year, and then to 1.5 million tonnes/year [1].

A technology was devised to raise the temperature of reducing gas (bustle gas) by coating the raw material with lime hydrate which has a melting point higher than that of DRI. This has raised the reducing gas temperature to about 900℃ and improved shaft furnace productivity by more than 10%.

3.2 Oxygen injection into reducing gas (2000 -)

Injecting high purity oxygen into the hot reducing gas has further raised the reducing gas temperature to about 1,000℃ (**Fig. 4**). Although a portion of hydrogen and carbon monoxide is consumed by combustion with oxygen, raising the temperature of the reducing gas has improved shaft furnace productivity by 10 to 20%[2), 3)].

3.3 Improvement of oxygen injection technology (2005 -)

The oxygen injection, described above, has evolved into an improved technology, called "OXY+®", which was made possible by the introduction of a partial combustion technique. As shown in **Fig. 5**, the OXY+ employs a combustor in addition to the reformer. The combustor partially burns natural gas and oxygen to produce hydrogen and carbon monoxide, which are added to the reducing gas generated by the reformer[2), 3)].

Fig. 6 shows the transition of shaft furnace productivity.

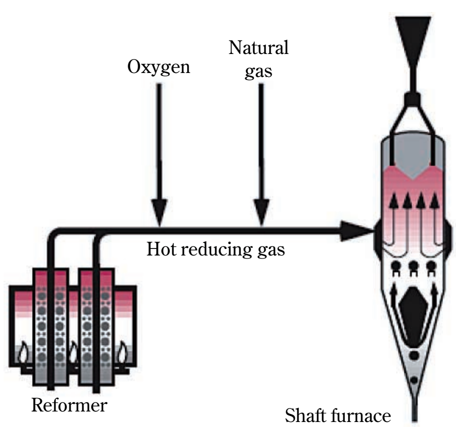

Fig. 4 Oxygen injection flow

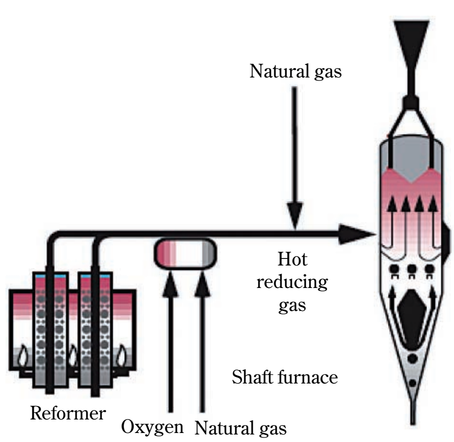

Fig. 5 OXY+ flow

3.4 Development of a shaft furnace, SUPER MEGAMOD®, and enhancement of engineering (2007-)

The experience of operating the shaft furnace with a diameter of 6.5m has led to the construction of a larger shaft furnace at Saudi Iron & Steel Company in Hadeed, Saudi Arabia in 2007. This shaft furnace has a diameter of 7.15m and an increased production capacity of 1.8 million tonnes/year (**Fig. 7**).

Another shaft furnace, SUPER MEGAMOD, currently under development, is to have a further increased production capacity in the range of 2 million tonnes/year. The increased size of the shaft furnace enlarges the entire facility, which requires even more sophisticated design and construction

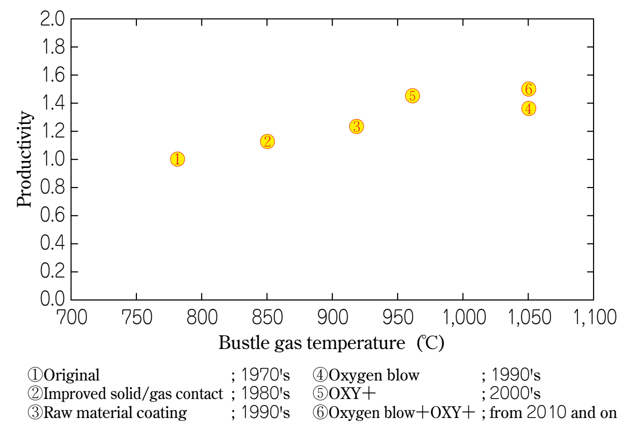

Fig. 6 Changes in productivity of MIDREX shaft furnace

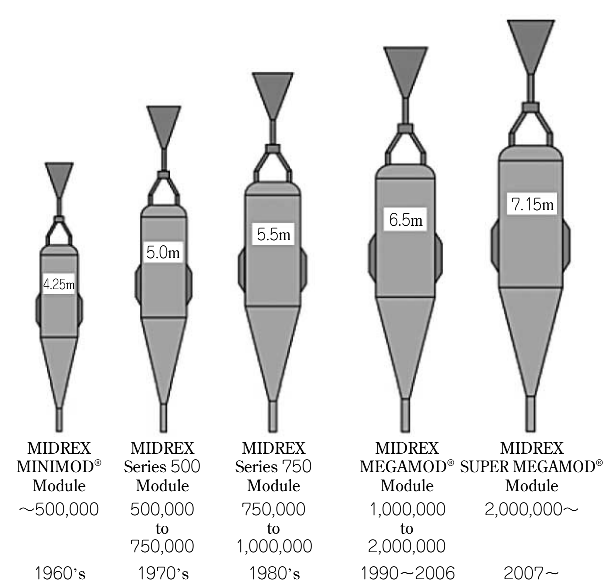

Fig. 7 Changes in shaft furnace diameter and annual production

management. Because of this, since 2004, a three-dimensional CAD has been adopted for the entire designing process. The three-dimensional CAD allows the retrieval of structural calculation data, as well as the direct output of isometric drawings of piping and material spreadsheets. The three-dimensional CAD is also utilized at construction sites for planning construction schedules. **Fig. 8** is a three-dimensional CAD drawing showing an entire DR Plant for Qatar Steel.

3.5 Delivery record

Table 2 shows the delivery record of MIDREX plants. The following is an outline of the major plants.

3.5.1 LION plant

This plant with a rated capacity of 1.5 million tonnes/year was constructed for the Lion Group, Malaysia, and began operations in 2007 (**Fig. 9**)[4]. It produces two types of products, hot DRI (HDRI) and HBI. The HDRI is supplied as hot metal to a neighboring EAF facility by a hot transport vessel. The HBI is mainly exported and is occasionally used by the neighboring EAF facility.

3.5.2 HADEED Module-E plant

This is the world's largest MIDREX plant. Constructed at the Saudi Iron & Steel Company in Hadeed, Saudi Arabia, it began operations in 2007 (**Fig.10**)[4]. The plant was the first to adopt a shaft

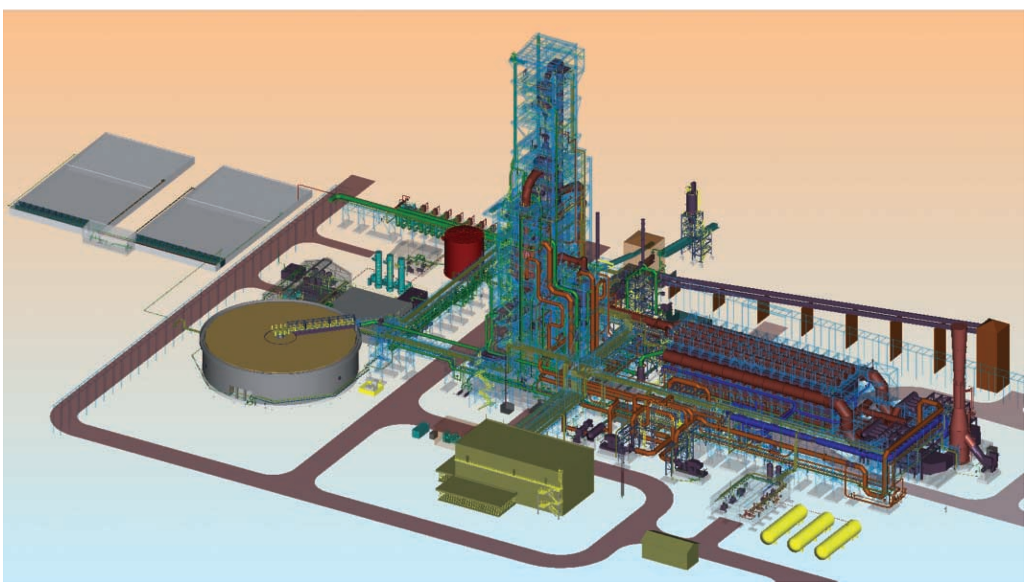

Fig. 8 CAD drawing of QASCO Module-II plant

Table 2 Recent delivery record of MIDREX plants

	Plant	Location	Capacity (million tont/y)	Start up
*	EZDK III	Egypt	0.8	2000
	Essar Steel Module-IV	India	1.0	2004
	Nu-Iron	Trinidad	1.6	2006
	Essar Steel Module-V	India	1.5	2007
	HADEED Module-E	Saudi Arabia	1.76	2007
*	QASCO Module-II	Qatar	1.5	2007
	LGOK Module-II	Russia	1.4	2007
	Al-Tuwairqi Damman	Saudi Arabia	1.0	2007
	LION	Malaysia	1.54	2008
	Essar Steel Module-VI	India	1.8	2009
*	SHADEED	Oman	1.5	2010
	ESISCO	Egypt	1.76	2010
	Al-Tuwairqi Pakistan	Pakistan	1.28	2010

*: Kobe Steel constructed

Fig. 9 LION plant

furnace having a diameter of 7.15m and has a rated capacity of 1.8 million tonnes/year. This capacity is comparable to that of a small blast furnace. The plant produces both HDRI and DRI. The HDRI that it produces is supplied as hot metal directly to a neighboring EAF facility, being transferred by a hot transport conveyor. The DRI is stored temporarily in a silo and supplied to the neighboring EAF facility as necessary.

3.5.3 QASCO Module-Ⅱ

This plant with a rated capacity of 1.5 million tonnes/year was constructed by Kobe Steel at Qatar Steel Company in the State of Qatar and began to operate in 2007 (**Fig.11**). It is to be noted that in 1975 Kobe Steel delivered a plant, Module-I, with a rated capacity of 400 thousand tonnes/year, to Qatar Steel Company. The design and operational improvements that Kobe Steel made on the MIDREX process, which was still immature at the time, have stabilized operations. This plant has won high acclaim and led to an order for Module-Ⅱ.

The Module-Ⅱ plant produces both DRI and HBI. The DRI is supplied to a neighboring steelmaking plant, while the HBI is exported. The DRI is melted at the steelmaking plant and is supplied to a rolling mill that produces billets, rebars and wire rod coils to be exported.

Fig.10 HADEED Module-E plant

Fig.11 QASCO Module-II plant

Fig.12 SHADEED plant

3.5.4 SHADEED plant

In 2008, Kobe Steel completed construction of a plant with a capacity of 1.5 million tonnes/year at SHADEED Iron & Steel Co. in Oman (**Fig.12**). The plant, which is to produce DRI and HBI, is currently in the preparation stage. It is the first plant to adopt a method called HOTLINK® for supplying HDRI to an adjacent EAF by gravity.

4. Recent technological trend

4.1 Hot discharge of DRI

Conventionally, DRI was cooled before being discharged from the shaft furnace. Technical modifications are being implemented to discharge hot DRI (HDRI) in order to improve the specific energy consumption and productivity of the plant, including the downstream steelmaking process. A combination of two discharge methods, cold and hot, was proposed and implemented to allow flexibility in production planning, which improves productivity[3), 5)].

Fig.13 depicts the overall flow in an integrated steel mill equipped with a MIDREX plant. The following three methods (**Fig.14**) allow the transfer of HDRI from the shaft furnace to the downstream steelmaking plant:

a) transfer and supply by a hot transport vessel (Fig.14-①)
b) transfer and supply by a hot transport conveyor (Fig.14-②) and
c) supply by gravity (HOTLINK) (Fig.14-③ and **Fig.15**).

The HDRI discharge methods have been adopted by various plants as summarized in **Table 3**.

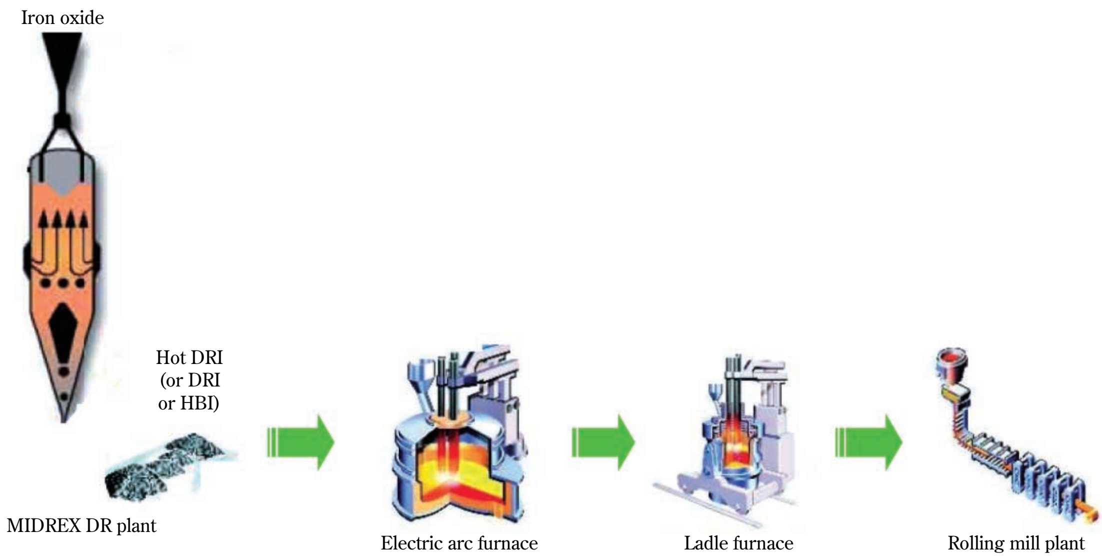

Fig.13 Overall flow sheet for integrated steel mill equipped with MIDREX plant

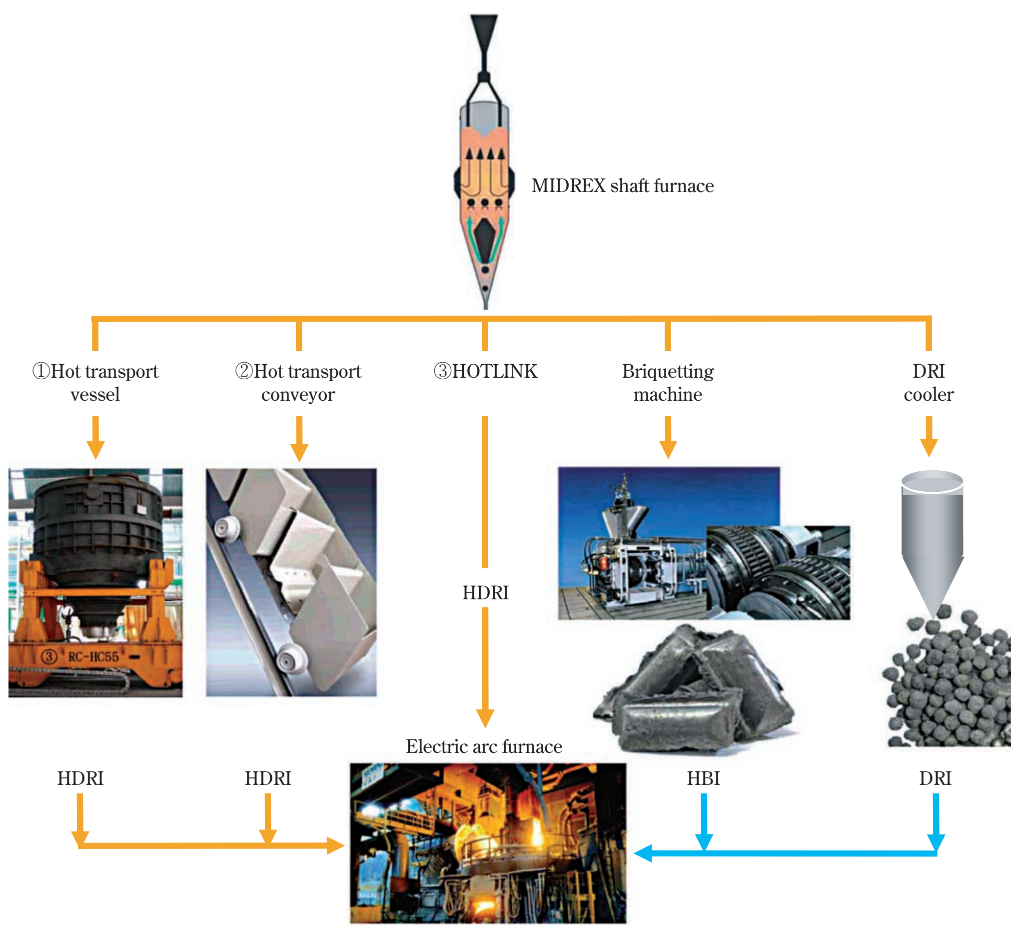

Fig.14 Variation of discharging products

4.2 Improving specific energy consumption and productivity using HDRI

Supplying HDRI at an elevated temperature directly to a steelmaking plant significantly improves the specific energy consumption and productivity of the plant. As shown in **Fig.16**, raising the HDRI supply temperature saves power consumed by the electric arc furnace (EAF). In addition, this power saving reduces the consumption of the EAF's electrode, which decreases the operational cost (**Fig.17**).

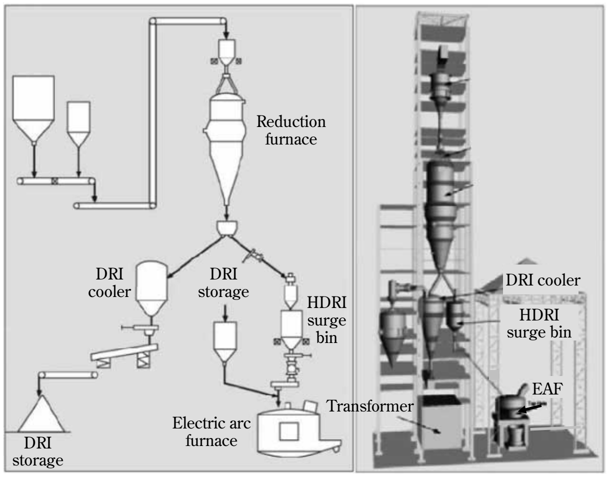

Fig.15 Material flow of HOTLINK and equipment arrange

Table 3 MIDREX plants discharging HDRI

PLANT	LOCATION	START-UP	TYPE SYSTEM
Essar steel Module-I, II, III, IV	India	1999～2004	Hot transport vessel
HADEED Module-E	Saudi Arabia	2007	Hot transport conveyor
LION	Malaysia	2008	Hot transport vessel
ESISCO	Egypt	2010	HOTLINK
SHADEED	Oman	2010	HOTLINK

Furthermore, charging HDRI to an EAF shortens the cycle time of the EAF, which increases the production volume by 10 to 15%.

4.3 CO_2 emission reduction

Various improvements have been made to the MIDREX process to reduce the specific energy consumption of the process, including downstream steelmaking, and to improve the productivity of the shaft furnace. These energy-saving measures not only decrease the operational cost, but also decrease the environmental burden with reduced emissions of CO_2 and other types of exhaust.

The MIDREX process, which is based on natural gas, emits intrinsically less CO_2 than other processes using coal. Because of this, the MIDREX process can also contribute to emission reduction in coal based ironmaking processes. For example, charging HBI produced by a MIDREX plant into a blast furnace reduces CO_2 emissions as a whole.

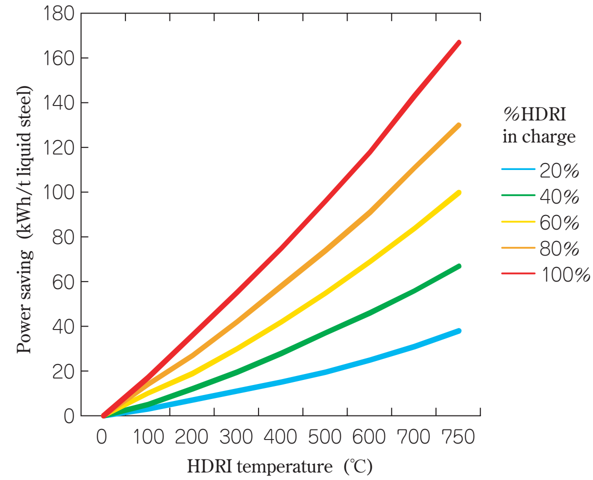

Fig.16 Correlation between HDRI temperature and power savings at EAF

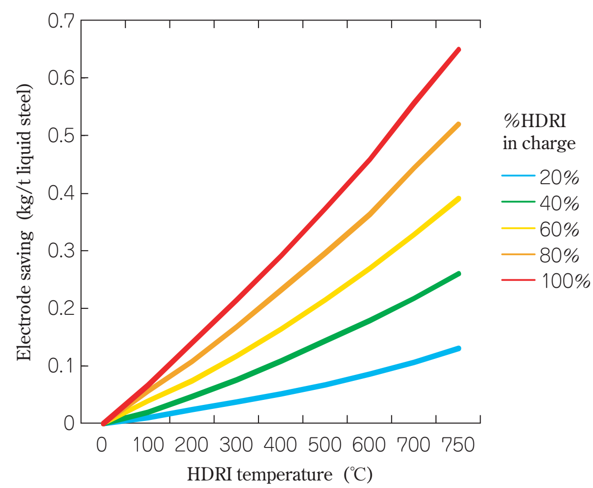

Fig.17 Correlation between HDRI temperature and electrode savings at EAF

4.4 Combination with coal-based fuel

The MIDREX process can utilize not only the reducing gas modified from natural gas, but also coke oven gas and other reducing gases derived from PET coke or from bottom oil generated in oil refineries. Thus the construction of MIDREX plants, formerly restricted to sites in natural gas producing countries, no longer suffers from such limitations. For example, the MIDREX process can be incorporated into a blast furnace based ironmaking facility that has a coking process. The HBI produced by using the coke oven gas can be charged into the blast furnace to decrease the reduction load of the blast furnace. This will decrease the ratio of the reductant used as a heat source (reductant ratio) and reduce CO_2 emissions.

Fig.18 depicts the process flow of the MIDREX process combined with a gasification plant.

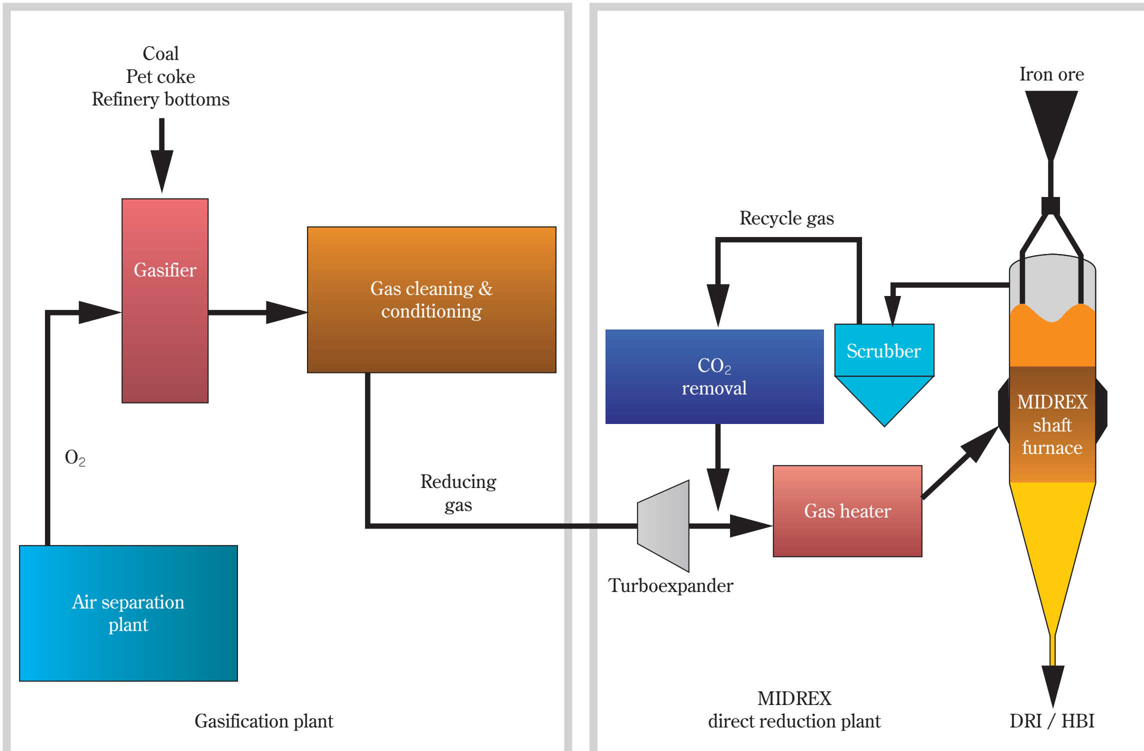

Fig.18 Process flow of MIDREX process combined with coal gasification plant

Conclusions

The origin and development of the MIDREX process have been introduced along with the new technologies that have been developed or are presently being developed by Kobe Steel.

Since the inauguration of the first commercial plant in 1969, seventy-two MIDREX plants have been built in twenty-one countries so far. The MIDREX process occupies a market share of about 60% among DRI making plants. This is a result of the improved reliability of the MIDREX process, as well as improved process efficiency, which is widely recognized and highly evaluated.

Kobe Steel will continue striving to decrease the environmental burden, increase the versatility of raw materials and further improve efficiency so as to contribute to the world's iron and steel production.

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KOBELCO Pelletizing Process

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Kobe Steel's history of pelletizing plants began when the company built a plant at its Kobe Works in 1966. This paper introduces the history of pelletizing plants, including process outlines and the latest achievements in the construction of plants overseas. In the past, plant owners had focused mainly on the quality of the product pellets and plant equipment, as well as the cost of the plants. Lately, however, the environmental aspects of plant operation have also been attracting more attention. Kobe Steel, with its experience in design, construction and operation, is contributing to the further improvement and development of pelletizing plants that meet all the requirements.

Introduction

In 1966, Kobe Steel installed a pelletizing plant based on the kiln process at its Kobe Works. Since then the company has built and run many pelletizing plants using this process. This paper introduces the history of the development of pelletizing plants and the features of various processes. Also included are the advantages of KOBELCO pelletizing, as well as the current status of the projects conducted by Kobe Steel.

There are two major methods of ironmaking: (1) ironmaking on large-scale using a blast furnace and (2) ironmaking on small-to-mid scale using an electric arc furnace (EAF). The raw materials for ironmaking that are charged into a blast furnace include lump ore, sintered ore and pellets. The ones charged into an EAF include iron scrap, reduced iron pellets and reduced iron briquettes. Sintered ore is made by partially melting and sintering coarse iron ore 1 to 3mm in size into products having a size of 15 to 30mm. The sintering process uses the combustion heat of coke breeze (fuel). Pellets are made from iron ore that is finer than that used for sintered ore. The ore fine is formed into spheroids, called green balls, approximately 12mm in diameter. The green balls are fired into product pellets. The pellets are used as the raw materials not only for blast furnaces but also for gas-based direct reduction furnaces, the process becoming popular among natural gas producing countries.

The history of pellets began in 1912 when A.G. Andersson, a Swede, invented a pelletizing method. The commercial use of pellets, however, began in the USA after World War Ⅱ. Various studies were conducted with the aim of developing the vast reserves of taconite in the area around the Great Lakes. In 1943, Dr. Davis, a professor at the University of Minnesota, Mines Experiment Station, invented a method for processing taconite containing low grade iron ore. His process involved grinding taconite to remove gangues and upgrading the iron ore (i.e., an ore beneficiation process). The resultant high-grade ore is in the form of fine particles, as small as 0.1mm or less, which are not suitable for sintering. This issue led to the use of pelletizing.

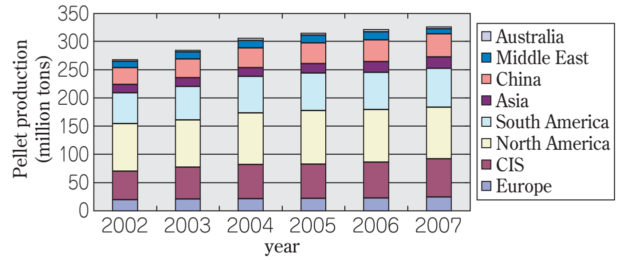

Fig. 1 Worldwide pellet production

Pelletizing plants are expected to play an important role in an era when the global reserve of high-grade lump ore is shrinking. The plants promote the concentrating of low-grade ore into upgraded pellets, which will be increasingly used by blast furnaces and direct reduction furnaces.

Fig. 1 shows the total global production of pellets along with the regional production[1].

1. Equipment for pelletizing plants

A pelletizing plant includes four processes:

1) raw material receiving,
2) pretreatment,
3) balling, and
4) indurating.

This chapter outlines these processing steps.

1.1 Process of receiving raw material

The location of a pelletizing plant affects the method of receiving raw materials such as iron ore, additives and binders. Many pelletizing plants are located near ore mines. This is because these plants were developed to pelletize the raw materials that are beneficiated at these mines. Such plants receive the raw materials via railways and/or slurry pipelines. Other pelletizing plants exist at a distance from and independent of ore mines. In such cases, the receiving method involves the transportation of the ore in a dedicated ship, unloading the ore at a quay and stockpiling it in a yard. Iron ore must be shipped in bulk for maximum economy.

1.2 Pretreatment process

In this process, the iron ore is ground into fines having qualities required for the subsequent balling process. The pretreatment includes concentrating, dewatering, grinding, drying and prewetting.

In general, low-grade iron ore is ground into fines to upgrade the quality of the iron ore, remove gangues containing sulfur and phosphorus, and control the size of the grains. In the case of magnetite, a magnetic separator is employed for upgrading and gangue removal. With hematite, on the other hand, these operations are accomplished by gravity beneficiation, flotation, and/or a wet-type, high-magnetic separator. **Fig. 2** schematically shows a magnetic separator, a typical machine used for magnetite beneficiation[2].

The grinding methods are roughly categorized as to the following three aspects:

1) wet grinding – dry grinding
2) open-circuit grinding – closed circuit grinding
3) single stage grinding – multiple stage grinding

These methods are used in combination depending on the types and characteristics of the ore and the mixing ratio, taking into account the economic feasibility. A wet grinding system (**Fig. 3**) accompanies a dewatering unit with a thickener and filter, while a dry grinding system (**Fig. 4**) requires a prewetting unit. Drying is usually provided in association with dry grinding. Prewetting includes adding an adequate amount of water homogeneously into the dry-ground material to prepare pre-wetted material suitable for balling. This is a process for adjusting the

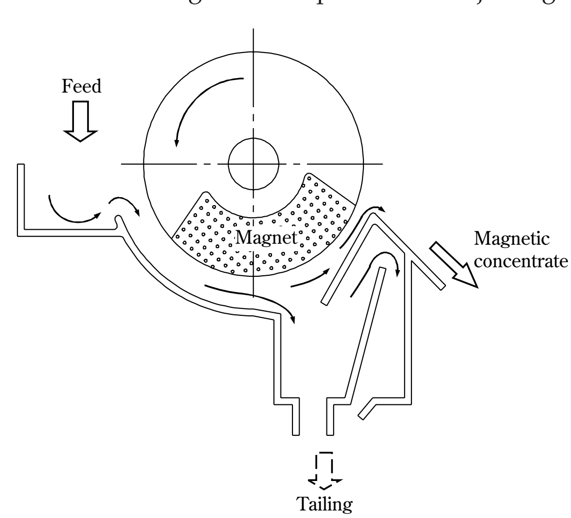

Fig. 2 Magnetic separator

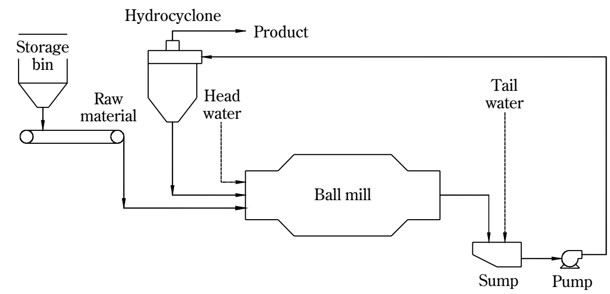

Fig. 3 Flow of closed circuit wet-grinding system

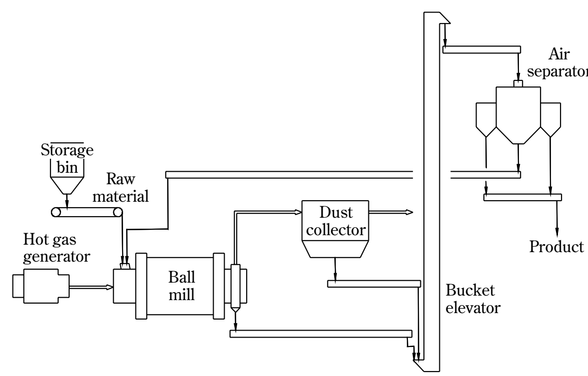

Fig. 4 Flow of closed circuit dry-grinding system

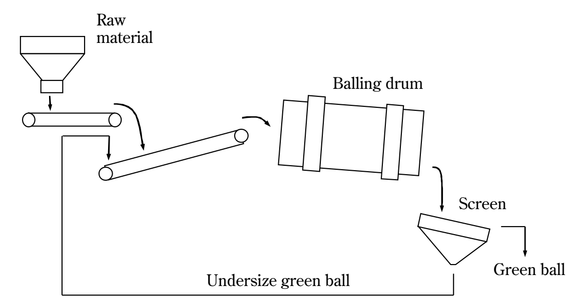

Fig. 5 Flow of balling drum

characteristics of the material that significantly affect pellet quality. Occasionally, the chemical composition of the product pellets is also adjusted in this process to produce high quality pellets. A typical binder is bentonite or organic binder. Adding lime and/or dolomite to the ore adjusts the pellets so as to have the target chemical composition[3].

1.3 Balling process

In this process, balling equipment produces green balls from the pre-wetted material prepared in the previous process. The green balls are produced either by a balling drum (**Fig. 5**), or by a balling pan (disc) (**Fig. 6**). Both of the units utilize centrifugal force to form the fine materials into spheroids. The green balls produced by a drum are not uniform in diameter. A significant portion of the discharge (about 70%) is smaller than target size and must be returned to the drum after screening. It is difficult

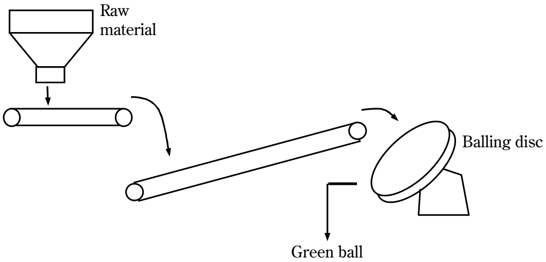

Fig. 6 Flow of balling disc

to adjust the drum operation for varying raw material conditions. The operation, however, is stable for uniform raw material conditions (chemical composition, particle size, moisture, etc.). A balling disc, on the other hand, classifies green balls by itself, reducing the amount of pellets returned. The disc operation can easily be adjusted for varying raw material conditions by changing the revolution, inclined angle and depth of the pan.

1.4 Indurating process

The firing of pellets establishes the binding of hematite particles at an elevated temperature ranging from 1,250 to 1,350℃ in oxidizing condition. Slag with a low melting point may form in the pellets during this firing step, if the raw material contains fluxed gangue, or if limestone is added to it. In these cases, the product may have an intermediate structure with both hematite binding and slag binding. The firing process is characterized by process temperatures lower than those required by sintering which requires partially melting and sintering fine ore mixed with coke breeze, a fuel which generates combustion heat.

Three systems are used for indurating pellets, i.e., a shaft furnace system, a straight grate system and a grate-kiln-cooler system. Shaft furnaces are the most traditional facilities; however, few plants use this system these days because of their limited scale. A straight grate system emerged in the industry soon after the shaft furnaces. It consists of a single unit which moves a static layer of pellets. The system has a simple structure for drying, preheating, firing and cooling pellets. Due to its relative ease of operation, along with ease of scaling-up, makes the system one used by many plants. A grate-kiln-cooler system consists mainly of a grate, a kiln and a cooler, respectively designed for drying/preheating, firing, and cooling the pellets. The system is easy to control, and the product pellets have a uniform quality. It can also be scaled up to a fairly large degree, and these systems are used by many plants along with straight grate systems.

Table 1 compares a grate-kiln-cooler system and a straight grate system.

Table 1 Comparison of grate-kiln-cooler process and straight-grate process

No.	Items	Grate-Kiln -Cooler	Straight -Grate	Comments
1	Pellet quality			
	a) Uniformity	○	△	Grate-Kiln-Cooler process enables all pellets to be uniformly and adequately heat-hardened by tumbling action and be held at the peak temperature for longer period than in Straight-Grate.
	b) Cold compression strength	○	△	
	c) Tumble index	○	△	
	d) Chemical composition	○	○	Iron grade and impurity contents are basically influenced by ore beneficiation processes, but not by the pelletizing process.
	e) Reducibility	○	○	Reducibility (final reduction degree in DR) and clustering tendency depend basically on the characteristics of iron ore itself. Generally, the higher iron content of pellets have the higher reducibility and the higher clustering tendency. Remark: Addition of lime (hydrated lime or limestone) and/or dolomite to iron ore results in lower clustering tendency of pellets and higher compression strength of sponge iron.
	f) Clustering tendency during reduction	○	○	
	g) Disintegrating tendency during reduction	○	△	The pellets uniformly and adequately heat-hardened in Grate-Kiln-Cooler process have lower disintegrating tendency.
2	Fuel consumption	○	△	Grate-Kiln-Cooler process attains lower fuel consumption, due to the followings ; a) No hearth layer and side layer b) Efficient heat transfer mechanism in grate, kiln and cooler to meet each specific requirement
3	Power consumption	○	△	No requirement of hearth layer and low height of pellet bed on the grate of Grate-Kiln-Cooler process lower the pressure drop across the pellet bed, which reduces the power consumption of process fans.
4	Maintenance cost	○	△	Straight-Grate process needs more spare parts of grate bars which suffer from considerable cyclic thermal stresses through drying, preheating, firing and cooling.
5	Process versatility	○	△	Grate-Kiln-Cooler process allows independent operation adjustment of grate, kiln and cooler, which enables the operators ; a) to, easily and without any risk, decrease and increase the rate of pellet production. b) to overcome radical changes in the characteristics of iron ore materials fed to the pelletizing plant, and to utilize various kinds of additives ; bentonite, hydrated lime and/or limestone. c) produce pellets of differing metallurgical characteristics. The single burner applied for Grate-Kiln-Cooler process simplifies the process control. When required, the burner has ability to simultaneously fire two fuels, gas and oil, and switch on-stream from one fuel to another.
6	Plant availability	○	○	No specific difference on plant availability

2. Kobe Steel pelletizing plants

A pelletizing plant was built at the Kobe Works of Kobe Steel in September 1966, with the aim of increasing the productivity of the blast furnaces by utilizing pellets. This involves optimizing the raw materials. The raw materials are separately treated, depending on their characteristics, in a sintering plant and a pelletizing plant. This makes the pretreatment more versatile and enables the use of fine ores.

The raw material for the plant includes fines of various hematites such as limonite. Thus the plant adopts a dry grinding/pre-wetting system suitable for such raw material. For the indurating process, Kobe Steel introduced a Grate-kiln system developed by Allis-Chalmers for assuring homogenous firing at a high temperature. The plant had a capacity of one million tonnes/year.

Then Kobe Steel built the No.1 pelletizing plant at the Kakogawa Works in 1970 and the No.2 pelletizing plant in 1973, each having a production capacity of 2 million tonnes/year. The only pelletizing plant still in service is the No.1 pelletizing plant at the Kakogawa Works. The plant now has an increased capacity of about 4 million tonnes/year, the result of various modifications for capacity enhancement, labor-saving and energy-saving.

Kobe Steel is in the advantageous position of operating its own pelletizing plants and using the product pellets for its own blast furnaces. This has led the company to the practical application of self-fluxed pellets and the development of dolomite pellets. Kobe Steel has taken a leading position in utilizing pellets for large blast furnaces in Japan.

Fig. 7 depicts the typical flow in a KOBELCO pelletizing plant.

3. Features of pellet indurating equipment

As described previously, Kobe Steel built pelletizing plants based on the Grate-kiln process at the Kobe Works and Kakogawa Works. After many unique modifications, the company constructed various pelletizing plants as KOBELCO pelletizing systems, not only domestically, but also overseas. All the systems adopt a grate-kiln-cooler process for their indurating step.

This chapter describes more details of the three indurating systems[4].

3.1 Shaft furnace system

A shaft furnace (**Fig. 8**) in an old system employs an external combustion chamber to generate the heat required for indurating and introduces the hot gas into the furnace. The green balls, charged from the furnace top, make contact with the hot gas as they descend and exchange heat to increase their temperature. The heated pellets pass a cooling zone before being discharged outside the furnace. The pellets charged from the furnace top come into sufficient contact with the hot gas to ensure high thermal efficiency, which is a feature of shaft furnaces. However, it is difficult to attain a uniform temperature distribution in the furnaces. This results

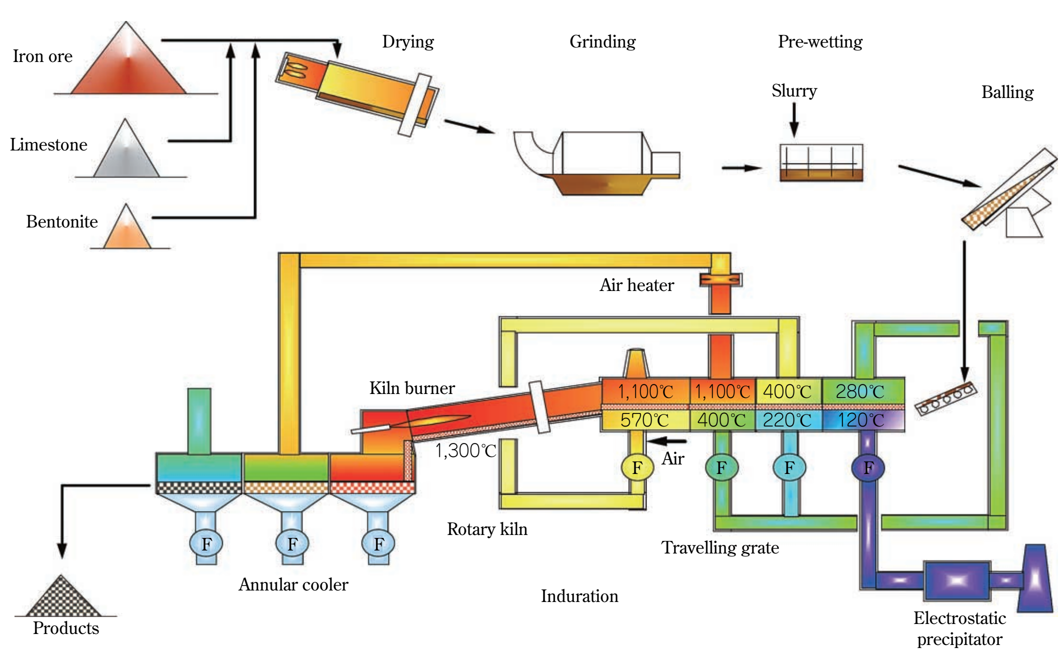

Fig. 7 Typical flow of KOBELCO pelletizing plant

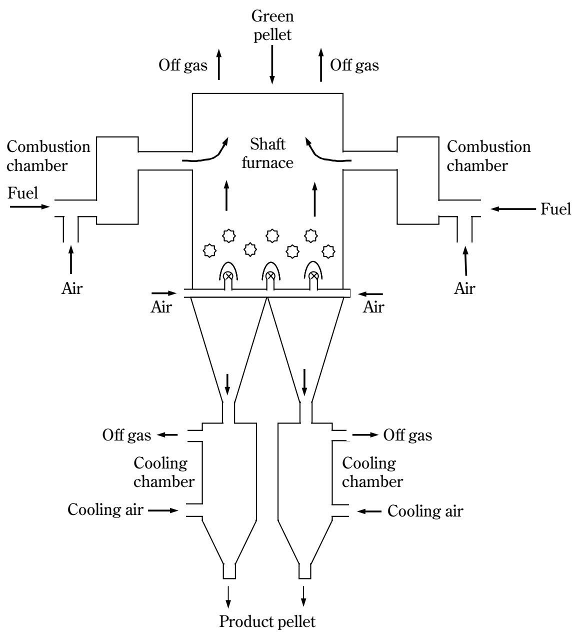

Fig. 8 Flow of shaft furnace system

in nonuniform heating of the pellets, causing them to cluster and/or to adhere to the furnace wall, leading to difficulty of operation. In addition, the scale of the plant is limited to about 450 thousand tonnes/year at maximum, which limits the cost savings. This technology has become obsolete due to the difficulty of increasing the furnace size.

3.2 Straight grate system

A straight grate system (**Fig. 9**) emerged in the industry soon after shaft furnaces. The system comprises a grate which transfers green balls charged onto it. The grate feeds the green balls sequentially through the steps of drying, preheating, firing and cooling. The advantage of a straight grate over a shaft furnace exists in the wider range of temperature control for the processing steps of drying, preheating, firing and cooling. This system, however, suffers from the disadvantage that a change in the grate speed at once changes all the conditions for the subsequent process steps.

A straight grate machine includes an endless grate car consisting of grate bars with side walls. A layer (about 100mm thick) of fired pellets is placed on the grate bars and on the side walls (**Fig.10**). Green balls are placed on top of this to form a layer of about 300mm in thickness. The layer of fired pellets protects the grate bar and side wall from high temperatures and prevents the green balls from being inhomogeneously fired. The green balls on the grate pass through the zones for drying, preheating, firing and cooling. Each zone is held at a predetermined temperature, and heat exchange occurs via hot air and/or combustion gas to fire the pellets.

The straight grate system, consisting essentially of a single unit which moves a static layer, is easy to operate. However, the system must re-circulate a portion of the fired pellets to form the layers on the grate bars and side walls to protect the mechanical

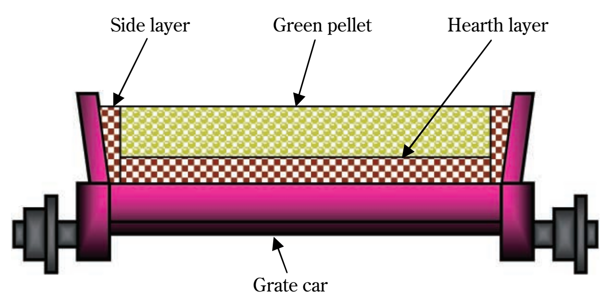

Fig.10 Cross sectional sketch of straight grate

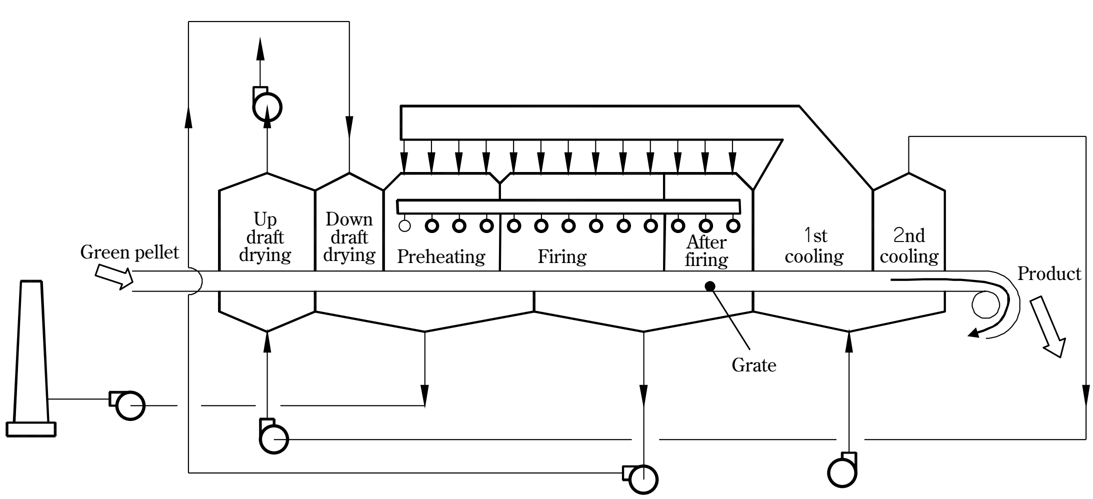

Fig. 9 Flow of straight grate system

parts and prevent variations in pellet quality. Despite this protection, the pellets are subject to wear when passing through the process steps at elevated temperatures. In addition, as previously described, this system involves a thick layer (300mm), which is prone to temperature variation between its top and bottom portions. This leads to variations in the quality of the product pellets.

3.3 Grate-kiln-cooler system

A grate-kiln-cooler system (**Fig.11**) consists of three major components: a grate (e.g., a traveling grate), a kiln (e.g., a rotary kiln) and a cooler (e.g., an annular cooler). The green balls, fed uniformly onto the grate, pass sequentially through the steps of drying and preheating. The preheating step hardens them to a strength great enough to endure the tumbling and heating that occur in the subsequent kiln step. The pellets, after being fired at an elevated temperature inside the kiln, are cooled in the following step to produce fired pellets.

The basic concept for designing a system including a grate, kiln and cooler consists in allocating the thermal transfer, occurring at temperatures from ambient to 1,300℃ or higher, to each process step so as not to cause any mechanical problems.

The grate is partitioned into drying zones and preheating zones. In these zones, heat exchanges at relatively low temperatures occur for drying and preheating the green balls. Forced convection is applied to the heating for high thermal efficiency. The source of the heat for drying and preheating the pellets is not only the kiln off gas, but also recoup gas from the cooler, an arrangement that gives the plant as a whole high thermal efficiency.

A kiln with a relatively short length is connected with the grate at its inlet and with the cooler at its outlet. The kiln is lined with refractory materials for firing the preheated pellets discharged from the grate. The firing is conducted at an elevated temperature, and radiation heating is applied to fire the pellets efficiently and homogeneously. The kiln is placed at a slight incline to the discharge and rotates at a low revolution. The pellets tumble inside the rotating kiln to be fired at a predetermined temperature (**Fig.12**) and are subsequently transferred to the cooler. The tumbling action ensures the homogenous heating of all the pellets inside the kiln and consistently yields high quality.

An annular-shaped, horizontally rotating cooler decreases the temperature of the fired pellets to a level suitable for subsequent transportation. This step employs the forced convection of air blow for cooling. A part of the hot gas collected from the cooler is used as secondary air for fuel combustion in the kiln. The hot gas is also used for the process steps of drying and preheating the green balls, making the entire system thermally efficient.

A grate-kiln-cooler system has the following features:

1) The system produces homogeneous products, since the pellets are subject to tumbling action during the firing in the kiln.
2) Each of the steps of preheating, firing and cooling can be controlled either in conjunction with the others, or independently from the others, as needed. This enables heating the hot

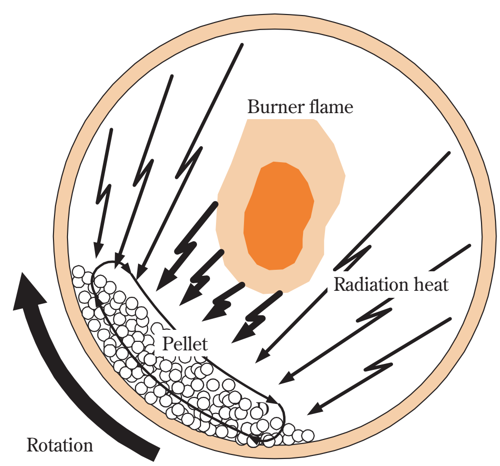

Fig.12 Cross sectional sketch of rotary kiln

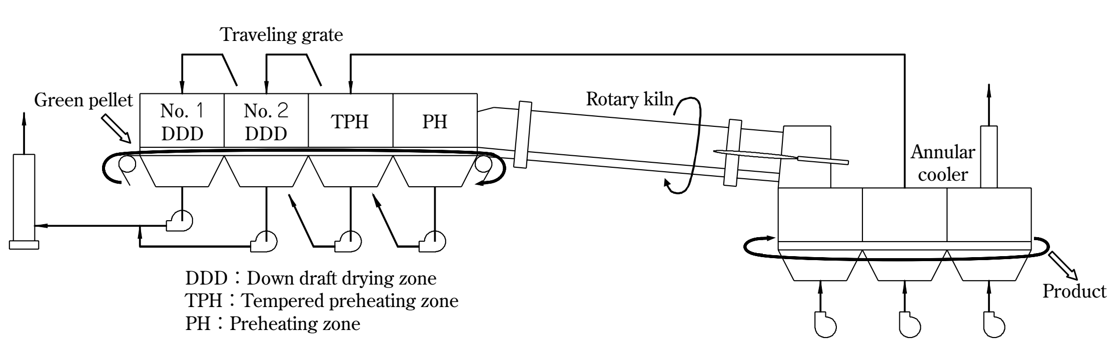

Fig.11 Flow of grate-kiln-cooler system

gas and pellets in the pattern most suitable for each process step and makes the process versatile with regard to variations in raw material quality and the production rate.

3) The ease of temperature control enables the homogenous production of self-fluxed pellets, whose production requires strict temperature control.
4) Low fuel and power consumption can be achieved.
5) The grate, kiln and cooler of the system are independently designed and constructed according to their respective thermal loads. This reduces the frequency of replacing parts such as the refractory material and grate-plate, and consequently improves the availability of the plant.

4. Product quality and features

The quality of the pellets depends on the process of pellet production. A straight grate system transfers pellets as a static layer. The system consists of a single unit for drying, preheating, firing and cooling the pellets. The pellet layer is relatively thick, about 300mm, causing a difference in the heating profile of pellets in the upper and lower portions of the layer. This causes variations in pellet quality, especially in compression strength and tumble strength.

On the other hand, the pellets produced by the KOBELCO pelletizing system have been heated uniformly by the tumbling action inside the kiln during the firing step. The firing temperature can be adjusted with ease and accuracy by controlling the fuel ratio for the kiln burner.

Fig.13 compares the distribution in the compression strength of pellets produced by the KOBELCO pelletizing system and those produced by the straight grate process.

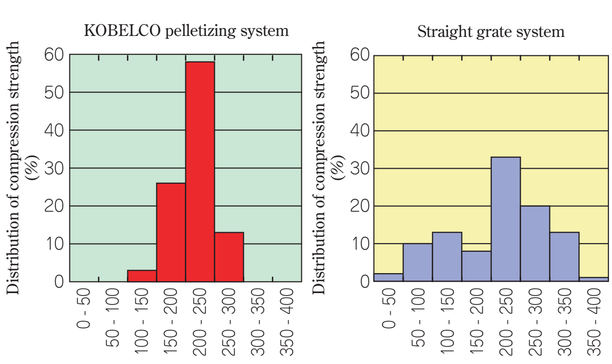

Fig.13 Comparison of product pellets

5. Ability to adapt to various raw materials

In a grate-kiln-cooler system, the drying/ preheating, firing and cooling steps are performed by separate units, making it possible to control each of the steps independently. An advantage of the grate-kiln-cooler system is its capability of providing the heat patterns most suitable for various raw materials. In other words, it can accommodate any mixture of ore, from 100% magnetite to 100% hematite. In a case where the raw ore contains a large amount of crystal water, the crystal water may explosively vaporize to cause bursting of the green balls. KOBELCO pelletizing systems can avoid such bursting by providing a dewatering step, performed at a relatively low temperature to prevent rapid heating of the green balls.

6. Sample test and process design

When designing a pelletizing plant, the equipment must be sized appropriately to achieve the most suitable process conditions determined by the types of ore to be processed by the plant.

More specifically, the approach involves

- computing the material and heat balance based on the design conditions, such as the plant capacity, types of raw materials and the properties required for the product pellets, and
- determining the heat patterns best suited for the grate, kiln and cooler.

The computation is conducted by a process-designing simulation program owned by Kobe Steel. The program's calculation parameters are based on the company's wide experience. The heat patterns thus determined are applied to sample tests to confirm the qualities of the preheated pellets and fired pellets.

The heat pattern thus obtained determines the size of the grate, kiln, cooler, and other process equipment, such as process fans and dust collectors, all of which are reflected in the plant design.

The sample test involves the actual ore to be processed, the ore being subjected to tests simulating actual processes to confirm the qualities required for the pellets.

Kobe Steel owns the following testing apparatuses to conduct the process designing based on the above procedure.

1) Batch-type ball mill : This apparatus is used to grind iron ore and additives to predetermined sizes and adopts the dry-grinding method described in 1.2.
2) Batch-type mixer : This apparatus mixes raw materials, such as iron-ore, binder and

additives, together homogeneously. The mixture may also be moistened by this mixer for the subsequent balling step.

3) Continuous disc type balling apparatus (**Fig.14**) : The apparatus produces green balls to verify the green ball quality required by actual plants. If the required quality is not achieved, the balling test is repeated for different fineness of iron ore and binder types until an optimal result is obtained.
4) Pot grate (**Fig.15**) : This pot grate dries and pre-heats the green balls. The apparatus allows for freely setting the temperature and flow rate of the process gas, as well as the process time. In an actual plant, pellets are transferred from a grate to a kiln via a chute and are tumbled inside the kiln. Thus, the preheated pellets must have a certain strength. This apparatus can be used to confirm whether or not the grate can produce such preheated pellets. To produce preheated pellets satisfying required specifications, the temperature and flow rate of process-gas, as well as the process time, must be controlled to establish an appropriate heat pattern and grate size.
5) Batch type kiln (**Fig.16**) : This apparatus is used for firing the preheated pellets produced by the pot grate. Since it allows for freely setting the firing temperature and process time, the apparatus is used to determine the firing temperature and process time for achieving the qualities required for the pellets.
6) Batch type cooler : This cools the pellets fired by the kiln.
7) Quality testing apparatuses for pellets : The apparatuses determine pellet qualities, such as their physical properties, reduction characteristics and chemical composition.

Fig.14 Photograph of balling disc

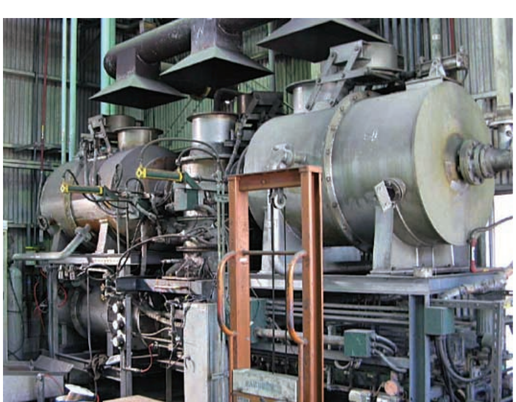

Fig.15 Photograph of pot grate

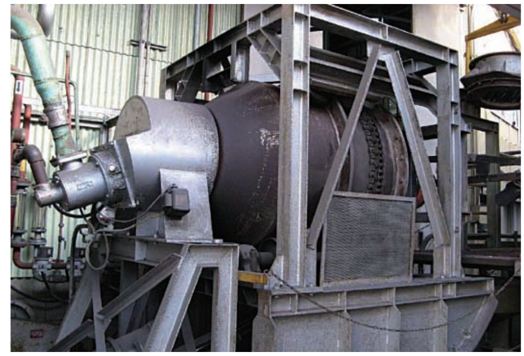

Fig.16 Photograph of batch type kiln

Table 2 Typical required figures for pellets

Phase	Physical propertty	Typical target figure
Green ball	Drop strength	>5
	Compression strength	>1kg
Product pellet	Compression strength	>250kg
	Tumble strength	>95%
	Abrasion Index	<4%
	Reduction behaviour	
	(a) For BF pellet	
	Reducibility	>60%
	Swelling	<15%
	(b) For DR pellet	
	Metallization	>92%
	Fragmentation	<3.5%

Kobe Steel designs pelletizing plants by conducting sample tests using the above apparatuses for appropriate equipment sizing.

Table 2 summarizes the typical values for the pellet qualities that provide indices for the process designing and sample test[5].

7. Pelletizing plants recently constructed

The following outlines the pelletizing plants constructed by Kobe Steel in recent years. **Table 3** summarizes the main specifications for each pelletizing plant.

1) Iran : Ardakan Pelletizing Plant (**Fig.17**)

This plant is located near the city of Yazd, an inland area of Iran. The contract covered the entire pelletizing plant, from receiving the concentrate to the loading out of the product pellets, both by

Table 3 Reference list of pelletizing plant

Plant	FMO Venezuela	Chador Malu Ardakan / Iran	GIIC No.2 Bahrain	Vale Sohar / Oman
Nominal capacity	3,300,000 ton/year	3,400,000 t/year	6,000,000 t/year	4,500,000 t/year×2 lines
Start-up	1994	2007	2009	2010
Feed material	Hemetite	Magnetite-Hematite	Hematite	Hematite
Product	DR Pellet	DR pellet	DR pellet	DR pellet
Balling disc	ϕ7,500mm×5units	ϕ7,500mm×6units	ϕ7,500mm×9units	ϕ7,500mm×7units (×2 lines)
Travelling grate	4,716mm W×66,388mm L	4,716mm W×63,975mm L	5,782mm W×83,020mm L	4,716mm W×68,801mm L (×2 lines)
Effective area	284.5m^2	273.1m^2	440.8m^2	295.9m^2
No. of windbox	25	24	25	26
Length/bay	2,413mm	2,413mm	3,050mm	2,413mm
Rotary kiln	6,000mm ID×46,000mm L	6,000mm ID×46,000mm L	7,200mm ID×50,000mm L	6,900mm ID×45,000mm L (×2 lines)
Annular cooler	ϕ18,500mm×2,800mm W	ϕ20,000mm×3,100mm W	ϕ22,000mm×3,700mm W	ϕ22,000mm×3,700mm W (×2 lines)
Effective area	145.5m^2	177.5m^2	234.0m^2	234.0m^2

Fig.17 Photograph of Ardakan pelletizing plant

Fig.18 Photograph of GIIC No.2 pelletizing plant

railway. A consortium was set up by Kobe Steel, TAIM-TFG, S.A. (Spain), and ABB (Swiss), Kobe Steel taking charge of designing the process, supplying the processing equipment and managing construction, while TAIM supplied the material handling equipment, and ABB assumed responsibility for the electric equipment and control system.

This pelletizing plant receives iron ore concentrate (a mixture of magnetite and hematite) produced by the ore beneficiation plant of a mine located about 200km away. The ore beneficiation plant, also constructed by Kobe Steel, has a capacity of 5 million tonnes/year.

The product pellets are used as a raw material for direct reduction furnace feed and are delivered by rail to, for example, Mobarakeh Steel, one of the companies operating a gas-based direct reduction plant with the MIDREX process, which was constructed by Kobe Steel.

General-purpose equipment, such as small fans and pumps, and the plate working used for the pelletizing plant were locally procured from domestic companies in Iran. With various sorts of training on production and project management, the construction was completed successfully and the plant inaugurated in 2008.

2) Bahrain : The No.2 pelletizing plant, Gulf Industrial Investment Co. (GIIC: **Fig.18**)

The No.1 plant, constructed by Kobe Steel in 1985, led to the contract for the No.2 plant. This project was on a full turnkey basis, including the designing, equipment supply, construction and commissioning of the plant, encompassing everything from the receiving of raw materials to the shipping of product pellets.

The pellets produced by the No.1 plant are delivered to direct reduction plants with the MIDREX process utilizing natural gas in the countries neighboring Bahrain. The high quality of the products, as well as the high achievement of the direct reduction plant constructed by Kobe Steel in Qatar, led to the contract for the No.2 plant.

The pelletizing plants constructed by Kobe Steel had a maximum capacity of 4 million tonnes/year. As the No.2 plant constructed for GIIC, Bahrain, a plant with a capacity of 6 million tonnes/year was developed in response to the client's requirement for upsizing. The plant started operation at the end of 2009, as planned.

3) Oman : Vale/Sohar pelletizing plant (**Fig.19**)

This is the first overseas pelletizing plant for Vale, a Brazilian mining giant and the world's largest

Fig.19 Bird's-eye view of Sohar pelletizing plant

producer of iron ore. The plant is being constructed in Sohar, Oman, as a base for supplying ore and pellets to the Middle East. Kobe Steel has received an order for the basic design of the process area, including the processes of mixing and pre-wetting of raw materials, balling, indurating and screening. The basic designing of facilities for port, yard, ore-grinding and utility is being done by Vale and other Brazilian firms. In the first phase, two lines, each having a capacity of 4.5 million tonnes/year (4.5 million tonnes/year×2), are being constructed. Similarly, two lines (4.5 million tonnes/year×2) are to be constructed in the second phase, for a total pellet production capacity of 18 million tonnes/year. The plant is to become a supply base stockpiling forty million tonnes of iron ore.

All the pelletizing plants owned by Vale in Brazil have straight grate systems. The choice of a KOBELCO pelletizing plant was made in consideration of the high quality pellet production of Kobe Steel's grate-kiln-cooler system. Construction work started in 2009, with operations to begin in 2010.

4) Malaysia : Vale pelletizing plant

This is the second overseas pelletizing plant for Vale and is to be constructed in Perak, Malaysia, as a base for supplying ore and pellets to Asia. The plans call for a pelletizing plant having four lines, each with a capacity of 4.5 million tonnes/year (4.5 million tonnes/year×4). The plant adopts Kobe Steel's KOBELCO pelletizing in the same manner as the one in Oman. Designing started at the end of 2009.

8. Environmental responsiveness of pelletizing plants

The environmental regulations applied to pelletizing plants are becoming more and more stringent in developing nations. The regulations that a pelletizing plant is required to follow in order to reduce environmental pollution are almost the same as those in Japan.

The following describes the environmental regulations relating to pelletizing plants and the measures taken to comply with them.

1) Dust

The dust generated by the process is collected by dust collectors, such as electrostatic precipitators, bag filters and scrubbers, without being emitted into the atmosphere. The collected dust is reused as one of the raw materials. In recent years, dust emission control at material handling areas such as stock yards has become a concern for developing nations. Measures are being implemented to prevent the scattering of dust by sprinkling water and erecting large fences.

2) Sulfuric oxide (SOx)

Raw materials, such as iron ore, lime, bentonite and dolomite contain sulfur in various amounts, as do fuels such as natural gas, oil and coal. Sulfur is fed into the process along with various materials used for pellet production. All the sulfur is oxidized in the pelletizing process, generating SOx, most of which is emitted as exhaust.

Unlike nitrogen oxide (NOx), SOx can not be reduced by the process itself. There are two ways of reducing SOx in the exhaust. One is to use raw materials and fuels containing less sulfur. The other way is to install desulfurization equipment for removing the SOx that is generated.

A typical desulfurization method, called the lime slurry method, involves mixing water and lime into slurry, which reacts with SO_2 in the exhaust to collect sulfur in the form of gypsum ($CaSO_4 \cdot 2H_2O$).

3) Nitrogen oxide (NOx)

The heat for a grate-kiln-cooler system is supplied by a burner provided with the kiln; the burner uses the hot air from the cooler as combustion air. The temperature of this combustion air is in the range from 1,000 to 1,100℃, while the flame temperature is 1,600℃ or higher. Thus the NOx generated is, for the most part, thermal NOx, a product of the nitrogen being oxidized in the combustion air.

More thermal NOx is generated as the temperatures of the burner flame and combustion air rise. There are two approaches to reducing NOx emissions. One is low-NOx combustion and the other is installing a de-NOx system. Low-NOx combustion is an approach to reduce NOx generation by improving the process and adopting low NOx burners. This approach includes

- decreasing the amount and/or temperature of the combustion air
- reducing the kiln burner's fuel combustion by providing additional burners for the grate,

・reducing NOx generation by creating a localized reducing atmosphere inside the flame, and
・making the flame area larger to decrease the flame temperature and to reduce the amount of NOx generated
(but this may reduce the thermal efficiency of the entire process).

There are two de-NOx approaches for reducing generated NOx using a reductant and/or catalyst.
・Selective non-catalytic reduction (SNCR)
・Selective catalytic reduction (SCR)

Both methods use ammonia or urea to reduce NOx. In SNCR, ammonia (urea) is blown into the atmosphere at a temperature from 900 to 1,000℃. In SCR, the reduction reaction is promoted by a catalyst at a temperature between 250 and 380℃.

For a newly constructed pelletizing plant using natural gas or heavy oil for its fuel, the NOx reduction achieved by a low NOx burner (i.e., about a 20% reduction) may not be enough to keep the plant within the environmental limits. In such a case, the addition of a de-NOx system may be required[6].

Conclusions

In the past, countries constructing new plants focused on the quality of the product pellets and equipment and the cost, and Kobe Steel responded to these concerns. In recent years, however, the focus has shifted to environmental issues, making environmental responsiveness an important factor in contemplating a plant.

Pelletizing plants are playing a more and more important role as they are integrated into iron ore terminals all over the world. Some of them are being integrated into direct reduction plants with EAF steelmaking plants in their downstream.

Kobe Steel continues to accumulate experience in the construction and operation of pelletizing plants and thus contribute to the development of technologies in this field.

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Prospects for Coal-based Direct Reduction Process

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Kobe Steel has developed coal-based direct reduction (DR) technologies, the FASTMET, FASTMELT and ITmk3 processes, which reduce carbon composite agglomerates (pellets or briquettes) on the hearth of a rotary hearth furnace (RHF). This paper outlines the features of each process, status of technical development and commercialization. Also described is the contribution of these technologies to environmental compatibility and the security of raw materials, which are becoming critical issues for the steel industry worldwide.

Introduction

Unlike blast furnaces, direct reduction ironmaking plants using natural gas (e.g., the MIDREX® process and HYL process) have the characteristics of requiring a smaller capital expenditure and no coking coal. Many direct reduction plants have been built in developing contries, particularly those that produce natural gas. In recent years, there has been an increased demand for direct reduced iron (hereinafter referred to as "DRI") as an alternative to high quality scrap. Electric arc furnace (EAF) mills are dominant in the steel industry in advanced countries, which is boosting the demand for DRI. **Fig. 1** shows the annual increase in DRI production[1]. The natural-gas-based DRI processes, however, limit plant locations to places where natural gas is available. On the other hand, coal-based DRI plants are flexible as to plant location, because coal is widely distributed in large deposits and is easy to transport. This has significantly increased the production of coal-based DRI. Out of the global DRI production of 68.5 million tonnes in 2008, the production of coal-based DRI occupies 17.6 million tonnes, which equates to 25.7% of the total[1]. Most coal-based reduction processes including SL/RN[2] employ rotary kilns. Pellets, or lump-ore, mixed with coal are/is charged into the rotary kilns[2] and heated by coal burners to produce DRI. To avoid the significant formation of the kiln rings, their operating temperatures must be maintained in a range from 1,000 to 1,100℃[3]. As a result, the processes require about 12 hours of reduction time. Thus, the productivity of the processes is limited to a range between 150 and 250 thousand tonnes/year, which is rather low for steel plants. Because of this, there has been a need for an alternative process.

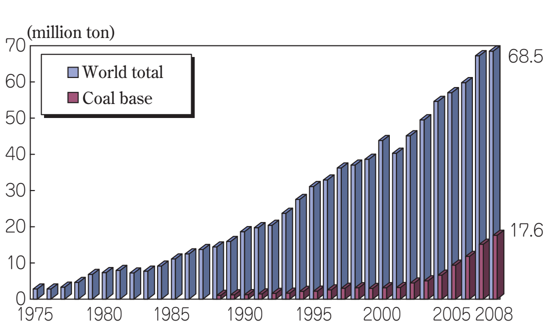


Fig. 1 World DRI production by year [1]

With this background, Kobe Steel has developed a coal-based reduction process using a rotary hearth furnace (RHF) in collaboration with MIDREX Technologies, a subsidiary of Kobe Steel in the USA. This process involves carbon composite agglomerates, in the form of pellets or briquettes, laid on the hearth of the RHF, in which the composite agglomerates are heated and reduced in a static manner. Because of this, the furnace can be maintained at a temperature in the range from 1,300 to 1,400℃, which is higher than that for rotary kilns and increases the reduction rate and productivity. The process is also characterized by flexibility regarding various raw materials, including iron ore fines, steel mill waste and non-coking coal.

This paper outlines the features and development status of Kobe Steel's coal-based reduction processes, each employing an RHF for reducing carbon composite agglomerates. Also described is the role of these processes in resolving the issues faced by the steel industry, e.g., securing raw materials and preserving the environment.

1. Features of reduction process using carbon composite agglomerates

The reduction reaction kinematic for conventional pellets and sintered ore is controlled by reduction gas diffusion from outside. On the other hand, the reaction of carbon composite agglomerates occurs inside the agglomerates themselves, which consist of iron ore fines and pulverized coal. Once the agglomerates are heated, carbon monoxide is generated inside them, promoting the reduction of iron oxide. Thus, the reduction reaction proceeds

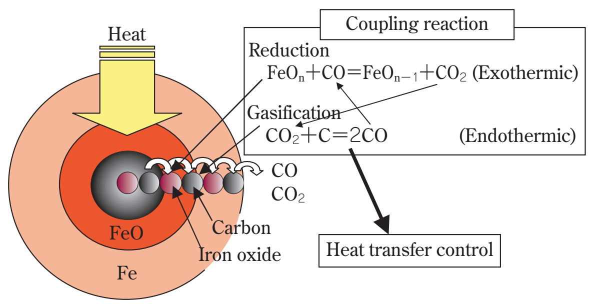


Fig. 2 Reduction mechanism of carbon composite pellet

faster in the carbon composite agglomerates than in conventional pellets and sintered ore, whose reaction is controlled by diffusion from outside. **Fig. 2** shows the reduction mechanism of a carbon composite pellet, where the following reactions are considered to occur:

$Fe_xO_y + yC \rightarrow xFe + yCO$ (endothermic) ·········(1)

$CO_2 + C \rightarrow 2CO$ (endothermic) ·····················(2)

$Fe_xO_y + yCO \rightarrow xFe + yCO_2$ (exothermic) ······(3)

At temperatures at which the iron ore does not melt, it has hardly any direct reaction with solid carbon such as pulverized coal and coke. In other words, the reaction as expressed by Equation 1 does not dominate the reaction kinematics. At elevated temperatures no lower than 1,000℃, the following reactions proceed in series inside the carbon composite agglomerates: the generation of carbon monoxide by carbon solution loss (Eq. 2) and the reduction of iron oxide by carbon monoxide (Eq. 3)[2].

In the reduction reaction described above, CO gas generation (Eq. 2) controls the reaction kinematics with its highly endothermic nature[2]. Therefore, to promote the reaction, it is essential to supply the heat required for the reaction to the inside of a carbon composite agglomerate at an elevated temperature of 1,000℃ or higher. In other words, heat must be transferred efficiently by radiation from the atmosphere to the surface of the agglomerate and, by conduction from the agglomerate surface to its interior.

It should be noted that coal accounts for about half of the volume of each agglomerate. Thus the agglomerates become porous as the reduction reaction proceeds, decreasing the strength of the DRI. The carbon composite agglomerates become progressively weaker until they reach the temperature at which sintering occurs. This may cause fragmentation due to reduction degradation.

Although fragmentation increases the surface area for thermal transfer, it makes the CO gas generated prone to being released from the agglomerates without contributing to the reduction reaction. It also decreases the shielding effect of CO gas and allows some re-oxidation of the reduced iron. Thus, it is important to prevent the agglomerates from fragmentizing inside the furnace.

2. FASTMET® process

A process of creating a thin layer of carbon composite agglomerates on the hearth of an RHF and heating the layer statically to subject it to a reduction reaction is being contemplated. In such a process, heat transfer occurs efficiently by radiation, with much less risk of reduction fragmentation. Thus, this process would be more advantageous than any conventional process using a rotary kiln or a shaft furnace. In the early 1960s, Midland Ross Corp., the predecessor of MIDREX Technologies, started developing a process called "HEATFAST," which involves carbon composite pellets reduced in an RHF. In 1965, the company built a pilot plant having a capacity of 2 tonnes/hour.

The development of the HEATFAST process, however, did not reach the point of commercialization. Due to the current low price of natural gas, the company's priority has shifted toward the gas-based MIDREX process.

In the 1990s, when the price of natural gas increased, Kobe Steel and MIDREX Technologies (hereinafter collectively referred to as "the companies") began to collaborate in developing a new process, named "FASTMET," for producing DRI from carbon composite pellets charged into an RHF.

In 1992, the companies built a pilot plant with a capacity of 160kg/h, at the MIDREX Technical Center in North Carolina, USA. In 1995, after a series of fundamental test runs, the companies constructed a demonstration plant with a capacity of 16,000 tonnes/year at the Kakogawa Works of Kobe Steel. By 1998, the demonstration plant had not only substantiated the applicability of various raw materials, such as iron-ore, dust and coal, but also yielded the various data necessary to design a commercial plant. In 2001, Kobe Steel modified the demonstration plant into a commercial plant for processing steel mill dust generated at the Kakogawa Works.

Fig. 3 shows the FASTMET process flow. The process includes mixing ore fines with pulverized coal, agglomerating the mixture into pellets or briquettes, and placing them onto the hearth of an RHF in one or two layers. For raw materials superior in pelletizing characteristics with a pan pelletizer or a balling drum, pellets with a spherical shape are applied. For other material not suitable for pelletizing, briquettes made with a dual-roller type briquetting machine are applied. The agglomerates

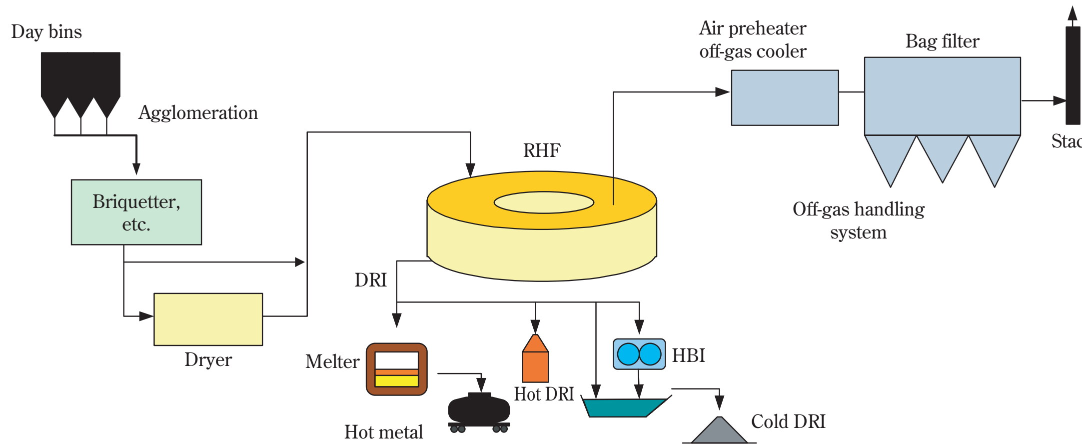


Fig. 3 Process flow sheet for FASTMET

are dried before being charged into the RHF. In the RHF, the temperature of the agglomerates is increased rapidly to 1,350℃ or higher and maintained for 6 to 12 minutes before they are discharged as DRI. The process, involving carbon composite agglomerates placed statically on the hearth, prevents them from breaking into fragments and generates few dust particles that could become entrained in the exhaust gas. The reduction reaction at high temperature reduction reaction vaporizes metallic zinc and lead in the exhaust gas.

The exhaust gas contains almost no unburned components (CO and H_2), because the CO gas generated through the reduction reaction is completely combusted by secondary combustion in the furnace. The process further includes cooling and cleaning the exhaust gas, as well as recovering sensible heat, using a heat exchanger, before discharging to the atmosphere. The vapor of zinc and lead in the furnace exhaust gas is oxidized, solidified, and thereafter collected by a bag filter together with the dust entrained in the exhaust gas.

As described above, the FASTMET process was originally developed as an alternative to gas-based DRI, making DRI from iron-ore and coal. The process, however, has a drawback: the DRI produced may have a decreased iron content and/or increased sulfur content, depending on the quality of the coal used. This impedes the commercial use of the process for producing DRI from iron ore.

On the other hand, with an eye to resource sustainability, various methods have been tried for recycling the dust generated in ironworks. Conventional sintering/pelletizing facilities and blast furnaces, however, have difficulty in using dust with a high zinc content and is alkaline, which has been an issue in the industry. The FASTMET process enables the separating of zinc contained in the dust as crude zinc-oxide and recycling it as the raw material for zinc refining. The process recycles the remaining iron as DRI. With this feature, the FASTMET process is commercially used for processing steel mill dust.

Currently, five commercial plants are producing DRI from the iron bearing dust generated in iron- and steel-making processes (**Table 1**).

The DRI takes one of two forms: 1) DRI maintaining the form of pellets/briquettes charged into the RHF and 2) The HBI (hot briquetted Iron) having strength and weather resistance for transportation and storage.

Table 2 shows the typical chemical compositions of DRI and secondary dust (zinc dust), both made

Table 1 FASTMET commercial plant specifications

	NSC Hirohata #1	NSC Hirohata #2	NSC Hirohata #3	JFE Fukuyama	KSL Kakogawa
RHF feed rate (t/y)	190,000	190,000	190,000	190,000	14,000
Raw materials	BOF dust	BOF dust	BOF dust	BF dust BOF dust	BF dust BOF dust EAF dust
Product application	BOF feed DRI	BOF feed DRI	BOF feed HBI	BF feed DRI	BF & BOF feed DRI
RHF outer dia. (m)	21.5	21.5	21.5	27.0	8.5
Operation start	Apr. 2000	Jan. 2005	Dec. 2008	Apr. 2009	Apr. 2001

Table 2 Anaysis of DRI and zinc dust

(1) Dry ball and DRI analysis (wt%)

	T.Fe	M.Fe	FeO	C	S	Zn
Dry ball	50.0	4.3	17.7	11.1	0.29	0.33
DRI	72.9	56.2	16.9	0.2	0.44	0.009

(2) Secondary dust (wt%)

	Zn	T.Fe
Dust	63.4	1.11

from steel mill waste by the FASTMET process[5]. The FASTMET process produces DRI at a high reduction ratio and crude zinc oxide of high purity, as it gives rise to little entrained metal dust. This characteristic of the process contributes to the recycling of iron and zinc from steel mill waste.

3. FASTMELT® process

As previously mentioned, the higher gangue and sulfur content derived from the coal is an issue with DRI produced by the FASTMET process. To resolve this issue, the companies developed a process called "FASTMELT." The process includes producing DRI using an RHF (the FASTMET process), transferring the DRI at a high (as-discharged) temperature to a furnace, melting the DRI in the furnace, and removing sulfur and separating slag to produce molten iron[6), 7)]. The melting furnace can be either an electric arc furnace[6)] or a coal-based melter[7)] using the thermal energy of coal and oxygen that are supplied.

In 1995, MIDREX Technologies built a pilot plant based on the FASTMELT process by adding an electric arc furnace to the FASTMET pilot plant at the MIDREX Technical Center (**Fig. 4**). Various tests had been conducted at the pilot plant to prove the production of high quality molten iron from DRI made by the FASTMET process. The campaigns also provided various process parameters.

In 2006, Kobe Steel built a pilot plant using a coal-base melter of 16,000 tonnes/year capacity at the Kakogawa Works (**Fig. 5**). This pilot plant project was funded by the Ministry of Economy, Trade and Industry (METI). The plant operated continuously to produce high quality hot metal, as shown in **Table 3**[9)], using DRI made from steel mill waste. **Table 4** shows a comparison of carbon unit consumption at the pilot and the commercial plant[9)].

A FASTMELT plant consists essentially of an RHF and a melting furnace. The RHF discharges DRI with a metallization of about 85% at a high temperature. The DRI is then transferred, while hot, to the melting furnace, either by gravity or by a hot transfer conveyor. To adopt gravity transfer, the RHF must be placed higher than the melting furnace. The furnace, either an EAF or a coal-based melter, turns the DRI into molten iron, during which the coal-derived ash and sulfur content transfers into slag, and the slag is removed to produce clean hot metal. The exhaust gas from the melting furnace, which consists mainly of CO, is used as a fuel for the RHF.

The FASTMELT process, which can produce molten iron from iron ore fines and non-coking coal, provides a solution to the current issues of securing stable supplies of lump ore and coking coal and

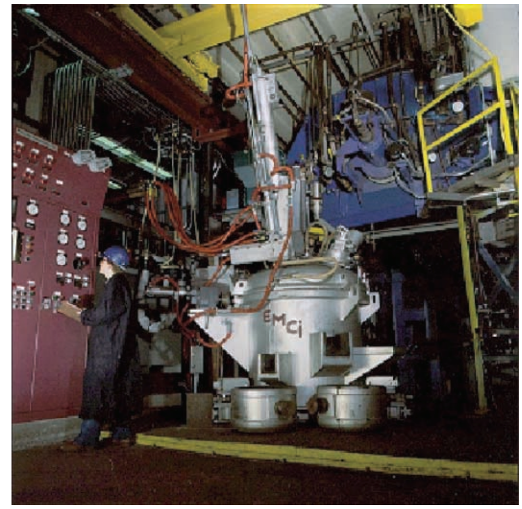


Fig. 4 Test furnace at the MIDREX Technical Center

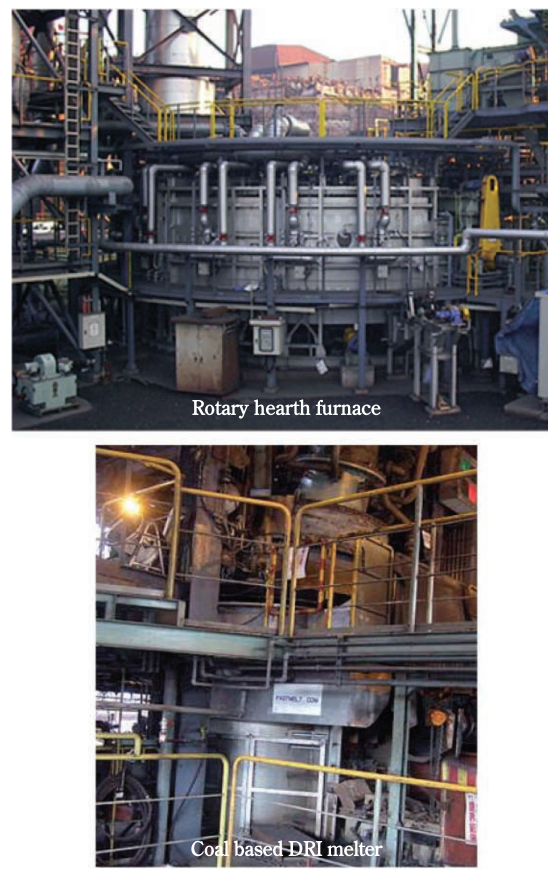


Fig. 5 FASTMELT Kakogawa pilot plant

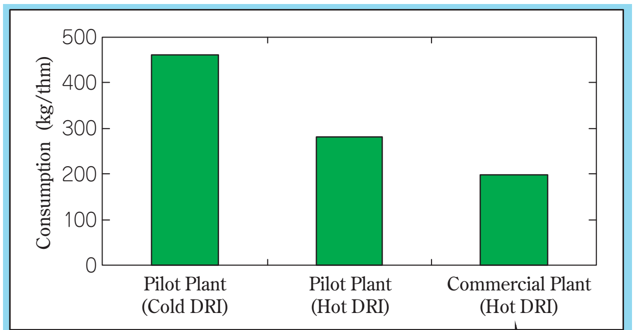
Table 3 Typical chemical analysis of charging hot-metal

(%)

C	Si	S	P
4.3～4.7	0.15～0.30	0.030～0.060	0.090～0.120

the associated price increase. A commercial scale FASTMELT plant has a molten iron discharging capacity of from 300 to 800 thousand tonnes/year. Such plants are expected not only to supply molten

Table 4 Prediction of total carbon unit consumption for pilot plant and commercial plant



		Pilot plant (Cold DRI)	Pilot plant (Hot DRI)	Commercial plant (Hot DRI)
DRI temperature	℃	25	800	800
Hot metal production rate	t/h	1.1	1.7	67
Coal+Coke breeze	kg/thm	1008	798	707
Coal for RHF	kg/thm	547	517	509
Coke breeze for melter	kg/thm	461	281	198
Oxygen	Nm^3/thm	415	237	206

Energy saving by hot DRI charge

iron to EAF mills, but also to become supplemental iron sources for blast furnace based integrated steel mills.

FASTMELT plants have an advantage over mini blast furnaces of similar capacity, which have recently become popular and are being operated in Southeast Asia, as FASTMELT does not generate any by-product gas, are energy self-sufficient, and consist of simple equipment because it requires fewer ancillary facilities, such as those for pre-treating utilities and raw materials.

4. ITmk3® process

In 1995, the companies found a clue to a new process while conducting an experiment for the FASTMET process. The experiment, which involved an RHF operating at a high temperature, revealed that the high temperature process can separate metallic iron from slag to produce pure DRI. This led to the development of a new process, ITmk3, for producing the granulated iron called "iron nuggets" from carbon composite agglomerate.

The ITmk3 process includes placing carbon composite pellets on the hearth of an RHF in a manner similar to that in the FASTMET process, heating and reducing the pellets in a temperature range that will melt DRI, and separating the slag to produce the granulated iron, iron nuggets[8]. ITmk3 is now defined as a third-generation ironmaking process based on a concept totally different from other conventional processes using carbon composite agglomerate[5].

Since 1996, Kobe Steel and others, e.g., domestic and overseas institutes, conducted fundamental research on this process. In 1999, Kobe Steel built a pilot plant at the Kakogawa Works to verify the process concept.

In 2002, a pilot demonstration plant was built in Minnesota, USA. Demonstration testing continued until 2004, by which time, all the engineering data had become available for continuous operation and for designing a commercial plant. In 2009, the first commercial plant, with a capacity of 500 thousand tonnes/year, was built in Minnesota. The plant started producing iron nuggets on a commercial basis in January, 2010. **Table 5** summarizes the specifications of the pilot, demonstration and commercial plant.

Like the FASTMET process, the ITmk3 process involves producing carbon composite pellets from ore fines and pulverized coal, pre-drying the pellets using a dryer and charging the pellets into an RHF. Heating the carbon composite pellets at a temperature between 1,350 and 1,450℃ in the RHF promotes the generation of CO gas, which reduces the iron oxide to produce metallic iron, as described previously. The metallic iron is carburized simultaneously, which causes the iron to coalesce and separates the slag from the molten iron faster at a lower temperature, in comparison with blast

Table 5 ITmk3 plant specifications

	Kakogawa pilot plant	Mesabi pilot demonstration plant	1st commercial plant
Location	KSL Kakogawa works	Northshore, MN, USA	Hoyt Lake, MN, USA
Operating period	1999/8 ～ 2000/12	2003/5 ～ 2004/8	2010/1～
Capacity (t/y)	3,000	25,000	500,000
RHF diameter (m)	5	14	60

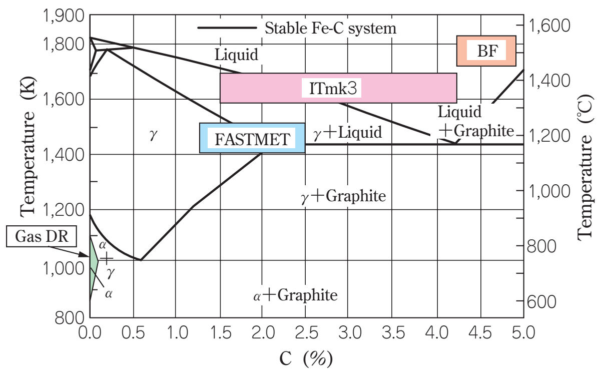


Fig. 6 Fe-C phase diagram

Table 6 Iron nugget specifications

Metallic Iron	96〜97%
Carbon	2.5〜3.0%
Sulfur	0.05〜0.07%
Size	5〜25mm

Fig. 7 Iron nugget shape

furnaces, as explained by the phase diagram in **Fig. 6**[4]. After cooling, the solid nuggets and slag are discharged out of the RHF. This series of reactions is completed within 8 to 10 minutes, during which time, the iron is distinctly separated from the slag[4].

The features of the ITmk3 process include flexibility as to the raw materials used and the high value added to the product. **Table 6**[4] summarizes the quality of the iron nuggets that are a typical product of the process, and **Fig. 7**[4] shows their appearance. The iron nuggets are free of slag and have a high iron content with an adequate amount of carbon. In addition to excellent chemical characteristics, they have superior physical properties, including suitability for handling, transportation and storage, as well as excellent melting characteristics. Thus, they are expected to be used as a raw material (pure iron source) for steelmaking furnaces such as BOFs and EAFs and improve productivity, unit consumption and product quality.

5. Prospects for coal-based reduction processes

The steel industry is facing the issues of securing raw materials and decreasing CO_2 emissions. With this background, the following describes the role expected for the coal-based reduction process.

5.1 Securing iron raw material

World crude steel production reached 1.33 billion tonnes in 2008, of which China was responsible for 500 million tonnes. It was 900 million tonnes in 2002, with 180 million tonnes in China. Thus, the global production increased by 1.5 times and Chinese production increased by a factor of 2.8 during this period. This pushed up the price of iron ore from 20 to 30 USD/tonne (CIF Japan) in 2002 to a level exceeding 100 USD/tonne. The price of coking coal soared, from 50 USD/tonne (CIF Japan) in 2002 up to 130 USD/tonne in 2009.

The production and prices of crude steel have stabilized in major countries since the financial crisis in 2008. In the mid- to long-term, however, newly industrializing economies such as India will follow China, further increasing the global demand for crude steel. As the iron ore and coal markets become increasingly controlled by mining majors, concern is growing as to whether the necessary amounts of raw material can be secured at reasonable prices.

Most high-grade iron ore with an iron content of 60% or higher is mined from banded iron formations (BIFs) of hematite. BIFs typically exist in the form of upthrust sedimentary deposits, with enriched iron content due to the weathering action of rain water or water heated by igneous rocks. Such deposits are found only in limited areas of the earth and are bound to become depleted.

As a result, the iron ore commonly available will shift to the low grade ore mined from sedimentary deposits, which requires beneficiation to upgrade them. To facilitate beneficiation, the separation of iron from gangue, low grade ore must be ground into fines with a size distribution of $-44\mu > 80\%$. Such ore fines must be pelletized before being charged into a blast furnace. However, the price-cost margin for the pelletizing process is so slim that a pelletizing plant is only feasible on the condition that a large scale plant be built together with a sufficient infrastructure, including a port and harbor. Thus, ore-fines produced by small mines are being abandoned, which promotes oligopoly by mining majors.

Coal-based reduction processes allow the use of iron ore fines and do not require a pelletizing plant. The processes are applicable to various types of ores, including those from small-scale mines. Further, the production scale of an ITmk3 plant well fits the production scale of small mines. Beside the mines, an ITmk3 plant can be built to produce a valuable product in the form of iron nuggets. This is a new business model which allows the use of low grade ore that was never before utilized. The first commercial ITmk3 plant, build in Minnesota, USA, is not an exception. An American EAF maker seeking for a stable source of iron purchased an abandoned iron mine where high grade ore had been depleted and only low grade ore can be mined. The company produces iron nuggets for its own use, using the low grade ore at the ITmk3 plant.

Thus, the coal-based reduction process by Kobe Steel promotes the supply of iron from mines that are producing low grade ore on a small scale. The process is expected to prevent an oligopoly by mining giants and contribute to a stable supply of iron at a reasonable price.

The possible depletion of coking coal is another concern. Blast furnaces require high grade coking coal. The reserve for such coking coal is estimated to be only 10% of the total coal reserves. Coke ovens also pose issues of environmental burden, including CO_2 emissions. Decrepit coke ovens, existing mainly in advanced countries, are difficult to refit or replace, making the supply of coke to blast furnaces tighter and tighter. Coal-based reduction that enables the use of non-coking coal is now drawing attention as a coke-less ironmaking process.

5.2 CO_2 emission reduction by utilizing scrap

At COP15 held in September 2009, the Japanese government committed to decrease CO_2 emissions by 25% of the 1990 level by 2020. Now the Japanese iron and steel industry, responsible for approximately 16% of the country's total CO_2 emissions, is under even greater pressure. The ironmaking process, in particular, is responsible for more than 60% of the industry's CO_2 emissions, which makes it important to decrease the CO_2 emissions from this process.

In the iron & steel making process at a blast furnace integrated steel works, the largest amount of energy is consumed in reducing iron ore. The BF (blast furnace) - BOF (basic oxygen furnace) process emits approximately two tonnes of CO_2 in producing one tonne of molten steel. On the other hand, an EAF process emits only a quarter of that amount, or approximately 0.5 tonnes, of CO_2 when it melts scrap to produce the same amount of molten steel. Thus, shifting from the BF (blast furnace) - BOF (basic oxygen furnace) process to the scrap-based EAF process is an effective approach for reducing CO_2 emissions.

The BF (blast furnace) - BOF (basic oxygen furnace) process has utilized scrap in recent years; however, there is a limit to the quantity of scrap that can be used. Blast furnaces can process only a limited amount of scrap because zinc contained in the scrap can adhere to the top shell of the furnace. Scrap is also difficult to handle using the existing equipment for charging raw materials. A BOF (basic oxygen furnace) can melt only a limited amount of scrap without supplemental energy. Further, the impurities contained in the scrap may impair the product quality, which also limits the applicable amount. As a result, the BF (blast furnace) - BOF (basic oxygen furnace) process can use only up to 10 to 15% of scrap.

On the other hand, the EAF process can effectively use scrap to decrease CO_2 emissions; however, this process is susceptible to issues of scrap quality and the fluctuation of scrap prices. General scrap contains tramp elements, such as Cu and Sn, which can adversely affect the quality of downstream processes, including continuous casting and rolling. These tramp elements are difficult to remove from molten iron or steel. Thus their content must be controlled either by choosing clean scrap free from these elements or by diluting the scrap with clean iron such as DRI and pig-iron. Despite the growing trend toward scrap recycling, it is unlikely that the amount of available clean scrap, such as machining scrap, will increase significantly. Securing high quality scrap will become more difficult.

Thus, as more scrap is used, the demand for clean iron such as DRI will certainly increase to maintain the quality and cost of products. On the other hand, there is concern as to whether the supply of DRI can meet the growing demand for clean iron. Seventy-five percent of DRI is currently produced by the natural gas based direct reduction process, but its production is limited to locations where natural gas is available. In addition, the process can use only high quality pellets specially produced for the process.

Under such circumstances, coal-based direct reduction is gaining attention as an alternative process for producing clean iron such as DRI, which will fill the supply and demand gap. The process is expected to promote shifting from the BF (blast furnace) - BOF (basic oxygen furnace) process to the scrap-based EAF process and eventually reduce CO_2 emissions in the iron and steel industry.

5.3 Processing ironmaking dust

The FASTMET process not only recovers iron from ironmaking dust, which otherwise would be

Table 7 EAF dust, DRI and crude zinc oxide analysis

(1) EAF dust analysis (wt%)

	T.Fe	Zn	Pb	C	CaO	SiO_2	S	Cl
Dust #1	31～33	17～19	1	3	3～4	4～8	0.4	1～2
Dust #2	21～25	26～29	1～3	3～6	2～4	3～5	0.4～0.6	5～7

(2) DRI analysis (wt%)

	T.Fe	M.Fe	Zn	Pb	C	CaO	SiO_2	S
Dust #1	46～53	40～46	0.7～2.4	0.1	5～11	5～8	9～13	0.6
Dust #2	42～50	35～41	1～4	0.1～0.6	3～15	6～12	8～14	0.6～1.0

(3) Crude zinc oxide analysis (wt%)

	T.Fe	Zn	Pb	C	CaO	SiO_2	S	Cl
Dust #1	～0.2	64～70	3～4	～0.1	0.1～0.2	0.1～0.2	0.4	5～8
Dust #2	～0.7	57～62	4～6	～0.1	0.1～0.8	0.1～0.2	0.2～0.5	9～16

discarded, but also is effective in reducing CO_2 emissions. In ironmaking dust, iron (Fe) exists as a partially oxidized mixture of Fe and FeO. Using such dust decreases the reduction energy. In addition, the carbon contained in the dust is utilized as a reductant, which decreases the consumption of coal and coke and, thus, reduces CO_2 emissions.

It is anticipated that, even if the amount of scrap used by the BF (blast furnace) - BOF (basic oxygen furnace) process remains at the same level, the quality of scrap will deteriorate as the content of zinc and alkali increases. Thus, the demand is expected to grow for the FASTMET process, which separates out zinc and alkali elements and enables iron recycling in the form of DRI.

The amount of dust generated from EAFs is expected to increase as the conversion from BF (blast furnace) - BOF (basic oxygen furnace) to EAF proceeds. As shown in **Table 7**[6], typical EAF dust has a high content of zinc and salt and a low iron content. Thus, EAF dust has been mostly disposed of in landfills.

Under the circumstance, the FASTMET process is expected to provide a solution to this sort of issue by treating EAF dust to recover iron and zinc. EAF dust processing has been demonstrated by the pilot plant at the Kakogawa Works of Kobe Steel. Now that the experimental and demonstration stage has ended, FASTMET is ready to be applied at the commercial-scale EAF dust processing plant.

5.4 Utilizing green energy

All three of the FASTMET, FASTMELT and ITmk3 processes involve reductant carbon and burner fuel. It is technically possible to utilize the carbon derived from biomass such as wood chips and to utilize the synthetic fuel gas derived from the biomass or industrial waste. These processes will reduce CO_2 emissions.

One idea is to recycle municipal solid waste, sewage sludge and industrial waste as environmentally sound carbon sources for DRI. Such a system may be incorporated into the social infrastructure.

Another idea may be to grow biomass in the vast land surrounding a mining site where an ITmk3 plant is built. The biomass would be used as a renewable energy source for DRI production.

Conclusions

1) Supplies of high grade iron ore and coking coal are becoming tight. Securing them is becoming more and more difficult. Coal-based direct reduction processes are expected to diversify the sources of raw materials, since they are coke-less processes and flexible as to raw materials. This will stave off an oligopoly by mining giants and ensure a stable supply of raw materials for the steel industry.
2) Having a stable supply of clean iron produced by a coal-based reduction process will make up for the shortage of high grade scrap, while scrap quality is expected to deteriorate in future. This will promote the conversion to the scrap-based EAF process and eventually decrease CO_2 emissions in the steel industry.
3) A DRI production technology developed for utilizing not only steel mill waste, but also municipal waste and biomass, will help the steel industry sustain its activity in harmony with the environment.

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ITmk3® Process

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The ITmk3 process, which produces high-quality iron (ITmk3 iron nuggets) from ore fines and coal fines, was developed based on a unique concept of iron ore and carbon composite technology. The development started in 1996, followed by test operations at a pilot plant and large-scale pilot plant. The first commercial plant was constructed in the U.S. and has started producing iron nuggets. This article outlines the history of the development, the features of the process, the product, and the future outlook.

Introduction

ITmk3 (pronounced as "[ai ti:] mark three") is a rapid ironmaking process that includes reducing ore, carburizing & melting iron and separating slag, all at relatively low temperatures.

Referring to generation classes of ironmaking processes, the first generation would be the blast furnace (BF) process, which is the current mainstream. The second is the direct reduction ironmaking (DRI) process as typified by the MIDREX process. ITmk3 (Ironmaking Technology Mark 3) falls in the third generation category; it is a process based on a concept totally different from those of the earlier generations. In the ITmk3 process, a series of reactions occur within about 10 minutes. The reactions occur much faster in this process than in BF and DRI processes. In a typical BF process, raw materials dwell in a furnace for about 8 hours, while in the MIDREX process, the materials stay in a shaft furnace for 6 hours.

1. Developmental background

Blast furnace processes require pretreatments such as producing coke from coking coal and preparing sinter from iron ore. Thus, an integrated steel mill with a blast furnace must have a capacity greater than 10,000 tonnes/day to be feasible. This limits the types of resources, such as raw materials, that can be used. The production may also lack in flexibility. Direct reduction ironmaking processes using natural gas, on the other hand, are limited as to plant locations. DRI plants can be built only in areas where natural gas is produced at a low cost.

Thus, the industry has focused on new processes that utilize the abundant reserves of fine ore and fuel coal. In the 1980s, various attempts were made to develop a new process, including the smelting reduction process. With this background, Kobe Steel and its US subsidary, MIDREX Technologies, Inc., developed a process called FASTMET, which produces reduced iron by heating agglomerates consisting of fine ore and coal.

In 1995, when developing the FASTMET process, the companies found that metallic iron can be separated from slag within ten minutes of heating. This reaction principle was adapted for a new ironmaking process, ITmk3. This paper describes the details of the new process.

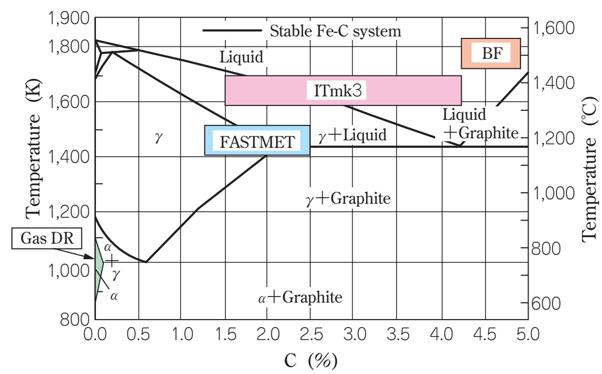


Fig. 1 Operational region of ironmaking processes

Fig. 1 is the iron-carbon phase diagram, which compares the operational regions of ironmaking processes, including ITmk3. The blast furnace (BF) process produces pig-iron saturated with carbon at a temperature around 1,500℃, while ITmk3 produces metallic iron with higher purity at a temperature lower than that required for BF.

2. Basic research

Kobe Steel began to study a new ironmaking process in 1996. Using a tube furnace installed at the Iron & Steel Research Center (Kakogawa Works, Kobe Steel), the company found that metallic iron grows rapidly, being separated from slag, at a relatively low temperature. **Fig. 2** shows this phenomenon occurring in the tube furnace. After this result was reported and became the subject of repeated discussions among researchers, domestic and overseas, the conclusion was reached that this was an unprecedented phenomenon. The new ironmaking process was called ITmk3.

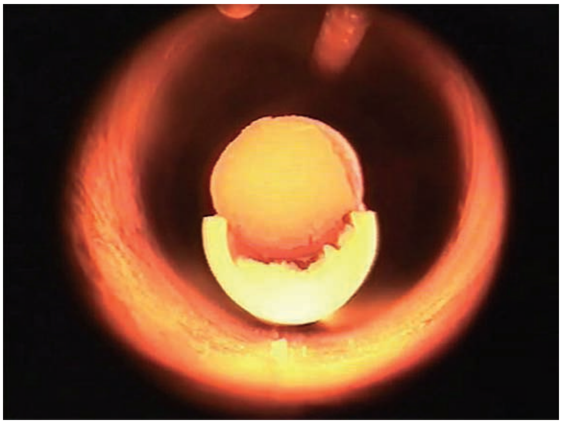


Fig. 2 Inside view of tube furnace

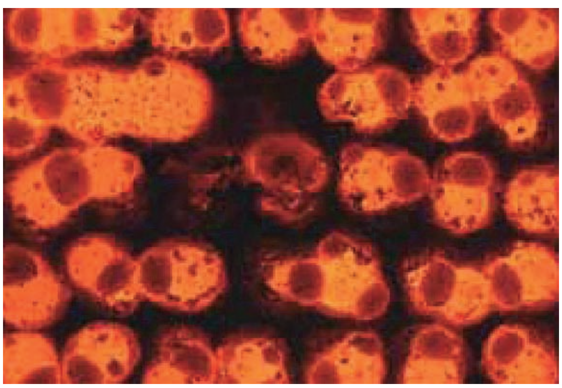


Fig. 3 Hot samples of box-type furnace test

Fig. 4 Test furnace at Surrey University

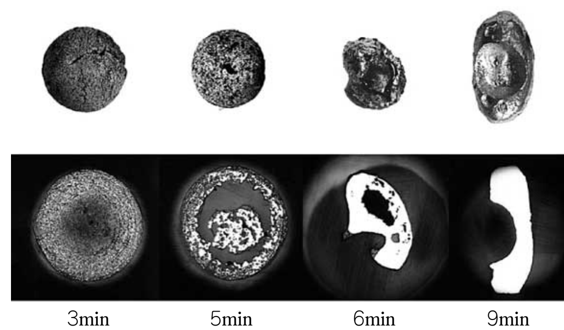


Fig. 5 ITmk3 reaction mechanism

The company initiated collaborative research involving universities and institutes, domestic and overseas, and installed a box-type furnace at the Iron & Steel Research Center to conduct experiments on a larger scale. **Fig. 3** shows hot samples discharged from the box furnace. Metallic iron has a bright orange color, while slag appears in dark orange, showing they are clearly separated from each other. Tohoku University and Tokyo Institute of Technology conducted research to elucidate the reaction mechanism of this new ironmaking phenomenon[1), 2)]. University of Surrey, in the UK, conducted research on heating methods, using a large multi-stage box furnace newly installed at their site (**Fig. 4**). Max Planck Institute in Germany studied the equation modeling of the reactions[3)].

The reaction between iron ore and coal remains the same as that for general ironmaking and is expressed as follows:

$$Fe_xO_y + yCO = xFe + yCO_2 \quad \cdots\cdots(1)$$

$$CO_2 + C = 2CO \quad \cdots\cdots(2)$$

$$C(s) = C\ (\text{carburized}) \quad \cdots\cdots(3)$$

$$Fe(s) = Fe(l)\ (\text{melt}) \quad \cdots\cdots(4)$$

Reactions (1) and (2) occur in the FASTMET process. In the ITmk3 process, there are the additional reactions (3) and (4), which separate metallic iron from slag.

In this new ironmaking process, particles of iron ore and coal exist next to each other in each agglomerate. This is in contrast with the BF and DRI processes, which use bulky materials such as iron ore and coke, and may explain the fast reaction of the new process to some extent. However, this does not fully explain the rapidity of the reactions.

Another series of experiments, conducted at the Kobe Steel Iron & Steel Research Center, confirmed a similar phenomenon. In these experiments, typical ores and coals, four types each, were combined and were heated in a box furnace. A study was conducted to clarify the effect of raw materials, temperature and furnace atmosphere on the reactions. Another study was conducted to elucidate the reaction mechanism. This study involved investigating the cross sections of agglomerates in the stages of reducing, melting and slag-separating, respectively. **Fig. 5** shows sample results of the cross-sectional study. During the first three minutes, the agglomerate, consisting of fine ore and coal, did not exhibit any significant change in appearance, despite the reduction reaction that should have occurred inside. After five minutes, the metallic iron and slag started to partially melt and became separated. In about six minutes, the entire agglomerate started to melt rapidly, with metallic iron being separated from the slag. After nine minutes, they had separated completely. University of Surrey conducted experiments to optimize this process reaction by separately controlling the reduction and melting. Separable control is a feature of their multi-stage box furnace.

In the reaction mechanism, the rapid carburizing phenomenon could not be explained by the conventional theories of gas carburization or solid carburization. Much time was devoted to elucidating the new carburizing phenomenon. Unlike the shaft furnaces used for DRI plants, the contribution of gas carburization is considered to be small. A recent study by Tohoku University found carburization via liquid slag [2], which appears to contribute to the rapid carburization along with solid carburization.

Using the box furnace at the Iron & Steel Research Center, Kobe Steel tested over a hundred types of raw materials, which verified the versatility of the raw materials that can be used for the ITmk3 process. The tests included applicability tests on low grade materials, such as iron ore containing a large amount of crystal water, oil coke and upgraded brown coal (UBC). They confirmed the applicability of these low grade materials.

3. Application of new ironmaking method

3.1 Pilot plant

In parallel with the basic research, application studies were conducted on the new ironmaking process based on this unique carburization phenomenon. Among the various processes deliberated, granular ironmaking was chosen as the most feasible approach. Designing of a pilot plant began in 1998. Unlike box furnaces, in which reactions occur under ideal conditions, the pilot plant had many issues to be addressed. Process development was conducted to resolve these issues.

Fig. 6 shows the process flow of granular ironmaking. The process comprises

1) agglomerating iron-ore and coal (blue),
2) reducing and melting the agglomerates (red),
3) separating metallic iron from slag (green), and
4) treating exhaust and recovering heat (yellow).

The pilot plant employs a rotary hearth furnace, which facilitates radiation heating, to exploit the rapid reaction feature of ITmk3. In a smelting reduction process, melting occurs before reduction, during which FeO may corrode furnace refractory. To avoid this, reduction and smelting technology was adopted in which melting occurs after reduction is completed.

In a rotary hearth furnace (RHF), the heating combustion gas from a burner may adversely affect the reductive atmosphere in the furnace. To resolve this issue, the Mechanical Research Laboratory at Kobe Steel conducted a simulation study based on the computational fluid dynamics (CFD) to optimize the RHF, in the designing stage, for gas characteristics such as temperature distribution and flow (**Fig. 7**).

There are many technical challenges in continuously producing metallic iron by melting raw materials on the hearth of a furnace. Once melted and separated from slag, the metallic iron is cooled, solidified and discharged out of the furnace. This subjects the furnace hearth to repetitive thermal stress in short cycles. The furnace hearth must also resist corrosion caused by the slag

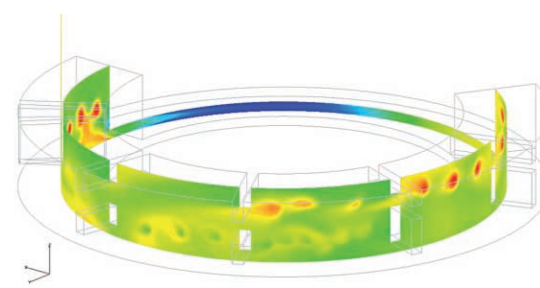


Fig. 7 CFD analysis result for rotary hearth furnace

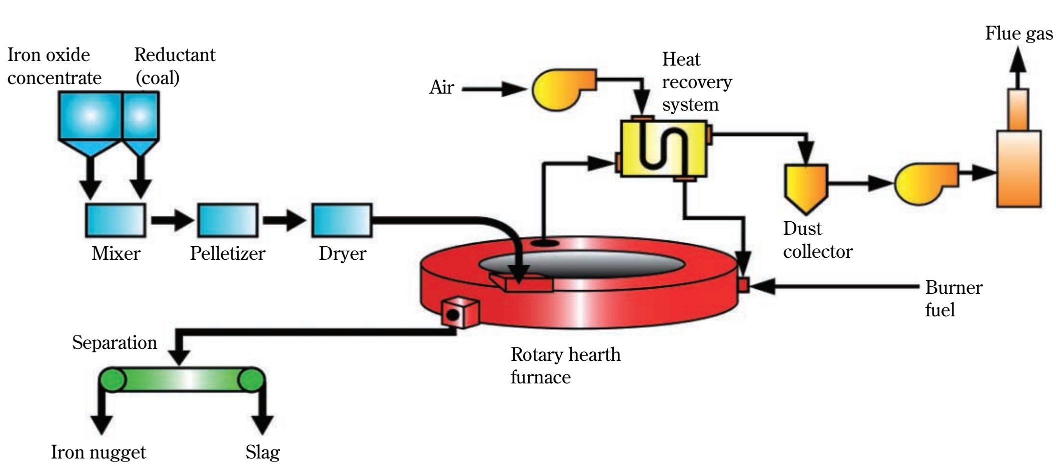


Fig. 6 Process flow

reacting on the hearth. Several tens of types of refractories were tested in order to identify the one best suited for the purpose. Repetitive thermal stress, involving rapid heating and cooling, was applied using an experimental furnace owned by a refractory manufacturer. A box furnace was used to clarify the corrosion behavior of slag. The hearth refractory was determined based on these experiments.

Although important, the selection of the hearth refractory does not resolve all the issues associated with the continuous production of granular iron. The key to the process is to maintain the hearth in good condition during the entire process, including the charging and discharging of materials to/from the furnace. Studies using the box furnace made such a technology available for the pilot plant.

A major difficulty was to design an apparatus for retrieving granular iron from an RHF. Although cooled and solidified, the granular iron is still at an elevated temperature. Several methods were contemplated. Having expertise in equipment for handling hot iron, specialists at Kobe Steel's Machinery and Engineering Company (currently, Machinary Business) designed the discharging apparatus. The Materials Research Laboratory of Kobe Steel collaborated in the selection of materials used for the apparatus.

Fig. 8 Small pilot plant in Kakogawa Works

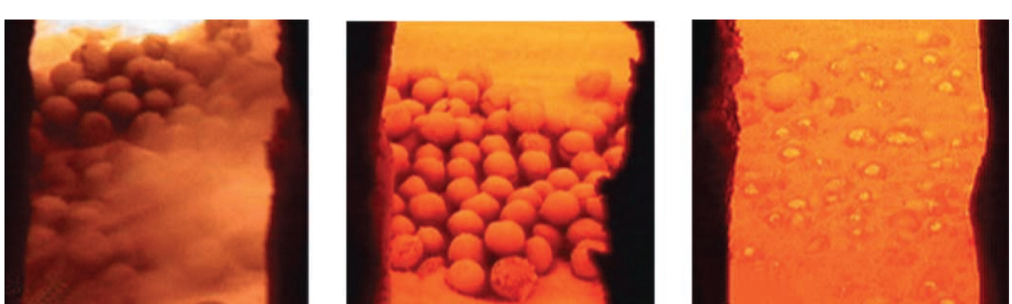
In June 1999, within one year of the beginning of process development and designing, Kobe Steel started the construction of a small pilot plant, with a capacity of 3,000 tonnes/year, at its Kakogawa Works (**Fig. 8**). Experimental operation began at the end of August 1999. In September, the operation began to produce reduced iron. The plant was confirmed as producing iron reduced over 90% as originally planned. Then, the operating temperature was raised to successfully produce granular iron for the first time. In the beginning, operation continued for about six hours a day, during which various adjustments were made to the raw material mixture, heat pattern, furnace atmosphere and retention time. Improvements were also pursued for productivity and the quality of the granular iron. During these continuous operations, each lasting for about six hours, there were no problems with the hearth−a major concern−nor was there any significant mechanical failure. Experiments continued at a good pace (**Fig. 9**).

In late November, when the company started continuous operations lasting for an extended period of time, a pool of molten iron began to form on the hearth and grew larger and larger. It was not possible to cool and solidify this large pool of molten iron, a problem that necessitated the development of a new technology.

In April 2000, a new technology for maintaining the hearth was developed through observing the changes that occur on the hearth, completing the first campaign of the pilot plant.

The second campaign operation began in the latter part of 2000 with a view to receiving visits from potential collaboration partners and operating for an extended period of time.

This campaign succeeded in conducting a stable operation that continued for the target number of days, the result of a modified hearth maintenance technology. The hearth was repaired periodically while producing granular iron, which enabled continuous operation. This approach has no theoretical limits on continuity and advanced the



Feed zone Reduction zone Melting zone

Fig. 9 Inside views of RHF at small pilot plant in Kakogawa Works application. During the campaign, data were collected for the design and operation of a large pilot plant that followed.

While conducting this experimental operation, Kobe Steel was visited by potential partners, who were given tours of the site. Among the visitors, the most interested were those in the consortium organized by Iron Range Resources, Cleveland-Cliffs Inc. (currently, Cliffs Natural Resources), the largest mining company in North America, and Steel Dynamics, Inc., the second largest EAF based steel manufacturer. Iron Range Resources and Cleveland-Cliffs Inc. had attempted to revitalize the mining industry, while Steel Dynamics, Inc. had been searching for a stable supply of iron source. Their aims coinciding, they were in search of a partner for collaborative development.

In March 2002, the decision was made to construct a large pilot plant in the beneficiation and pelletizing facility of Northshore Mining, Minnesota, owned by Cleveland-Cliffs. Different roles were allotted for the collaboration: Kobe Steel to provide technology and to design the pilot plant, Cleveland-Cliffs to supply iron ore and to provide operators, Steel Dynamics to receive and evaluate the product granular iron, and Iron Range Resources to finance the project. Later, the U.S. Department of Energy also provided financing, recognizing the project as the development of a new ironmaking technology with excellent energy efficiency.

3.2 Large pilot plant

In 2002, designing began for the large pilot plant. MIDREX Technologies, Inc. collaborated in designing the details. An RHF was the heart of the pilot plant. There were many rotary hearth furnaces for heating, with sizes up to 50m (diameter)×7m (hearth width), delivered to the market. A goal was set for the first commercial plant to have a size close to that described above (50m×7m). This would make the target capacity of the commercial plant about 500 thousand tonnes/year, judging from the productivity achieved by the small pilot plant.

The larger the pilot plant, the smaller the risk in upsizing it to a commercial scale; however, developing a large pilot plant may become too costly. Therefore, care must be taken in deciding the size of the pilot plant.

The following describes two factors emphasized in determining the size of the rotary hearth furnace used for the large pilot plant.

1) In the ITmk3 process, the secondary combustion of the carbon monoxide generated in carbon composite agglomerates significantly affects energy efficiency and the reductive atmosphere in the furnace. The energy input (furnace gas volume) for producing a tonne of granular iron was correlated to the production amount (**Fig.10**). The capacity of the large pilot plant was determined to be 25,000 tonnes/year, which is at the folding point of the correlation curve.

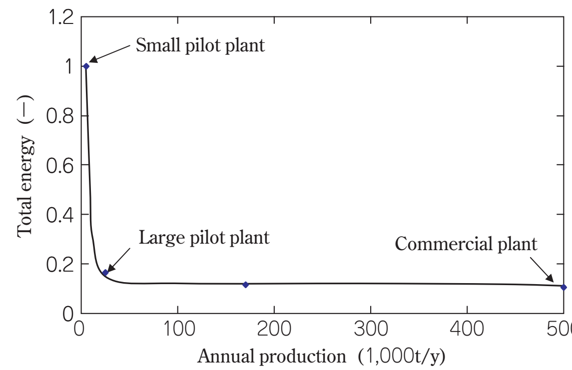


Fig.10 Production size vs. energy consumption

2) The key to this process is the maintenance technology for the furnace hearth, and the hearth width is an important factor. Considering the hearth width of 7m for the commercial plant, a conservative scale-up factor, from the pilot to commercial, was considered to be a factor of 3 or 4. Assuming a similar scale-up factor for the small pilot plant in Kakogawa, the hearth width for the large pilot plant was determined to be 2m.

The furnace profile was determined using the CFD model, which was further optimized by feedback data from the operation of the small pilot plant.

As it involves the development of a process, the project must minimize the risk to equipment. Because of this, the large pilot plant had to adopt industrially proven equipment as much as possible. Another prerequisite was that the equipment could be used for the commercial plant. In the end, the only apparatuses especially designed for this process were the charging and discharging units for the RHF. The rest were chosen from among those that had been industrially proven.

The process flow for the large pilot plant is basically the same as that for the small pilot plant, except that, for separating iron from slag, the small pilot plant adopts a batch-type process, while the large pilot plant adopts a continuous process.

The construction of the large pilot plant began in June 2002. The plant was completed and blown-in in May 2003. The first day was spent in producing reduced iron with a high metallic ratio, as in the

(a) Outside view of RHF

(b) Inside views of RHF (reduction zone)

(c) Inside views of RHF (cooling zone)

Fig.11 Rotary hearth furnace at large pilot plant

case of the small pilot plant. The production of granular iron succeeded on the second day. The large-scale demonstration followed and continued for 15 months until August 2004 (**Fig. 11**).

The following four campaigns were conducted during the demonstration operation:

1) optimizing the hearth maintenance technology
2) improving productivity and granular iron quality
3) improving the unit consumption of fuel (optimizing the secondary combustion)
4) testing performance

Various improvements were made during these campaigns. The demonstration by the prototype plant went smoothly for an extended period of time with an equipment utilization of 91 to 94%. A minor issue was the failure of a ceiling refractory caused by the insufficient firing of support anchor tiles by a refractory manufacturer.

Official environmental measurements, conducted twice during these campaigns, confirmed the process to be more environmentally friendly with higher energy efficiency than conventional ironmaking processes. The advantage was also confirmed by the Minnesota Pollution Control Agency[4] and the U.S. Department of Energy.

The following summarizes the features of the ITmk3 process.

- The process is simple.
- It allows the direct use of low grade materials (e.g., fine ore and fuel coal with neither sintering nor coking).
- It is highly energy efficient.
- It has a low environmental load.
- It facilitates the adjustment of production by starting and stopping.
- The facility cost is low.
- Most of the equipment involved in the process has been industrially proven with high reliability.
- The plant is easy to operate, without a need for handling molten iron, which is unprecedented in ironmaking processes; so operators with mining companies can run the plant in the same manner as they run a pelletizing plant.

Fig.12 Iron nugget product

The granular iron produced by the large pilot plant (**Fig. 12**) was received well by large EAF based steel makers in the U.S. and was used as a raw material for their steel products, such as sheet, plate and special rods. The granular iron, with its ease of melting in EAFs, increased the furnace productivity by 5 to 8% compared with conventionally used pig-iron. Thus the ITmk3 was demonstrated to be superior, not only in its ironmaking process, but also in its product, granular iron. The granular iron, which is to be continuously charged into EAFs, will further increase the productivity and energy consumption of the steelmaking process.

The following are the features of granular iron.

- It has a 2 - 4% carbon content.
- It is a clean iron with no impurities such as copper and nickel, which adversely affect the steelmaking process.
- It has a large specific gravity.
- It is easy to melt with a low melting point and high thermal conductivity.
- It is of an appropriate size for charging continuously into steelmaking furnaces.
- It has a size that is easy to handle.
- Unlike other reduced iron and hot briquette iron (HBI), the iron is completely reduced.
- Unlike other reduced iron and hot briquette iron (HBI), it does not reoxidize and ignite a fire.
- Unlike other reduced iron and hot briquette iron (HBI), it does not contain a gangue constituent.

In the U.S., granular iron is referred to as "iron nuggets," after gold nuggets.

Fig.13 Location of commercial plant

Fig.14 Commercial plant at Hoyt Lakes

3.3 Construction of commercial plants

The success of the large pilot plant immediately led to planning the construction of the first commercial plant. The Mesabi Iron Range, the largest ore mine in North America, lies from east to west, about 100km north of Lake Superior. There are many beneficiation/ pelletizing plants in this area. One of them is the plant run by LTV Mine, which closed in 2002 due to the steel recession. With this prospective site in mind, we have begun to work toward obtaining an environmental permit to construct a commercial plant (**Fig. 13**).

In 2007, stimulated by the recovering demand for steel, Steel Dynamics, Inc. decided to construct its first commercial plant with a capacity of 500 thousand tonnes/year of granular iron to secure a clean iron source. This project was co-financed with Kobe Steel. Kobe Steel's role included the provision of the process under license, engineering, major equipment and instructors. Steel Dynamics, Inc. agreed to accept all the granular iron produced and use it for their own EAFs. The construction of the commercial plant began in June 2007, and production started in 2010 (**Fig. 14**).

The construction of another commercial plant in Michigan, in the U.S., is being planned in collaboration with Cleveland-Cliffs Inc. (currently, Cliffs Natural Resources), one of the partners in collaborative development. Efforts to obtain an environmental permit are underway. Commercial plants are also being planned in many other countries, including Kazakhstan, India and Ukraine.

4. Business model

Granular iron manufacturing is a process suitable for locations adjacent to ore mines. The process converts iron ore, the major raw material, into value additive granular iron. The operation is similar to the conventional pelletization. The process also removes unwanted oxygen and gangue minerals contained in iron ore and pellets, allowing the shipment to steel mills of a product consisting essentially of iron. Unnecessary oxygen and gangue minerals account for about 40% of ore weight. Thus the new process decreases the shipping weight and significantly reduces CO_2 emissions during shipment. The steel mills that receive the granular iron can enjoy the benefit of granular iron that generates no slag and decreases the cost associated with the treatment of slag.

In the U.S., EAFs account for 63% of steelmaking, significantly exceeding the amount made by the blast furnace - converter method. However, the quality of scrap, the major raw material for EAFs, has become more degraded year by year, and securing clean iron source has become a major concern for EAF based steel makers. Clean iron source such as pig-iron and HBI, on the other hand, is almost totally dependent on imports from other countries, such as Venezuela, Brazil, Ukraine and Russia. Thus, US EAF makers are subject to supply instability and large price variations. These issues in the U.S. can be resolved by the prevalence of granular ironmaking plants.

In the U.S., most ore mines are found in the Mesabi Iron Range, to the north of the Great Lakes. Therefore, many steel makers are located in the area around the Great Lakes. They also import about ten million tonnes of clean iron source every year. The iron source is landed at New Orleans in the south and transferred upstream on the Mississippi River at a high transportation cost. The prevalence of ITmk3 plants around the Mesabi Iron Range, in the area around the Great Lakes, is expected to replace imported iron source, including scrap, with granular iron.

The following are the advantages to each sector of the industry that have been brought about by granular iron and granular ironmaking plants.

1) Mining sector
- Mining companies can make granular iron, which is much more value additive than conventional iron ore and pellets.
- Mining companies can expand their customer bases to EAF based steel mills in addition to blast furnace based integrated steel mills.
- Allowing the use of low grade ore will extend the lives of mines.
- The new process is feasible even for small scale mines.

2) EAF based steel manufacturers
- Use of granular iron improves the productivity and energy efficiency of the steelmaking process.
- The manufacturers can secure the source for clean iron.
- Granular iron allows conversion to higher end steel products.
- Installing granular ironmaking plants in steel mills allows the use of hot granular iron, which further increases energy efficiency.

3) Blast furnace based steel manufacturers
- The new process does not require equipment with a high environmental load, such as coke ovens and sinter plants.
- The new process allows the use of low grade materials.
- Ironmaking by the new process requires a small capital investment.
- The new process facilitates production adjustment.
- Granular iron production overseas enables the offsetting of CO_2.
- Granular iron decreases the cost and CO_2 emissions associated with transportation, compared with iron ore and pellets.
- Granular iron generates less slag than do iron ore and pellets.

Conclusions

The application of ITmk3 has just begun. In the same manner as blast furnaces have evolved for over a hundred years, ITmk3 is expected to expand its applicability from granular ironmaking to, for example, molten ironmaking and low temperature ironmaking. Kobe Steel will continue its efforts in the research and development of these new processes.

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Features of FASTMET® Process

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Over the past 10 years, Kobe Steel and its US subsidiary company, MIDREX Technologies, Inc., have been developing the FASTMET process. This process enables the conversion of metallic oxides from either steel mill waste or iron ore fines, into metallized iron in a rotary hearth furnace (RHF) using solid carbon sources, such as coal, as the reductant. Since 2000, the current commercial operations have enabled steelmakers to deal with metallic waste problems. In 2009, Kobe Steel filled order for two new FASTMET plants, each with 190,000 tonnes/h capacity. One of these is the third plant for Nippon Steel Hirohata Works with the first FASTMET-HBI process, and the other is the first plant for JFE Fukuyama Works, which produces DRI as a supplemental source for blast furnaces.

Introduction

Reducing iron ore in a rotary hearth furnace (hereafter referred to as an "RHF") was first attempted by Midland Ross Co., a forerunner of MIDREX Technologies, Inc., currently a U.S. subsidiary company of Kobe Steel. The process, called "Heat Fast", was unique in that it involved composite pellets, consisting of iron ore and carbonaceous material, which are pre-heated in a grate, pre-reduced in an RHF and cooled in a shaft cooler. A pilot plant was constructed in 1965, tests being conducted until 1966. The Midland Ross Co., however, prioritized the development of a process using natural gas, which is currently known as the MIDREX® process. The then low price of natural gas made this process seem more feasible, and as a result, the Heat Fast process was not commercialized.

In the 1990s, the price of natural gas rose; then Kobe Steel and MIDREX Technologies, Inc. collaborated to restart the development of the reduced ironmaking process using an RHF. A demonstration pilot plant was built in 1995 at Kobe Steel's Kakogawa Works. Through various demonstration operations conducted there, Kobe Steel and MIDREX Technologies, Inc. had established the FASTMET process for commercialization.

In 2000, a first commercial FASTMET plant was supplied to the Hirohata Works of Nippon Steel Co. for reducing 190,000 tonnes/year of steel mill waste. A second commercial plant was delivered in 2005 to the same company. The process was recognized for its ability to efficiently recycle ironwork dust. These achievements led the FASTMET process to win the Minister's award, Resources Recycling Technology and System, from the Clean Japan Center.

Table 1 Delivery record of FASTMET plant

Plant	Startup	Capacity (t/y)
1) Kobe Steel Kakogawa Works FASTMET	2001 Apr.	14,000
2) Nippon Steel Hirohata Works FASTMET No.1	2000 Mar.	190,000
3) Nippon Steel Hirohata Works FASTMET No.2	2005 Feb.	190,000
4) Nippon Steel Hirohata Works FASTMET No.3	2008 Dec.	190,000
5) JFE Steel West Japan Works (Fukuyama) FASTMET No.1	2009 Apr.	190,000

In 2008, a third plant was delivered to the Hirohata Works of Nippon Steel Co., and in 2009, JFE Steel, West Japan Works, Fukuyama (**Table 1**), took delivery of its first plant. Both plants have a processing capacity of 190,000 tonnes/year. The following introduces these plants and outlines the FASTMET process.

1. Features of the FASTMET process

The FASTMET process is clearly different from the gas-based reduction process using reforming gas derived from natural gas, in that it heats and reduces composite agglomerates, each consisting of iron ore, or steel mill waste, and coal. This simple and unique process involving rapid heating accomplishes a rapid reduction reaction. The agglomerates are placed in one or two even layers over the hearth and are heated using radiation heat. This prevents the oxidation of agglomerates, despite the in-furnace condition of combustion exhaust gas, which has a significant oxidation potential[1)]. It is important to mention that the process can achieve the heating and reducing of the agglomerates simultaneously and effectively at an ideal air-gas ratio in a furnace. In addition, the combustible gas generated from the carbon in the agglomerates burns in secondary combustion above them. This significantly suppresses the emission of NOx, despite the fact that this is a furnace that burns at high temperatures, another feature of the FASTMET process.

Raw materials such as steel mill plant dust may occasionally generate dioxin as they burn. In the FASTMET process, however, the furnace temperature is 1,300℃ or higher, which is high enough to suppress the generation of dioxin. The exhaust gas from the furnace is cooled rapidly through the temperature region in which dioxin may recombine, thus preventing it from recomposing.

FASTMET is a unique process using an RHF to reduce agglomerates containing coal with a high reduction ratio and high productivity. The reduced iron can be fed, not only into a blast furnace, but also directly into a melting process.

Fig. 1 shows a typical flow of the FASTMET process. The FASTMET process includes mixing steel mill waste consisting mainly of fine ore (i.e., iron oxide) with pulverized coal, agglomerating the mixture into pellets or briquettes using a pelletizer or a briquetter, drying the agglomerates in a dryer, and placing the agglomerates over the hearth of an RHF in one or two even layers.

The pellets or the briquettes must be isolated from air when they enter the furnace. Their feed rate must be controlled precisely at the same time. FASTMET contains a feed pipe system enabling the adjustment of the number of pipes according to the size of the furnace, thus simultaneously achieving isolation from the air and volume control[2]. A screw-type leveling system is adopted for placing the agglomerates in one or two even layers[3].

A rapid heating method, a proprietary technology of Kobe Steel[1], is adopted for heating the pellets or briquettes laid over the hearth, rapidly attaining a high temperature of 1,350℃. This heating generates the reaction of oxides and carbon as described in the formulae (1). Dwelling for 8 to 16 minutes, the agglomerates are converted into direct reduced iron (hereinafter referred to as "DRI"), which is discharged out of the furnace or supplied to the downstream process, at a temperature of 1,200 to 1,000℃ (**Fig. 2**).

$$\left.\begin{array}{l} Fe_2O_3 + 3C = 2Fe + 3CO \\ Fe_3O_4 + 4C = 3Fe + 4CO \\ Fe_2O_3 + 3CO = 2Fe + 3CO_2 \\ Fe_3O_4 + 4CO = 3Fe + 4CO_2 \\ FeO + CO = Fe + CO_2 \\ ZnO + CO = Zn + CO_2 \end{array}\right\} \cdots\cdots\cdots\cdots(1)$$

The stable and continuous discharge of DRI out of the furnace at a high temperature is achieved by such proprietary technology of KSL as elevating the hearth of a reduction furnace[4]. Unlike blast furnaces, the FASTMET can start and stop operation with relative ease depending on the amount of production, which enables production in response to demand.

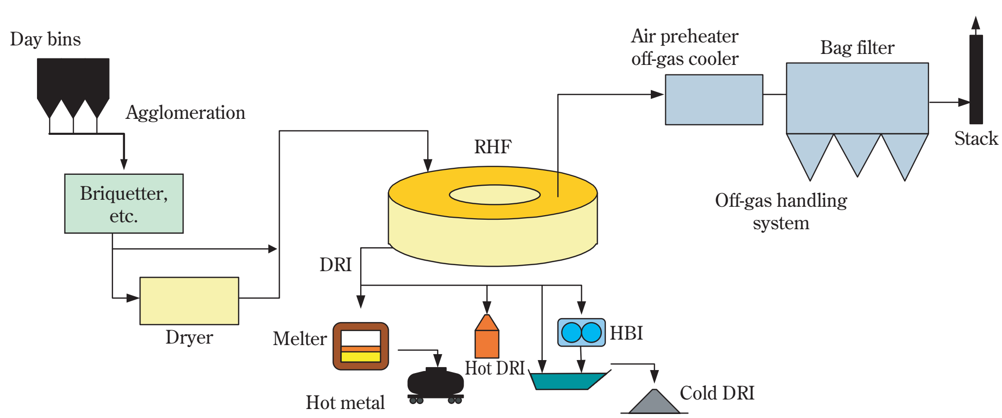

Fig. 1 FASTMET process flow

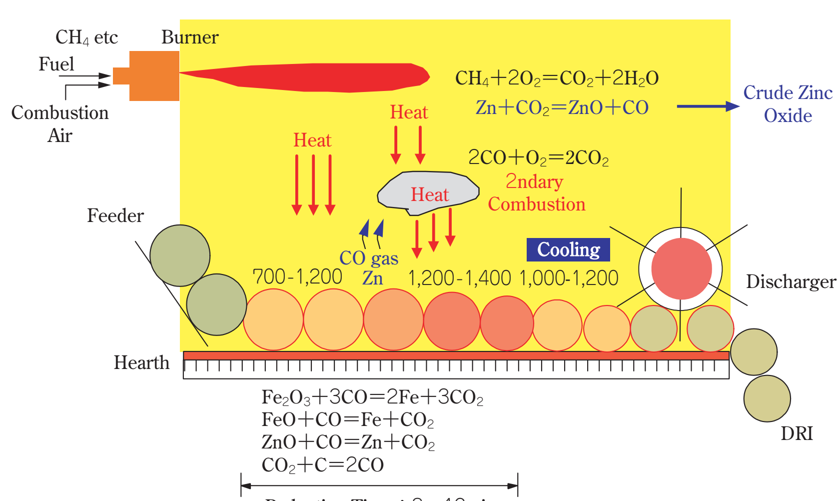

Fig. 2 Schematic drawing of reduction in FASTMET furnace

The DRI, discharged out of the furnace, is either transferred to a melting furnace in a transportation container, or is cooled and supplied into a blast furnace.

The DRI has many pores left after the reduction process. If exposed to air for a long time, the metallic iron reoxidizes into iron oxide, deteriorating its quality. If DRI is not used immediately as raw material for a melting furnace or a blast furnace, compacting and densifying the DRI into hot briquette iron (HBI) prevents reoxidation; this allows the storage of reduced iron for an extended period of time without quality degradation. The stored HBI can be fed to a melting furnace or to a blast furnace. Otherwise, the HBI can be transferred or sold to others.

Whether the reduced iron produced by the FASTMET process is used as DRI in the form of pellets/briquettes or is formed into HBI using HBI equipment depends on the application of the product (iron source) and its storage period.

The combustion gas (CO gas) emitted from the pellets/briquettes as a result of the reduction reaction can be used as a fuel for the RHF, which significantly decreases the amount of fuel supplied to the burner. The ore dust generated in steel mills has conventionally been pelletized or sintered in-house to recycle the dust as a raw material for blast furnaces. The blast furnace raw material, however, contains volatile components, particularly zinc, which vaporizes in the high temperature zone of a blast furnace. However, not all the vapor escapes from the furnace; some portion of it, cooled and trapped by newly-charged materials, remains in the furnace. The accumulated volatile components decrease the permeability of blast furnaces, and significantly impair their productivity.

The FASTMET process vaporizes heavy metals such as zinc and lead, which had inhibited the recycling of scrap iron, and converts them into crude zinc oxide and the like. This allows the discharging of these elements into exhaust lines without circulating them in the process. The off-gas treatment facilities are equipped with a Kobe Steel original cooling & dust collection system[5], which, combined with air cooling and water cooling, prevents the volatile components from adhering to the equipment walls. This has enabled stable and continuous operation for an extended period of time and the collection of crude zinc oxide and the like, using a bag filter. The collected crude zinc oxide is a valuable resource and is recycled along with the reduced iron.

A heat exchanger installed on the off-gas treatment equipment converts the energy contained in the high temperature exhaust into energy for heating the air that is used for either burning or drying the raw materials. This reduces the overall energy consumption.

2. FASTMET-HBI process, No. 3 plant at the Hirohata Works, Nippon Steel Co.

Kobe Steel delivered the FASTMET No. 1 plant (**Fig. 3**) to the Nippon Steel Hirohata Works in 2000. Another plant with a similar scale, the FASTMET No. 2, was delivered to the same site in 2005. The demonstration plant constructed at Kobe Steel's Kakogawa Works in the 1990s is still at work, recycling reduced iron from ore-dust generated in the ironworks, and contributing to resource reduction (**Fig. 4**).

Yet another plant, the FASTMET No. 3 (**Fig. 5**,

Fig. 3 No. 1 FASTMET plant in Nippon Steel Hirohata Works

Fig. 4 FASTMET plant in Kobe Steel Kakogawa Works

Fig. 5 No. 3 FASTMET plant in Nippon Steel Hirohata Works

hereinafter referred to as "the present plant"), was delivered to the Nippon Steel Hirohata Works. It has a dust-processing capacity of 190,000 tonnes/year, equal to the capacity of the No. 1 and No. 2 plants. The end product of the No. 1 and No. 2 plants is DRI, while that of the present plant is HBI, a hot-compressed, compacted form of DRI. In other words, the present plant is the first commercial plant adopting the FASTMET-HBI process.

As described above, in a case where reduced iron is stored in the atmosphere for an extended period of time, e.g., for sales, DRI is hot-compacted (briquetted) into HBI (**Fig. 6**), a form without pores. The briquetting of DRI to be used in a gas-based direct reduction ironmaking plant was developed in the 1990s, for the first time ever, by Kobe Steel and MIDREX Technologies, Inc. The knowledge accumulated to date has led many MIDREX process direct reduction plants to adopt the DRI-briquetting technology.

The FASTMET-HBI process is based on this proven process and uses a DRI cooler as ancillary equipment. Due to the difference in the discharge temperature of DRI, the MIDREX process does not use this DRI cooler. The DRI cooler is designed to bring the DRI, which is discharged from an RHF at a temperature of around 1,000℃, down to a temperature in the range of about 600 to 800℃. An HBI briquetter efficiently compacts it to obtain high quality HBI (**Fig. 7**).

In order to establish the technology for producing HBI from the DRI made by an RHF, an HBI pilot plant was built at the Kobe Steel Kakogawa Works as early as 1996, where forming campaigns were conducted[6]. **Table 2** shows the specifications of the pilot plant.

These experiments provided information on the way in which porosity and apparent density, typical characteristics of HBI, affect the weather resistance and strength required of it, as well as information on the conditions of temperature and residual carbon content required for HBI forming. On the basis of the results of the experiments, Kobe Steel proved that DRI reduced from raw materials such as iron-ore and steel mill waste (total iron content higher than about 50%), processed by an RHF operating under normal conditions (surrounding temperature: 1,200 to 1,400℃, residual carbon in DRI: 2 to 6%), can be formed, in a temperature range of about 600 to 800℃, into briquettes suitable for long-term storage and for charging into blast furnaces[6].

Fig. 8 contains an experimental result showing the relationship between residual carbon content and strength, an indicator of HBI quality, for given briquetting temperatures[7].

It was also found that when briquetting HBI, the higher the degree of metallization near the surface and the higher the residual carbon content toward the center of the DRI, the better the quality of the HBI, with increased adhesiveness among the briquettes[7]. **Fig. 9** is a full view of the HBI pilot plant in the Kakogawa works. **Fig. 10** shows the pilot plant producing HBI. **Table 3** summarizes the properties of the HBI that is produced. The experimental results obtained by this pilot plant have provided

Fig. 6 Sectional view of HBI

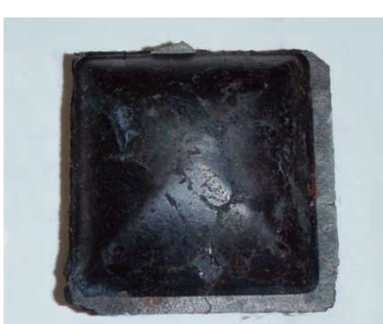

Fig. 7 Appearance of HBI

Table 2 Specifications of hot briquette machine of pilot plant[6]

Hot briquette machine	Roll Diameter	1.0 m
	Allowable feed temp.	800℃
	Feed material temp. (typical)	658℃
	Feeder speed (typical)	86 rpm
	Roll pressure (typical)	16.5 MPa
	Roller speed (typical)	5 rpm
	Production rate (typical)	9.5 t/h
	Motor Power	200 kW

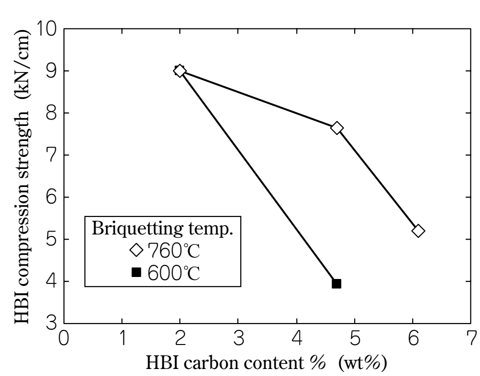

Fig. 8 Relationship between compression strength and carbon content of HBI

Fig. 9 Kakogawa HBI pilot plant

Fig.10 Agglomerate test in Kakogawa HBI pilot plant

Table 3 Properties of HBI produced by the pilot plant

Metallization:	80－85%
Carbon:	2－6%
Density:	4.2 g/mL
Compression Strength:	5－7 t/HBI
Drop Strength +38.1mm:	85%
6－38.1mm:	11%
－6 mm:	4%

information on the required heat transfer dimensions and the cooling time of the DRI cooler located between the RHF and the HBI briquetter, as well as the influence of the DRI cooler on HBI quality.

The dust generated at ironworks includes blast furnace dust, steelmaking dust and sludge. They are generated in many different ways and it is difficult to determine at the planning stage if such dust can be reduced at a commercial level, or whether it can be formed into HBI. Kobe Steel has testing equipment, such as apparatuses for testing reduction and briquetting, which enables appropriate assessments, such that suitable feasibility studies can be conducted in the planning stage. In the case of the No. 3 plant at the Nippon Steel Hirohata Works, planning began in 2005, exploiting the above environment, and the detailed designing began in 2007 after confirming the commercial feasibility.

Kobe Steel designed and supplied the RHF, HBI-making plant, briquette dryer and exhaust treatment system, and began installation in May 2008. Test operation began in October, and hot operation in December, filling the order within a short lead time. Commercial operation started at the end of December.

The HBI equipment, which is located below the RHF, fits in a very compact layout and has a height almost the same as that of the previously delivered No. 1 and No. 2 plants, which did not have HBI equipment.

Its environmentally-conscious design includes dust collectors disposed at various locations to prevent dust from generating during the transfer of the raw material, dust briquettes.

In both the No. 1 plant and the No. 2 plant, the DRI discharged from the RHF is transferred to the downstream steelmaking process, while being maintained at a high temperature. On the other hand, in the FASTMET-HBI process at our plant, the DRI discharged from the RHF passes through a screen[8] to remove foreign matter, a DRI cooler that cools the DRI to a temperature suitable for hot briquetting, and a hopper that supplies the DRI to an HBI briquetter which forms the DRI into HBI (**Fig.11**).

During the time in the DRI cooler, it is important that the temperature of the DRI be maintained in a range suitable for briquetting. If the temperature at the outlet of the DRI cooler is too high, the rolls and feeder of the HBI briquetter rapidly wear out, increasing the cost of maintenance. If the temperature is too low, the ductility of the DRI is decreased, and that also causes rapid wearing of the rolls. Decreased ductility is also detrimental to certain qualities of the HBI; for example, it may not

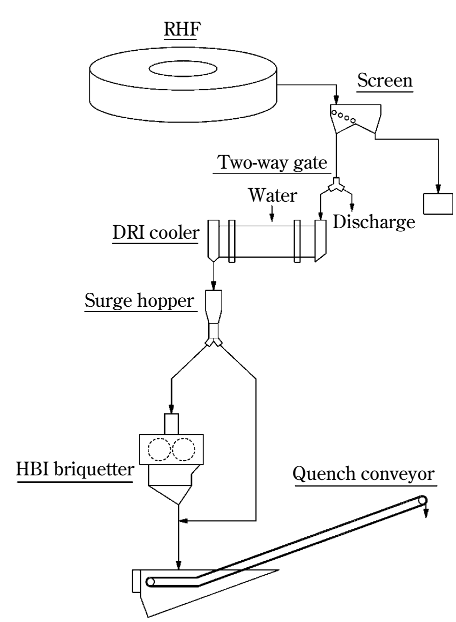

Fig.11 HBI line process flow of 3rd FASTMET plant in Nippon Steel Hirohata Works

attain the required degree of strength. The DRI cooler adopts an indirect water-cooling drum system. The DRI cooler of the present plant allows temperature control for the first time, not only by adjusting drum revolution, but also by adjusting the volume of nitrogen that is supplied to the DRI cooler, as nitrogen gas maintains an inert atmosphere in the HBI system. This has been confirmed to provide a suitable control[9].

A surge hopper is provided as a buffer to adjust the difference in the DRI production volume of the RHF and the HBI production volume of the briquetter. Since the inside of the hopper is always at a high temperature, it is not easy to measure, from outside, the amount of DRI left inside. There are level meters that use gamma rays for similar applications. However, for safety reasons, such meters require the strict management of radiation sources, which increases the maintenance load and decreases the flexibility of operational adjustment. In order to lessen the maintenance load, the present plant adopts a level meter using microwaves, a first for this application, and the meter has proven to adjust well.

In order to prevent reoxidation, the HBI compacted by the HBI briquetter is cooled to nearly room temperature by a water spray in a quench conveyer and is then stored in a yard for transportation by belt conveyers or by trucks. Because HBI is known to lose its strength if cooled rapidly, Kobe Steel uses its original slow cooling technology, a slow quench system[10].

The fines of HBI that are generated during the cooling and handling in the quench conveyor are collected by a fine conveyor disposed underneath the quench conveyor, if they are large enough. Fine dust carried into the cooling water is sorted by a separator using gravity (a dust catcher), so that the fines will not clog the inlets of transfer pumps, for example.

An example of the characteristics of the HBI produced by the present plant is shown in **Table 4**, which indicates the high quality of the HBI produced.

In addition to the HBI system described above, the present plant has a new secondary combustion chamber at the off-take of the RHF. This is to prevent the combustion gas generated in the RHF from discharging into the exhaust system without being utilized and to exploit and burn the gas efficiently in the furnace as the heat source for the reduction reaction. The secondary combustion chamber is provided with a temperature monitoring system, which enables the adjusting of combustion in the chamber so as to adapt to changes in the combustion conditions; these changes are due to variation in the characteristics of the raw material.

Table 4 Properties of HBI produced by No. 3 FASTMET plant in Nippon Steel Hirohata Works

Metalization	>85%
Carbon	<3%
Density	>5g/mL

Fig.12 Exhaust gas cooler of No. 3 FASTMET plant in Nippon Steel Hirohata Works

The exhaust gas discharged from the RHF via the off-take must be cooled to a temperature which permits collection by a bag filter. Thus the off-gas treatment system is provided with a gas cooler, typically of the water-spray type. However, this sort of gas cooler has suffered from a problem; the water spray combined with the dust contained in the exhaust, such as zinc oxide, and was then deposited on the interior walls of the cooler, where it inhibited the flow of gas.

To prevent this, the present plant newly adopts opposed flow at the gas inlet of the cooler (**Fig.12**). The operation so far has proven to run stably for an extended period of time without disturbance due to deposit formation[11].

3. No. 1 FASTMET plant at JFE Steel West Japan Works

JFE Steel West Japan Works (Fukuyama) received its first FASTMET plant (**Fig.13**) in 2009. The company's order for this plant arose from its high appreciation of the achievements of the process at the Kobe Steel Kakogawa Works and the Nippon Steel Hirohata Works.

This plant is to reclaim the high zinc content dust emitted from the blast furnaces and steelmaking in the ironworks, and has a dust processing capacity

Fig.13 FASTMET plant in JFE Steel West Japan Works (Fukuyama)

rated at 190,000 tonnes/year. The produced DRI is charged into blast furnaces, contributing to the zero-emission operation of the ironworks.

The scope of Kobe Steel's work on this plant covered the designing, manufacturing, construction and dispatching of supervisors for commissioning of the RHF, off-gas treatment equipment and DRI cooling & transferring equipment. Designing began upon receipt of the order in September of 2007. The project was completed within a short period, the installation of machinery beginning in June of 2008, commissioning taking place in January of 2009, and operations beginning in April of 2009. In June of 2009, the plant ran at the rated capacity, achieving its guaranteed performance and demonstrating the possibility of inaugurating the process in a short time.

The DRI produced by this plant, which is charged into blast furnaces, must have enough strength not to be crushed before being charged into a blast furnace and must have a low zinc content so as not to increase the amount of zinc circulating in the furnace.

In order to maintain the strength of DRI at a high level, DRI must be sufficiently reduced, and its residual carbon content must be kept low. Sufficient reduction time must be allowed for reducing and vaporizing the zinc contained in the dust. To meet these requirements, this plant has an RHF with an effective hearth diameter of 27m, making it the largest FASTMET plant ever built. After adjustment during commissioning, this plant can produce DRI with the characteristics shown in **Table 5**. The DRI is currently being used for blast furnaces, and no problems have been observed.

Fig.14 shows the DRI cooling and transportation line flow of the plant. The DRI is reduced in the RHF and discharged from it at a high temperature of around 1,100℃. A cooler, an indirect cooling drum type, is used to cool the DRI down to 200℃. The drum has a transfer blade and a cooling fin inside it. Water is sprayed onto the outer wall of the drum. As the drum rotates, the transfer blade moves the DRI toward the outlet, and the DRI is simultaneously cooled by its contact with the drum wall and the cooling fin.

The DRI cooler is provided with a dual damper at its discharge outlet and with a seal at the sliding portion of the drum, in which nitrogen is blown into the damper and seal as seal gas. This makes it possible to maintain an inert atmosphere inside the DRI cooler and prevents the DRI from reoxidizing.

It is important that the temperature at the outlet of the DRI cooler be sufficiently low so that the discharged DRI does not reoxidize rapidly and can be transferred without any trouble. On the other hand, an indirect cooler requires a large heat transfer surface when the subject to be cooled reaches a temperature near the ambient temperature, where the cooling efficiency decreases. This increases the

Table 5 Properties of DRI

Reduction degree	>80%
Zinc removal degree	>90%
Compression strength	>100kg/piece

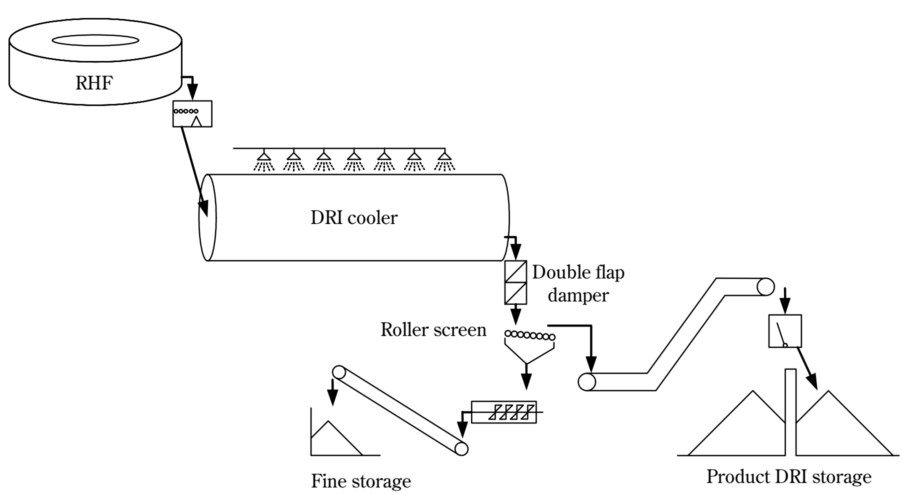

Fig.14 DRI line flow of Fukuyama Works

size of the equipment. Because of this, the temperature at the outlet of the DRI cooler of this apparatus is set to 200℃.

The DRI discharged from the DRI cooler is sieved using a roller screen to separate fines and is transferred to a product yard by a conveyor.

The off-gas system, which treats the exhaust gas from the RHF, adopts a gas cooler and heat exchanger proven in the past. The gas cooler, in particular, is a new type which adopts opposed flow for its gas inlet. In this, it is similar to the one installed in the No. 3 plant at the Nippon Steel Hirohata Works and has been running without problems for an extended period of time.

The combustion fuel for the RHF is coke oven gas (COG), which has been used by the demonstration plant in Kakogawa. Coke oven gas has lower heat value (approximately 18MJ/Nm^3) than other types of fuel such as LNG. This makes a greater amount of exhaust gas, discharged as off-gas, than the amount from the FASTMET plant installed at the Hirohata Works. Thus, it was necessary to upsize the equipment for the off-gas system. However, as described previously, the plant achieved a predetermined capacity, including the off-gas system equipment, at an early stage of its start-up.

The dust, captured by the bag filter in the off-gas system and consisting mainly of crude zinc oxide, is transferred by a conveyor to four hoppers for temporary storage before shipment.

Conclusions

It has been shown that steel mill waste containing zinc, dust which was hard to recycle, can now, using the FASTMET process, be efficiently recycled on a commercial scale, which enables the effective recycling of resources for iron and zinc. With the ever-increasing importance of environmental problems, such as the depletion of global resources and the need to reduce CO_2 emissions, it is expected that there will be an increasing need for introducing the FASTMET process.

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Demonstration of Upgraded Brown Coal (UBC®) Process by 600 tonnes/day Plant

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Utilization of low rank coal has been limited so far, due to its high moisture content, low calorific value and spontaneous combustibility. In Indonesia, more than half of the minable coal is low rank coal such as lignite or brown coal. Some lignite in Indonesia has the feature of low sulfur and low ash content. Therefore, it can be turned into an attractive fuel coal if it is upgraded using an economical dewatering method. Kobe Steel has been developing upgraded brown coal (UBC) technology since the early 1990s. Currently, a UBC demonstration plant project is underway in Indonesia, and operation of the plant has already commenced.

Introduction

Bituminous coal with a high calorific value is the fuel coal mainly used in Japan for the sake of efficiency in power generation, cost, and safety in logistics such as transportation and storage. In recent years, however, supplies of it have become tight on a global scale because of the economic growth of rising nations such as China and India. Low rank coal, including lignite, has a high moisture content, low calorific value, and spontaneously combusts, characteristics that make it difficult for Japanese consumers to utilize.

In Indonesia, a main producer of the coal imported by Japan, only 15% of the coal deposits consist of bituminous coal, while brown coal and subbituminous coal, both categorized as low rank coal, account for 58% and 27% respectively. The country has vast deposits of low rank coal with a low content of ash and sulfur. Upgrading (dewatering) low rank coal will enable the supplying of upgraded coal with a high calorific value and low ash and sulfur content, which is expected to secure a source of coal for consumers in Japan and to decrease the environmental burden of treating ash and sulfur.

Kobe Steel has been working on the technological development of upgrading low rank coal since the early 1990s. The process, called the upgraded brown coal (UBC) process, is based on the principle of "tempura (Japanese battered deep-fried food)" and efficiently removes the water contained in low rank coal in heated light oil.[1)] This technical development involves a pilot plant operation in Indonesia (production base capacity, 3 tonnes/day), whose operation has lasted for four years since FY 2001[1), 2)], and a demonstration project in the same country. The demonstration has been an ongoing project since 2006, subsidized by the Ministry of Economy, Trade and Industry (METI) and Japan Coal Energy Center (JCOAL). This paper introduces the outline of the project.

1. Process for dewatering low rank coal

1.1 Conventional process for dewatering low rank coal[3)]

Among conventional processes for dewatering low rank coal, the heating of low rank coal above the boiling point of water to vaporize fluid does not accompany thermal reforming at a high temperature. Thus, the process is characterized by having little of the thermal loss associated with thermal cracking and partial oxidation. Various dryers, such as steam tube dryers, are used for the process. However, the process has problems because the large latent heat of water vaporization increases its energy consumption and the product is spontaneously combustible. A process that can solve these issues would be more feasible.

1.2 Features of UBC process

The UBC process includes crushing low rank coal, dispersing the crushed coal in light oil containing a heavy oil such as asphalt, and dewatering the dispersion at a temperature of 130 to 160℃ under a pressure of 400 to 450 kPa. This process, whose conditions are rather mild, is expected to resolve the issues associated with the conventional processes for dewatering low rank coal. The following describes the features of the UBC process.

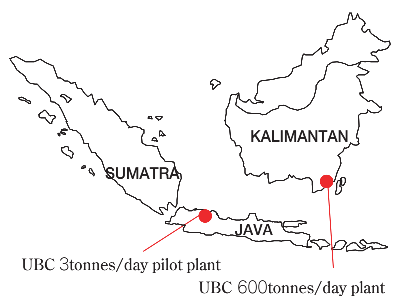
1) Essentially no chemical reaction occurs under the rather mild conditions of the dewatering, which minimizes the heat loss of the product and decreases the burden of waste water treatment.
2) The coal contains water that is vaporized into steam and separated from the coal during the dewatering in hot oil. The water steam is compressed and reused as a heat source, which makes it possible to decrease energy consumption.
3) The pores that remain in the low rank coal during the dewatering in oil absorb heavy oil such as

asphalt, which stabilizes the characteristics of the coal and prevents spontaneous combustion.

2. UBC demonstration project

2.1 Outline

This project is subsidized by the Ministry of Economy, Trade and Industry (METI) and Japan Coal Energy Center (JCOAL) and includes building a plant (production base capacity, 600 tonnes/day) at Satui, South Kalimantan, Indonesia, and running the plant to establish and demonstrate the technologies for commercialization during the period between FY 2006 and 2009. **Fig. 1** shows the outline and **Fig. 2** shows the schedule of the project.



Item	Detail
Project structure	By "JCOAL" jointed by Kobe Steel Ltd with the partnership of Arutmin & Bumi Resources. Indonesian government also supports the project.
Period	2006-2009
Budget	80M$
Scale	600tonnes/day (Product base), 1,000tonnes/day (Feed base)
Place	Satui area in South Kalimantan, Indonesia
Coal	Several lignites (4,000-5,000kcal/kg as received base)
Product evaluation	By several companies (Kobe Steel Ltd, Power companies)

Fig. 1 Outline of demonstration project

2.2 Purposes of demonstration

The demonstration purposes of the project are:

1) to evaluate the stability and reliability of the UBC process through long-term continuous operation and to obtain scale-up data for building a commercial plant
2) to evaluate the applicability of UBC by conducting a combustion experiment at a coal-fired power station using a large-scale sample of UBC transferred to Japan
3) to evaluate the economic feasibility of the process with accuracy improved by the experience of procuring the raw materials, producing, maintaining the plant and shipping the product

2.3 Process

As shown in **Fig. 3**, a UBC process comprises five steps: coal crushing, slurry dewatering, solid/liquid separation, oil recovery, and briquetting. **Fig. 4** is a full view of a UBC plant. The following outlines each step in the process.

1) Coal crushing

This step includes taking in raw coal, preliminarily rough-crushed to 50 mm or smaller in size, and crushing the raw coal to 5 mm or smaller using a grinding mill.

2) Slurry dewatering

This step includes mixing the crushed coal with light oil containing a heavy oil, such as asphalt, in a slurry preparation tank to prepare the coal slurry. This is followed by putting the coal slurry into a slurry dewatering tank, and

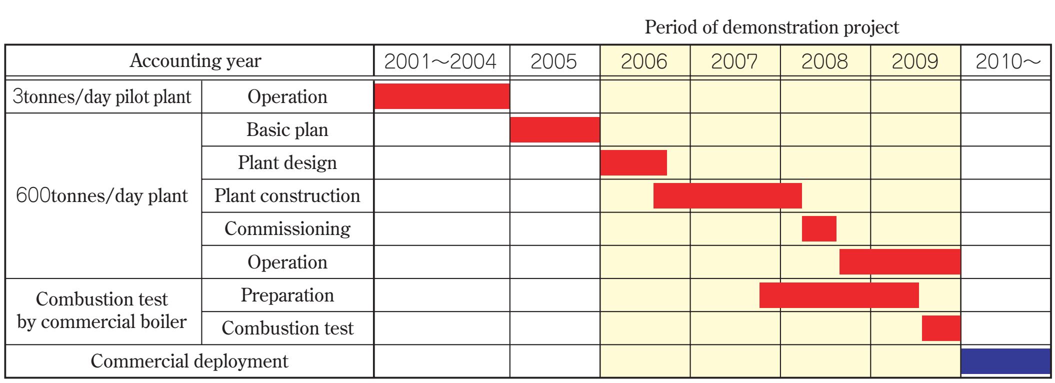


Fig. 2 Master schedule of UBC demonstration project

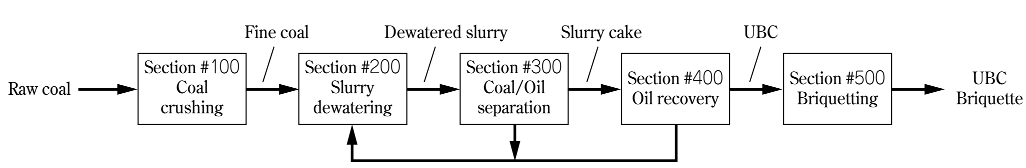


Fig. 3 Block flow diagram of UBC process

Fig. 4 Full view of UBC 600 tonnes/day plant

dewatering the slurry at a temperature from 130 to 160℃ and under a pressure of 400 to 450 kPa. The slurry dewatering generates mixed vapor (hereinafter referred to as "process vapor") consisting of water and light oil. The process vapor is compressed by a compressor to be reused as a heat source for coal slurry dewatering.

3) Solid/liquid separation
   This step includes transferring the dewatered coal slurry to a continuous centrifugal separator (decanter) to separate slurry cake from the light oil. The separated light oil is returned to an oil re-circulating tank and is reused as the light oil for slurry preparation.
4) Oil recovery
   This includes feeding the slurry cake, separated from liquid, to a dryer (steam tube dryer), vaporizing and drying the oil contained in the slurry cake through indirect heat exchange with high temperature steam to recover UBC in powder form (UBC powder). The oil vapor, contained in the circulating gas (mainly consisting of nitrogen) passing through the dryer, is condensed in a cooling tower and is separated from the nitrogen. The separated light oil is fed back to a circulating oil tank and is reused as the light oil for slurry preparation.
5) Briquetting
   In this step, the UBC powder is fed into a briquetting machine of the double roll type. The apparatus comprises a pair of rolls, rotating in opposite directions, each roll having a roll surface provided with pockets, whereby the UBC powder is formed into the product, pea-coal-shaped briquettes.

2.4 Ancillary equipment

The plant has utility equipment for treating raw water, a boiler (steam generation), equipment for cooling water, equipment for producing nitrogen, for compressing air, and for treating wastewater. Also provided are a tank yard for storing light oil and heavy oil and fire-fighting equipment. An analysis lab and workshop, established in parallel, support the demonstration operation.

2.5 Items of technical evaluation

This project is aimed at technically evaluating the UBC process, as shown in **Fig. 5**.

1) Coal crushing
   To be evaluated are the coal crushing performance of the crushing mill and its material characteristics (durability and wear resistance).
2) Slurry dewatering
   To be demonstrated is the stability of the slurry re-circulating operation, exploiting slurry handling techniques for preventing slurry sedimentation and the plugging of the slurry-distribution pipes and the like, the techniques for which are based on know-how accumulated through the operation of the pilot plant and other activities. Also to be demonstrated is the stability of compressor operation achieved by controlling slurry entrainment in the process steam. The thermal recovery performance of the compressor is yet to be evaluated.
3) Solid/liquid separation
   To be evaluated is solid/liquid separation performance in accordance with the operating conditions of the decanter (the supply volume of dewatered slurry, the revolution of the decanter, etc.).
4) Oil recovery
   Items to be evaluated include oil recovery performance as it relates to the operating conditions of the dryer (steam pressure, UBC residence time, etc.) and pressure loss in the gas circulation system.
5) Briquetting
   To be evaluated is the quality of the UBC briquettes in relation to the operating conditions of the briquetting machine (roll revolution, roll pressure, UBC temperature, etc.).
6) Combustion test
   To be evaluated are the handing properties and combustibility of the UBC briquettes

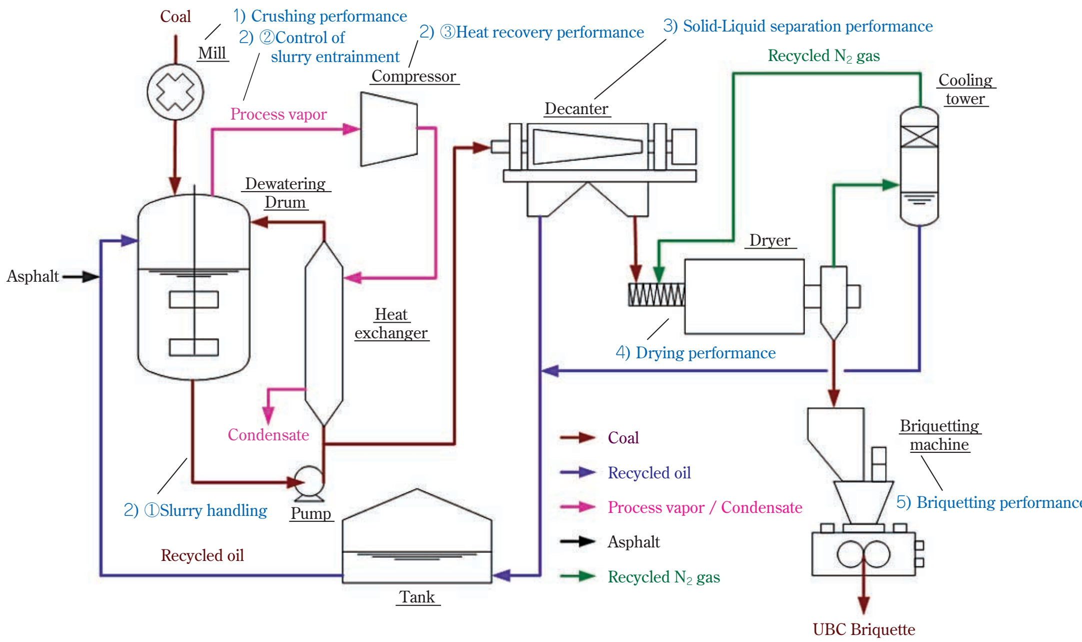


Fig. 5 Items of technical evaluation in UBC process

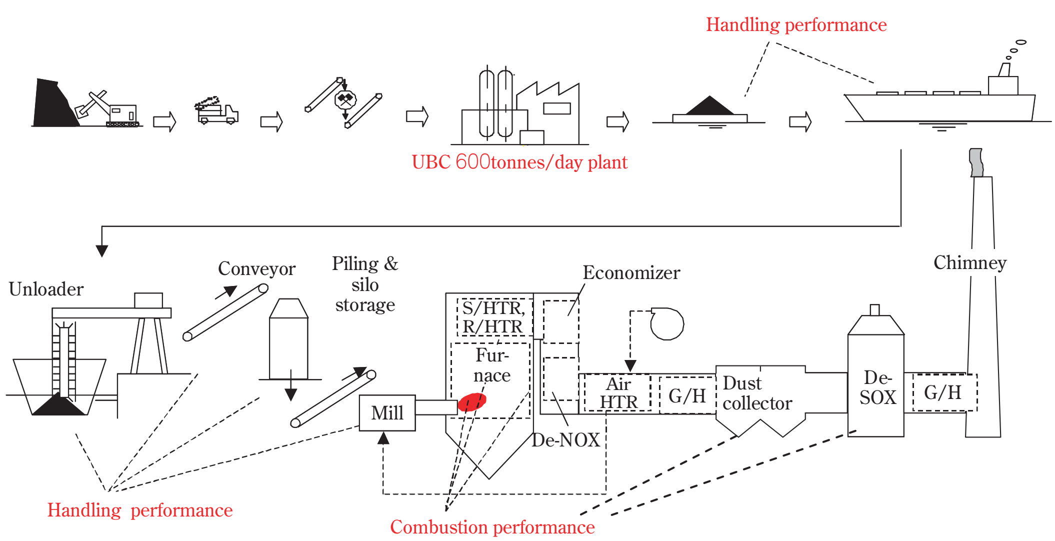


Fig. 6 Items of technical evaluation in combustion test

transferred to a coal-fired power plant in Japan. **Fig. 6** shows the items to be technically evaluated in the combustion test. The evaluation of the handing properties of UBC briquettes includes a drop test, pile test, crushing test (performed on coal mixed with bituminous coal), spontaneous combustibility test and hopper discharge test. The combustion performance to be evaluated includes the heat amount of the UBC, exhaust characteristics (NOx, SOx, residual coal, fly ash), furnace soiling (slagging and fouling), corrosion of the furnace interior and the exhaust treatment (dust-collection, desulfurization, gypsum quality, denitrification, trace element behavior, etc.).

2.6 Operational status of demonstration plant

After the completion of the construction of a 600 tonnes/day plant in July 2008, utility apparatuses were launched one after another, and the independent test operation of each system unit began. The continuous operation of the utility apparatuses began in August. Operation charged with coal, began in early November after a commissioning operation of the process equipment. This was followed by a continuous operation charged with coal, going through the entire process to verify the basic performance. **Fig. 7** shows the UBC briquettes produced by this plant. From here on, samples of UBC briquettes are to be produced for the combustion test, which will be followed by high-

Fig. 7 UBC briquette

load operation and long-term continuous operation. The following introduces the operation status of major process steps.

1) Slurry dewatering

One of the features of this process is to reuse process steam generated in the slurry dewatering tank. The steam is compressed by a compressor to be reused as a heat source for dewatering coal slurry. The introduction of a compressor increases the calorific value, exchangeable with the slurry, by a factor of twenty in comparison with the unit workload of the compressor, according to calculations made under ideal conditions, assuming the mechanical efficiency of the compressor to be 100%. Thus, there is a significant merit to this process in comparison with a case in which no heat is recovered from the process steam. The compressor, a Kobe Steel product, introduced this time, is designed for steam compression. In this process, however, it is supplied with steam (a mixture of water and light oil) from the process. Solid matter and/or liquid droplets, if caught in the compressor, can cause mechanical troubles such as abnormal vibrations and sounds. Thus, one of the key points of long-term continuous operation is to prevent slurry entrainment and condensation of the process steam.

Fig. 8 shows process flow diagrams, each incorporating a compressor. A first attempt was made with the compressor disconnected from the process steam line, as shown in Fig. 8 (a), in which steam was supplied to the compressor. The result confirmed that the compression performance follows the compressor's performance curve and that the vibration displacement falls in a range of 20μm or less as shown in **Table 1**, which indicates no mechanical problem.

The process steam was next supplied to the compressor as shown in Fig. 8 (b). Despite the difference in molecular weight between water vapor and the process steam (average molecular weight), compression performed almost as expected. The vibration displacement of the compressor body was almost the same as in the case of the operation with steam, verifying the stability of the operation.

The operation has been running smoothly without trouble such as slurry sedimentation and the plugging of pipes in the slurry circulation system.

2) Oil recovery

A steam tube dryer is a unit comprising a rotary cylinder laid at an inclination, the cylinder constituting a shell and a plurality of heating

Table 1 Operation conditions of compressor

Operation	Molecular weight	Pressure (MPa)		Flow rate	Vibration displacement
		Suction	Discharge	(Nm^3/h)	(μm)
Steam	18	0.41	0.60	11,000	10～20
Process Vapor	27	0.36	0.68	12,000	10～20

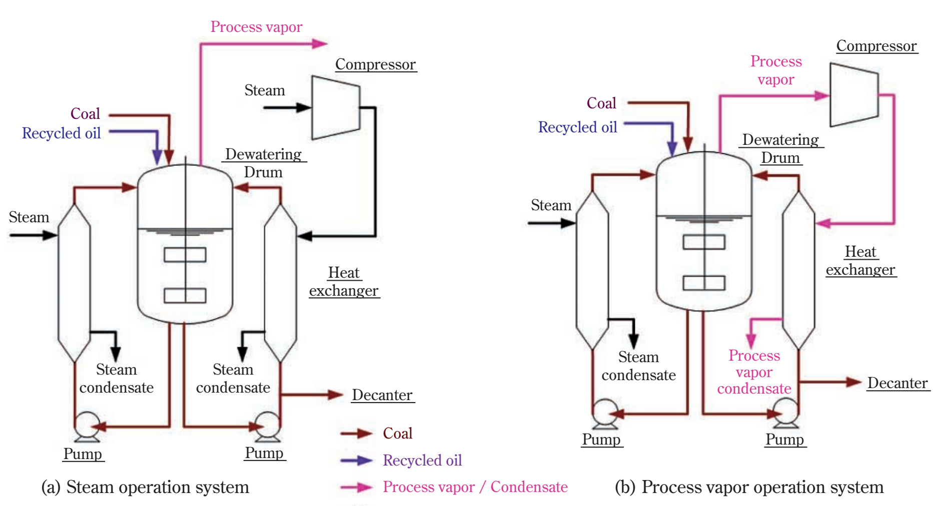


Fig. 8 Diagram of process flow around compressor

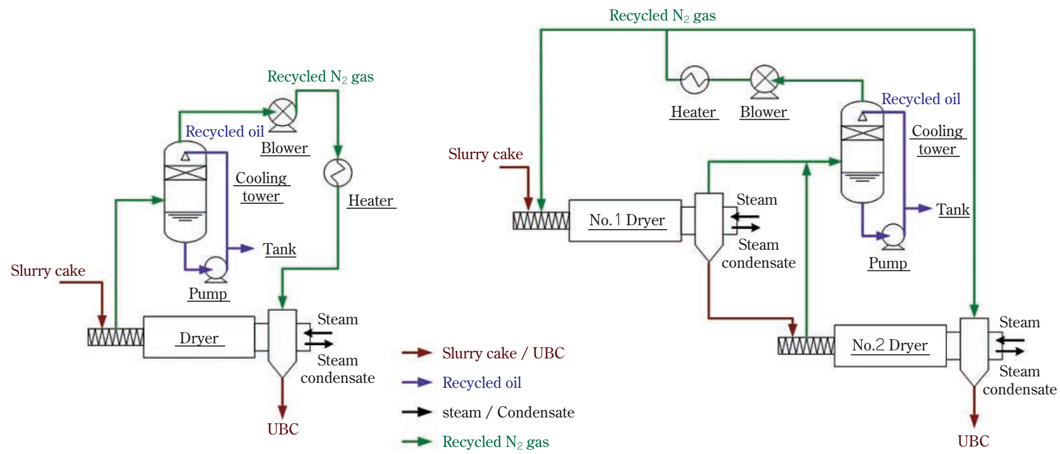


Fig. 9 Diagram of process flow around dryer

tubes housed in the shell of the cylinder, the tubes allowing the passage of a heating medium (e.g., steam), whereby the unit dries a subject moving in between the shell and the tubes. In order to discharge the volatile content transferred into the gas phase, a gas (nitrogen in this process) circulates on the shell side of the tubes. **Fig. 9** outlines the process flows, including the dryer(s). In a typical drying method using a steam tube dryer, circulating gas is caused to flow in a direction opposite to the flow of the subject to be dried as shown in Fig. 9(a), to ensure drying efficiency. In the pilot plant, which adopts this approach, however, a portion of the volatile oil component, contained in the circulating gas at a high temperature, was condensed by the slurry cake at a low temperature in the vicinity of the slurry cake inlet of the dryer as the gas passes out of the dryer, which increased the viscosity of the slurry cake. This caused the slurry cake to adhere to the steam tubes near said inlet of the dryer, deteriorating the dryer's heat transfer efficiency.

To resolve this issue, the demonstration plant has two steam tube dryers, disposed in series as shown in Fig. 9 (b), in which the circulating gas flows parallel with the flow of the slurry cake in the No. 1 dryer located in the upstream, while the gas flows in the direction opposing the flow of the slurry cake in the No. 2 dryer in the downstream. The following describes the features of this configuration[4].

a) At the inlet of the No. 1 dryer, the circulating gas with a low dew point suppresses the adhesion of slurry cake to the steam tube, despite the high oil content of the slurry cake.
b) At the outlet of the No. 2 dryer, the circulating gas with a low dew point is supplied in an opposite flow, increasing drying efficiency in the falling rate stage of drying.

Data, such as pressure loss, of the gas circulating system indicates that the operation has been stable so far, with neither obstruction caused by the slurry cake adhering to the steam tubes, nor a decrease in drying efficiency.

Conclusions

A plant with a capacity of 600 tonnes/year was constructed in Indonesia and has been running to demonstrate a process called the UBC process. In 2009, the basic performance of the entire process was verified through a continuous operation charged with coal. In 2010, samples of UBC briquettes are to be produced for a combustion test using a real combustor. This will be followed by loaded operation and long-term continuous operation, in accordance with the plan, to technically evaluate the stability and reliability of the UBC process, to obtain data for designing a scaled-up commercial plant, and to establish the quality and feasibility of the product as fuel.

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