Micro Steam Energy Generator

Hideaki KUWABARA[*1], **Makoto NISHIMURA**[*1], **Masaki MATSUKUMA**[*2], **Takayoshi MATSUI**[*2]
[*1] Mechanical Engineering Research Laboratory, Technical Development Group
[*2] Standard Compressor Plant, Compressor Division, Machinery Business

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.

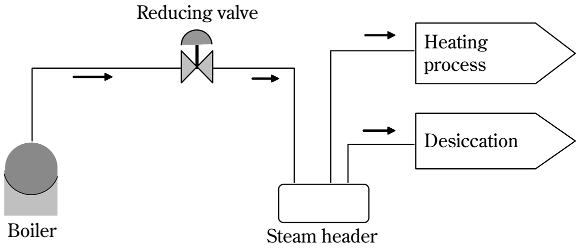

Fig. 1 General process flow in small-sized steam plant

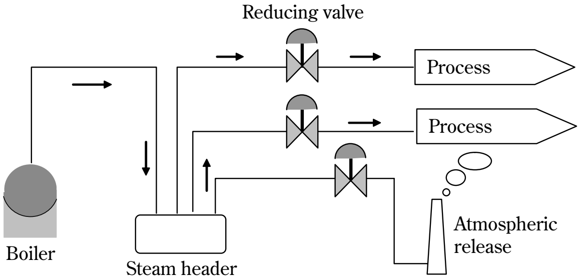

Fig. 2 Process flow in small-sized steam plant with excess steam

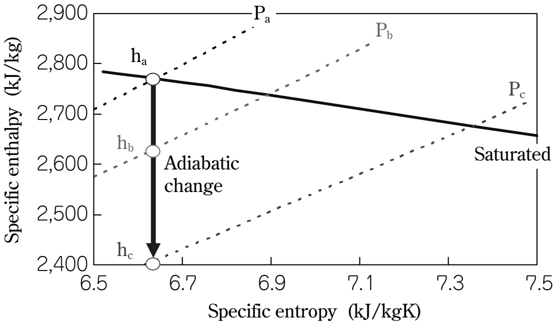

Fig. 3 State quantity of steam

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].

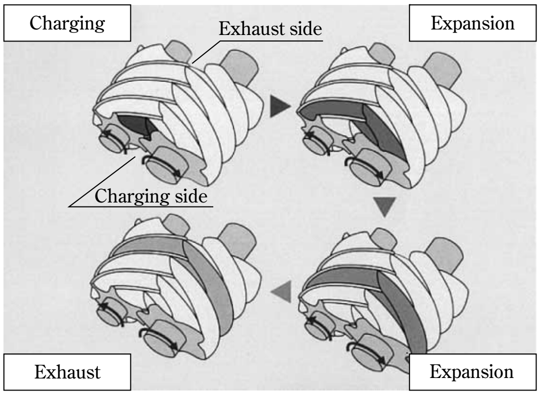

Fig. 4 Expansion stroke of screw expander

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,

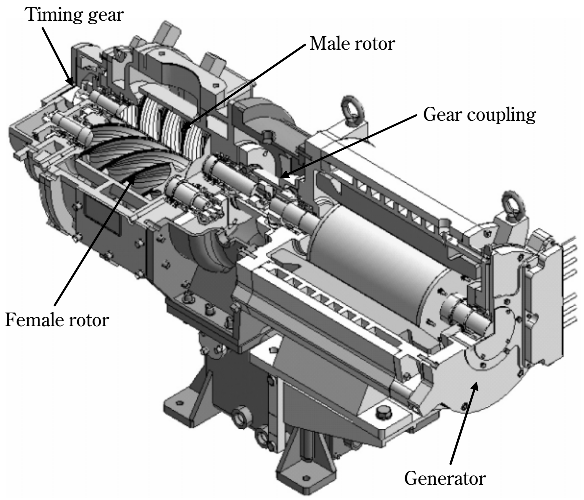

Fig. 5 Main structure of micro steam energy generator

Fig. 6 External view of micro steam energy generator

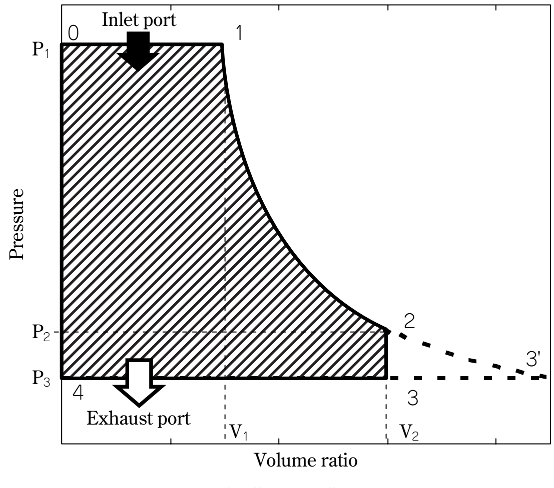

Fig. 7 Indicator diagram

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:

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

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

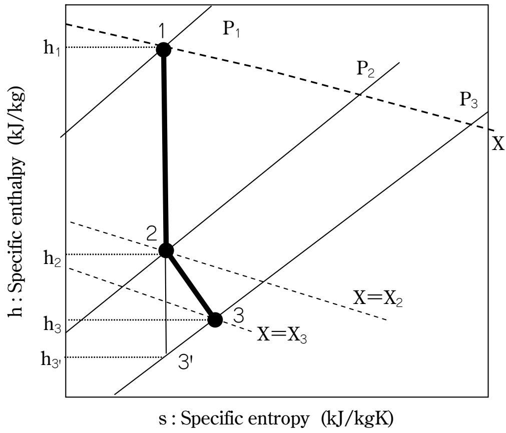

Fig. 8 h−s diagram of screw expander

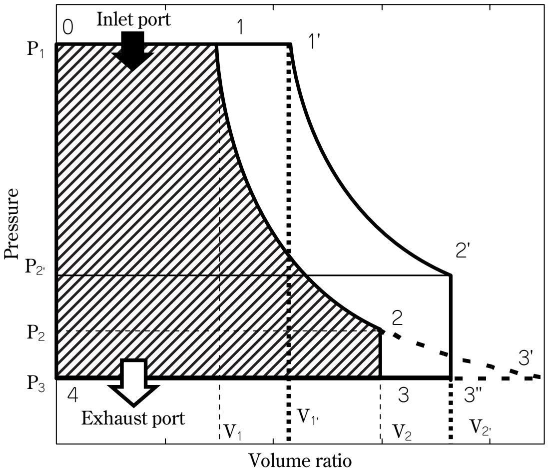

Fig. 9 Indicator diagram-1

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 expander. The kinetic energy is nearly adiabatic.

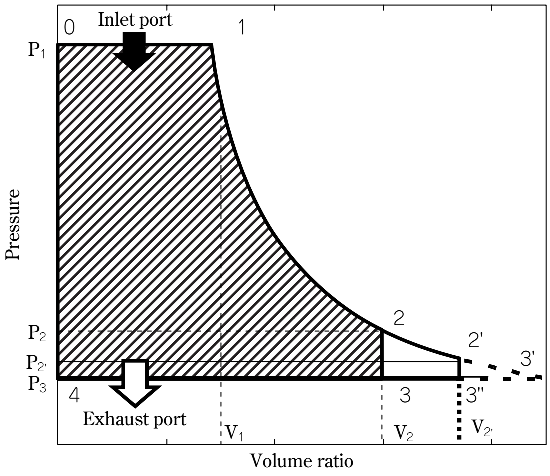

Fig.10 Indicator diagram-2

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	

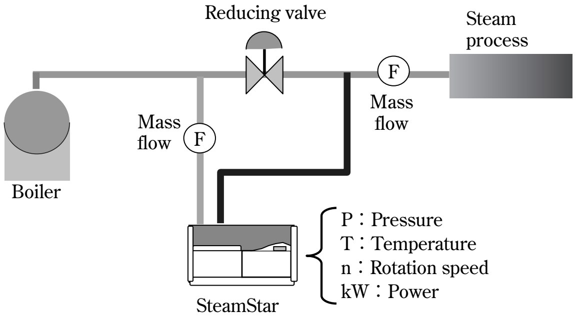

Fig.11 Flow chart of test facility

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 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

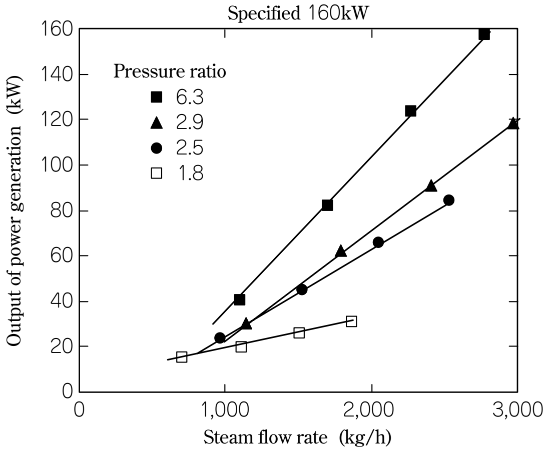

Fig.12 Relationship between output of power generation and steam flow rate for high pressure difference type expander

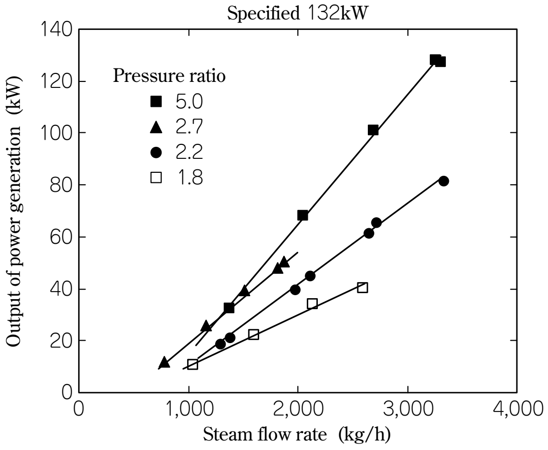

Fig.13 Relationship between output of power generation and steam flow rate for low pressure difference type expander

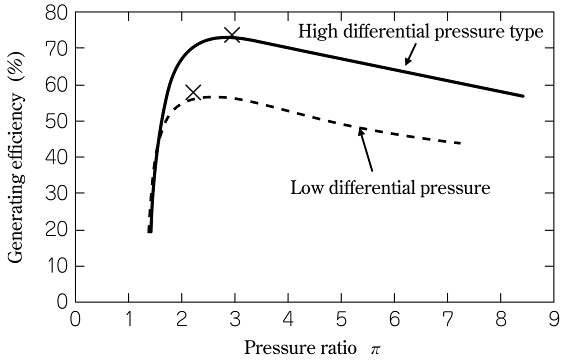

Fig.14 Relationship between pressure ratio and generating efficiency

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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