Thermal and fluid dynamics control technology

Thermal and Fluid Dynamics Control Technology Supporting Production Processes and Products to Realize Green Society

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Abstract

The thermal and fluid dynamics control technology contributing to a green society, such as CO_2 reduction, has, from its beginning, evolved in various production processes and product development. These technologies involve complex interactions of fluid dynamics, chemical reactions, and heat transfer behaviors. Therefore, using visualization to aid in understanding the internal phenomena and control for process optimization is a not straightforward task. Hence, thermal fluid analysis using computational fluid dynamics (CFD) has been employed. This paper focuses on application examples, centering on the evolution of thermal and fluid dynamics control technology in production processes involving high-temperature reactions such as those in direct-reduced iron plants, pulverized coal injection (PCI) in blast furnaces and coal-fired boilers, as well as machinery products like heat pumps, mixers, and vaporizers. Also provided is an explanation of the future prospects for realizing carbon neutrality.

Introduction

Kobe Steel's machinery business manufactures and distributes fluid machinery such as compressors, heat pumps, mixers, and heat exchangers. Our materials business makes use of manufacturing equipment such as power plant as well as blast, melting, and heating furnaces. Heat transfer and fluid flow dynamics govern process performance and product quality in both businesses. As such, thermal and fluid dynamics control technology has been critical in overcoming increasingly complex challenges and requirements. Kobe Steel's product portfolio and production processes are subjected to a wide range of temperatures, from cryogenic to ultra-high temperatures, as well as complex phenomena involving chemical reactions, heat transfer, and fluid dynamics. Our experiences with these parameters have shaped our thermal and fluid dynamics control technologies. We have developed numerous types of technologies based on preliminary studies and operational improvements. Examples include combustion control technology to support energy conservation, consistent quality, and low NOx emissions as well as fluid dynamics control technology to remove inclusions in molten steel. We have expanded our product portfolio by a number of industrial machines that combine energy efficiency and product quality through thermal and fluid dynamics control technologies.

Kobe Steel began developing numerical analysis for machinery products and steelmaking processes in the late 1960s. In this way, the company's use of CFD (computational fluid dynamics) contributed greatly to the aforementioned developments.

The nature of Kobe Steel's product lineup has enabled the company to reveal the mechanisms behind phenomena across a broad spectrum of temperature ranges, from -100℃ (LNG vaporizers), to several hundred degrees Celsius (construction machinery and nuclear reactor vessels),[1)] to over 1,000℃ (continuous steel casting,[2)] waste incinerators[3)]). We started by establishing theories and developing our own programs. Today, we have expanded our scope of application to solve complex challenges by applying combinations of general-purpose programs, the latest CFD technologies, and our proprietary programs. This is how we have created control technology for reduced iron plants, which are subject to chemical reactions and thermal fluid dynamics. We also use this methodology to define the complex conditions related to partial filling of resin mixers. This has enabled us to establish design guidelines for energy-efficient mixer rotors that yield high product quality.

Multiple technologies on top of energy-efficient solutions are being considered today to realize carbon neutrality. These include carbon sequestration technologies such as CO_2 capture and utilization and decarbonization technologies that foster conversion to low-carbon fuels such as hydrogen, ammonia, and biomass. The combustion characteristics in boilers versus heating furnaces and the reduction characteristics of iron ore versus other materials differ greatly due to differences in chemical properties. As such, conversion to low-carbon fuels requires knowledge about the operation of plant equipment, such as burners and fuel supply systems. Additionally, the differing physical properties of hydrogen and ammonia yield vastly different heat transfer and fluid flow dynamics, which in turn greatly influences the design guidelines for machinery products. This paper introduces the changes made among production processes and product development based on thermal and fluid dynamics control technologies that contribute to CO_2 reduction. Application examples and prospects for technological development toward a green society are covered as well.

1. Thermal fluid analysis by CFD

1.1 Direct reduced iron plants

Kobe Steel's goal for 2030 is to reduce CO_2 emissions in our production processes by 30 - 40% and to reduce CO_2 emissions by 61 million tons through our technologies, products, and services. One of the key technologies toward achieving this goal is the MIDREX® Process, which reduces iron ore using natural gas.[4] Although the MIDREX® Process does not involve molten iron, it is a complex process involving flow, chemical reactions, and heat transfer. As oxide pellets or lump ore descends through the high-temperature shaft furnace, it comes into contact with H_2-rich reducing gas derived from natural gas and becomes reduced iron. This reduced iron is then discharged from the bottom of the shaft furnace. Many types of reactions occur in the furnace, including CO and H_2 reduction reactions as well as reforming, shift, and carbonization/carburization reactions. To fully understand these conditions and improve the process, we are developing CFD-based thermal fluid analysis technology and various reaction model analysis technologies. For a detailed explanation of the mechanisms behind the reduced iron reaction, see "Utilizing Reduced-Iron Manufacturing Technology to Contribute to Green Society" (pp.131-136 of this issue). Our CFD-based program combines a chemical reaction computation function that analyzes chemical reactions with a thermal fluid analysis computation function that calculates the thermal characteristics affecting the reaction rate. Our program accurately reproduces the temperature and degree of metallization inside the shaft furnace, as shown in **Fig. 1**. We will use this technology to optimize the process conditions of hydrogen-based direct reduced iron (MIDREX H_2^{TM}) [Note 1] to achieve even lower carbon emissions and ultimately realize carbon neutrality.

[Note 1] MIDREX H_2^{TM} is a trademark of Kobe Steel.

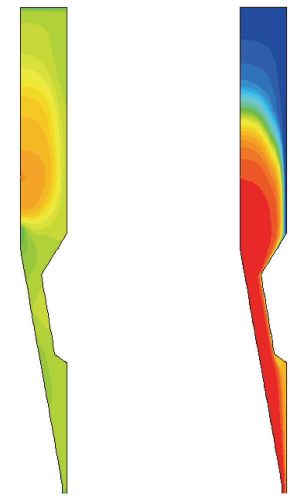

Fig. 1 Result of CFD analysis for shaft furnace

1.2 Rubber and plastic mixers

Kobe Steel manufactures and distributes an extensive array of environmentally compatible machinery products for the industrial sector. Tire and rubber machinery in this sector contributes to reduced CO_2 emissions by improving automobile fuel efficiency. Specifically, we have developed mixers for fuel-efficient tires that contain large amounts of silica, a difficult substance to work. Our energy-efficient plastic mixers yield high product quality while reducing CO_2 emissions. In particular, our LCM mixing and pelletizing systems for polyolefin manufacturing are the world's most commonly used product of its type. These machines produce high-performance plastic products that support weight reduction in vehicles, thereby further reducing CO_2 emissions.

Advanced multiphase fluid analysis technology is essential for the development of mixers, and CFD plays a role here. In equipment that handles highly viscous fluids such as resin and rubber, mesh-based methods such as the finite element method (FEM) and finite volume method (FVM) have conventionally been used to quantify values related to states such as material temperature and stress inside the mixer.[5] However, FEM and FVM cannot effectively evaluate the partially filled state (a state in which fluid and space exist) that occurs in mixers. Moreover, they cannot quantitatively evaluate phenomena related to this state such as the separation and confluence of viscous fluids. Kobe Steel has independently developed numerical analysis technologies, such as the volume of fluid (VOF) method and particle method, for the large fluctuations in free surface associated with partially filled flows inside a mixer. This has enabled us

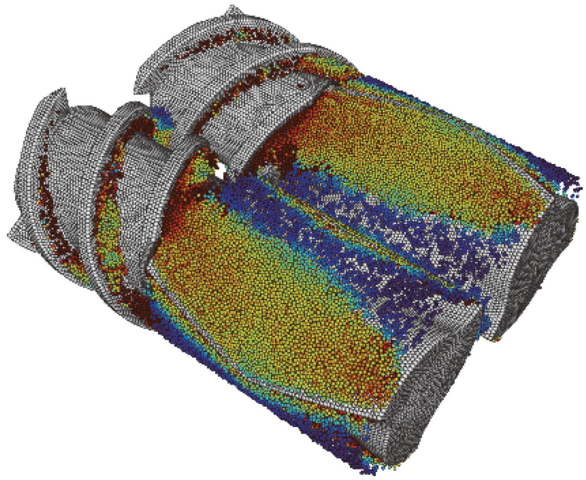

Fig. 2 Result of partially filled simulation for mixer

to evaluate the once poorly understood filling state inside the mixer and the devolatilization performance associated with by-products. **Fig. 2** shows an example of analysis via the particle method. Clarifying parameters surrounding the plastic filling state and mixing state made it possible to study appropriate operating conditions and to design the shape of the mixer rotor via CFD.[6)] We will continue using new numerical analysis and mixer technologies to develop energy-efficient, high-performance mixers and processes for plastic and rubber production.

2. Optimization of high-temperature reaction processes

2.1 Low-carbon blast furnace operations

Kobe Steel has devoted many years to reducing CO_2 emissions in blast furnaces, in which coke is used to reduce iron ore. One of our endeavors is blast furnace pulverized coal injection (PCI) operation, introduced in 1983. This technology can reduce CO_2 emissions from blast furnaces by replacing the reducing agent, coke, with pulverized coal. However, it requires a large pellet volume, so Kobe Steel focused on controlling the shape of the cohesive zone and ensuring gas flow in the center of the furnace to ensure stable operation. We established technologies to stabilize furnace conditions during PCI operation. Specifically, we optimized the process control technology in the blast furnace as it relates to center coke charging and optimized the location of pulverized coal injection and tuyere shape via numerical analysis and laboratory experiments. As a result, in March 1998, the Kakogawa Works No.1 blast furnace set a world record by achieving a pulverized coal injection rate of 254 kg/t.[7)] We also supported resource circulation by conducting waste plastic injection trials in the 2000s. Furthermore, our demonstration of high-volume charging of hot briquetted iron (HBI) produced using MIDREX® technology into a blast furnace, conducted from 2020 to 2023, yielded reduced CO_2 emissions.[8)] To further reduce blast furnace CO_2 emissions, we will continue to prove out fundamental technologies that stabilize operations and that foster the use of biomass, reduced iron, and other low-carbon fuels.

2.2 Low-carbon pulverized coal-fired boilers

We at Kobe Steel leveraged our expertise in in-house power generation for steel mill operations to begin commercial operation of the pulverized coal-fired Kobe Power Plant in 2002. This plant and the natural gas-fired Moka Power Plant, commissioned in 2019, have a combined capacity of 3948 MW. Pulverized coal combustion was first advanced via municipal waste combustion simulations to establish the aforementioned PCI technology and incinerator design guidelines. Soaring resource prices in the 2000s drove the development of technologies to use low-grade coal such as sub-bituminous coal and brown coal.[9), 10)] In recent years, technological development has centered around using carbon-neutral fuels.

Expanding the use of biomass requires clarification of behavior related to ash deposition on heat transfer tubes in boilers, which is associated with significant changes in ash properties. Ash deposition behavior is generally affected by the properties of the fuel (ash composition, ash fusion temperature, etc.) and combustion conditions (temperature, gas composition, flow rate, etc.), which depend on boiler geometry.[11)] However, there was no index that integrated these factors. This is why Kobe Steel developed ash deposition prediction technology for pulverized coal-fired boilers that combines CFD and thermodynamics equilibrium calculations to predict ash fusion conditions. We first established a technique to predict the clinker formation parameters of various boiler geometries and fuel conditions. Specifically, we used CFD to determine the gas composition and temperature near the heat transfer tubes, values that then served as inputs for computations related to ash fusion. **Fig. 3** shows the relationship between the ash deposition fraction (measured value) and the fraction of molten slag in ash (calculated value) for various fuel types and mixing conditions. The graph shows that the ash deposition fraction tends to increase when the

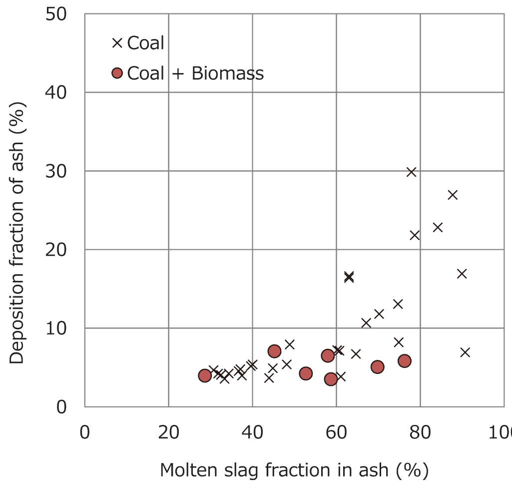

Fig. 3 Relationship between molten slag fraction and ash deposition

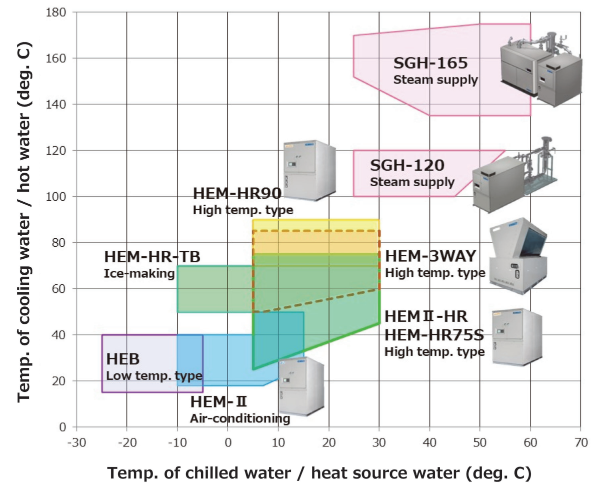

Fig. 4 Temperature map of products

fraction of molten slag in ash is relatively high. Carbon-neutral fuels such as sewage sludge exhibit similar behaviors to that of coal when cofired. It is believed that clinkers caused by ash deposition can be avoided by predicting the mixing conditions (cofiring ratio and cofiring product combination) that cause the fraction of molten slag in ash to fall below average. We will continue revealing the combustion characteristics of carbon-neutral fuels to develop technologies that enable stable use of these fuels.

3. Optimization of heat transfer and fluid flow processes

3.1 Utilization of waste heat by heat pumps

Since manufacturing Japan's first high-pressure reciprocating compressor in 1915, Kobe Steel has developed both compressors as well as products that use compressors, such as chillers and heat pumps. In the late 1980s, we participated in the development of the Super Heat Pump Energy Accumulation System within the Moonlight Project, which was launched in the wake of the oil crisis. The outcome for Kobe Steel was the development of a high-efficiency heat pump. Applying the core technologies acquired as part of the project has enabled us to develop and market a wide variety of high-efficiency heat pumps. Pivotal technologies include our highly efficient semi-hermetic screw compressor, Lorentz cycle chiller that uses a non-azeotropic refrigerant mixture, and low-temperature heat exchangers. As shown in **Fig. 4**, our products supply a wide range of temperatures, from low-temperature media to hot water and steam for industrial heating, and reduce energy consumption and CO_2 emissions in factories.[12] The 95℃ hot water recovery heat pump we developed in 2019 in collaboration with Kimura Chemical Plants Co., Ltd., a machinery manufacturer, is a prime example. Its evaporation and distillation processes, which are inherently energy-intensive processes, emit up to 60% lower CO_2 emissions than conventional products.[13]

Replacing fossil fuel boilers with heat pumps in support of carbon neutrality requires higher temperatures and higher compression ratios. Increasing the temperature differential between the outside air, which is the heat source, and the output requires a higher compression ratio. Kobe Steel products achieve high performance here by using single-stage or two-stage screw compressors. Additionally, the heating equipment industry, under which equipment such as heat pumps fall, is subject to increasingly stringent restrictions related to fluorocarbons. These substances are potent greenhouse gases. As such, designs that use HFO (hydrofluoroolefin) refrigerants with a GWP (global warming potential) of 1 or less are gradually being introduced.[14] We will continue to support the implementation of a green society with our highly efficient, energy-saving products.

3.2 Carbon emissions reduction via cryogenic LNG vaporizers

Kobe Steel launched its heat exchanger business in the 1960s by capitalizing on the innovations and expertise accumulated in the field of cryogenic technology through its air separation business. Kobe Steel introduced the ALEX® line of brazed aluminum heat exchangers in the 1970s as its entry into the cryogenic LNG vaporizer business, in line with the trend of converting thermal power plants to LNG. These heat exchangers are compact and capable of supporting heat exchange among multiple fluids simultaneously. We subsequently developed the open rack vaporizer (ORV). Osaka Gas Co., Ltd. later provided technology for our intermediate fuel vaporizer (IFV) to use the cold energy of LNG, leading to our independent development of these products. There are various types of vaporizers for cryogenic liquid fuels such as LNG. ORVs have low operating costs because they use seawater as their heat source, and they are the most common type of vaporizer encountered in large-scale applications. The temperature differential between LNG and ambient-temperature seawater in early designs was approximately 180℃, causing seawater to freeze on the heat transfer tubes of the ORV. This reduced the effective heat transfer area and thus reduced performance. SUPERORV®, developed jointly with Osaka Gas Co., Ltd., is an innovative vaporizer that uses a duplex tube configuration on the lower part of the heat transfer tube (**Fig. 5**). This prevents a temperature drop on the external surface of the heat transfer tube and approximately triples the gasification performance of each heat transfer tube compared with conventional models, yielding an economical and compact vaporizer.[15]

Demonstration projects for hydrogen cofiring and mono-firing in gas turbines are planned all over the world in support of carbon neutrality. As a leading manufacturer of LNG vaporizers, Kobe Steel is also promoting the development of liquid hydrogen vaporizers. NEDO (New Energy and Industrial Technology Development Organization) is sponsoring a project titled Building a Supply Chain for Hydrogen Derived from Unused Energy Resources to demonstrate stable gasification performance and cold energy utilization using a small (1 MPa or less, 1,200 Nm^3/h), low-pressure IFV liquid hydrogen vaporizer. We will continue to develop and demonstrate products exhibiting higher pressures, larger capacities, and greater contributions to carbon neutrality all around the globe.

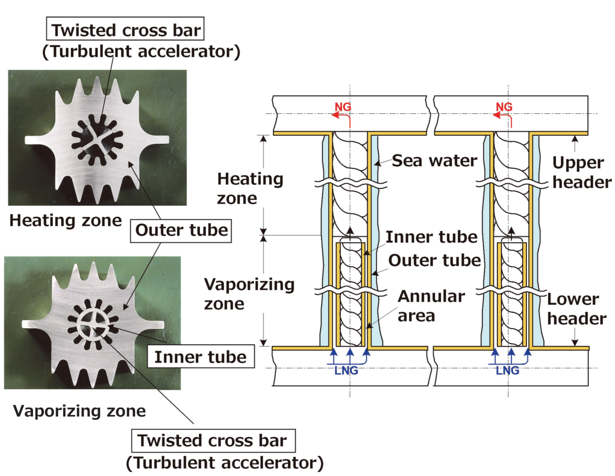

Fig. 5 Panel structure of SUPERORV®

Conclusions

This paper has presented the evolution of thermal and fluid dynamics control technologies for production processes and products alongside several application examples. Previously, we have reduced CO_2 emissions primarily through energy conservation measures related to the use of fossil fuels. For example, in conjunction with upgrading our steelworks equipment in the 1990s, we introduced low-NOx burners and regenerative burners in the heating furnaces of our plate and wire rod factories and developed new combustion and CFD technologies. We have expanded our portfolio of machinery products in line with the needs of the world, such as energy conservation and quality improvement. Decarbonization via alternative fuels and developments in thermal and fluid dynamics control technologies will be of great societal value, owing to the necessity of realizing a green society. Kobe Steel will continue to develop technologies to reduce CO_2 emissions in the production process and to contribute to CO_2 emission reductions around the world through products, technologies, and solutions.

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