Advanced Development of Pulverized Coal Firing Technologies

TAMURA Masato : General Manager, Combustion Engineering Department, Power Plant Division, Energy Systems Operations
WATANABE Shinji : Combustion Engineering Department, Power Plant Division, Energy Systems Operations
OONO Emi : Manager, Combustion Engineering Department, Power Plant Division, Energy Systems Operations
ITOKAZU Ryuunosuke : Combustion Engineering Department, Power Plant Division, Energy Systems Operations
KOZAKI Takahiro : Basic Design Department, Power Plant Division, Energy Systems Operations

IHI has been developing combustion technologies which give very low environmental impact. Various equipment and numerical tools support the development process at each stage. Small- and large-scale test furnaces are used for evaluating actual combustion behaviour. Numerical simulation is also used to assist theoretical understanding. An example of recent development is the realization of very low Air/Coal ratio burners for dried lignite coal firing. Another commercialized burner made it possible to reduce slagging when burning coals which have a low ash melting temperature, such as sub-bituminous coals. The dynamic and static performance of pulverizers, which play a very important role in fuel burning process as pulverized fuel size dominates burnout behaviour, has been improved. This paper gives an outline of recent development of combustion technologies. A large-scale coal combustion test facility which is newly installed is also described.

1. Introduction

Among the many types of fuels used to generate power, coal is essential for energy security as it is an inexpensive and abundant resource deposited throughout the world in a wide range of locations. That said, coal has high carbon content and emits a large amount of carbon dioxide (CO_2) per unit heat quantity. Amidst growing concern about recent global environmental issues, the need for reducing CO_2 is increasing. To reduce CO_2 emissions, it is necessary to improve efficiency, promote Carbon Capture and Storage (CCS), and expand the use of carbon-neutral woody biomass (the amount of CO_2 in the atmosphere should not be affected if plants that have been grown by absorbing CO_2 from the atmosphere are burnt.) As to energy security, there are active movements toward expanding the use of lignite coals, sub-bituminous coals, semi-anthracite, oil coke, and other resources that heretofore have not been used as fuels to generate power.

In response to the diversification of fuels used in pulverized coal power stations, IHI has been developing combustion technologies suited to each type of fuel. Recently, burners for single fuel firing of oil coke and of semi-anthracite as well as burners that produce minimal slagging that operate with low NO_x emissions during the firing of coals that usually tend to cause severe slagging have been commercialized. IHI has also been conducting various analyses and tests to improve pulverizer performance. During the development of these technologies, IHI is using existing test furnaces, such as the Perpendicular Industrial Combustion Test Furnaces (PIT) and Demonstration Combustion Test Furnaces (CFT), which IHI will also use in the future. In addition, we have built a new Coal Combustion Test Facility (CCTF) to further promote the development of combustion technologies.

This paper outlines the low-slagging burners and improved roller mills which have been developed by using our existing test furnaces and Computational Fluid Dynamics (CFD). We also describe a large-scale coal combustion test facility.

2. Development of burners

Social needs for coals to be used for pulverized coal fired boilers are moving from the bituminous coals toward the less expensive low quality coals such as lignite coals, sub-bituminous coals, semi-anthracite, and oil coke. Sub-bituminous coals have high volatile content and high combustibility, but also high moisture content and a low ash melting point, thereby causing slagging problems in the furnace. Lignite coals also have very high moisture content and so a drying process is being developed.(1)

Semi-anthracite coal and oil coke have higher heating values but are disadvantaged in their low ignitability due to their low volatile content. This section outlines the new burners that we have developed by using CFT to reduce the slagging caused by sub-bituminous coal and other types of coal, and also the ultra low A/C (Air/Coal ratio, the weight flow ratio of primary air to pulverized coal) burners designed for the combustion of dried lignite coal. We have already reported on our burners for single firing of semi-anthracite coal and of oil coke in previous reports.(2), (3)

2.1 A-DF burners

Sub-bituminous coals and other so-called "low-rank" coals are increasingly being used to meet needs to reduce the unit cost of power generation. Sub-bituminous coals have high volatile content in the range of 50 to 60 wt% (dry ash free) and generally have high combustibility. However, the low ash melting point results in the problem of slagging at the burner throats and other locations. To solve this difficulty, we have developed burners that can minimize such slagging without sacrificing combustion stability and environmental performance.

Figure 1 shows a comparison between a conventional burner (IHI-DF burner, hereinafter called a DF burner) and a low-slagging burner (Advanced DF burner, hereinafter called an A-DF burner). In the DF burner, air register vanes (a mechanism for swirling the air) adjust the swirl intensity of the secondary air and generate internal circulating flows near the central axis of the burner, directed from the inside of the furnace to the burner. To assure ignition stability, the swirling pulverized coal flow is blown into the high-temperature reducing atmosphere.

The A-DF burner reduces slagging by reinforcing the linear flow of the pulverized coal and restraining the pulverized coal from mixing with the secondary air and scattering into the external circulating flow. Just like the DF burner, the A-DF burner generates internal circulating flows by using air register vanes, realizing low-slagging firing while maintaining ignition stability and low NO_x emissions.

The low-slagging firing of the A-DF burner was verified by measuring temperature changes on the metal surface of a water-cooled probe inserted near the burner. **Figure 2** shows the changes in temperature of the probe metal surface. When the DF burner was used, the temperature of the metal surface decreased by approximately 20% in 20 minutes due to slagging. By contrast, the A-DF burner showed almost no decrease in the temperature of the metal surface, indicating a significant reduction in slagging.

2.2 Ultra low A/C burners

Recently, the range of coals used for power generation has broadened to include not only sub-bituminous coals but also younger coals, such as lignite. However, lignite coals have a high moisture content in the range of 40% to 60%, and thus have a lower combustion efficiency when fired in boilers directly after pulverization. For this reason, despite their abundance the use of lignite coals has not increased. To solve this problem, a pre-drying process is being

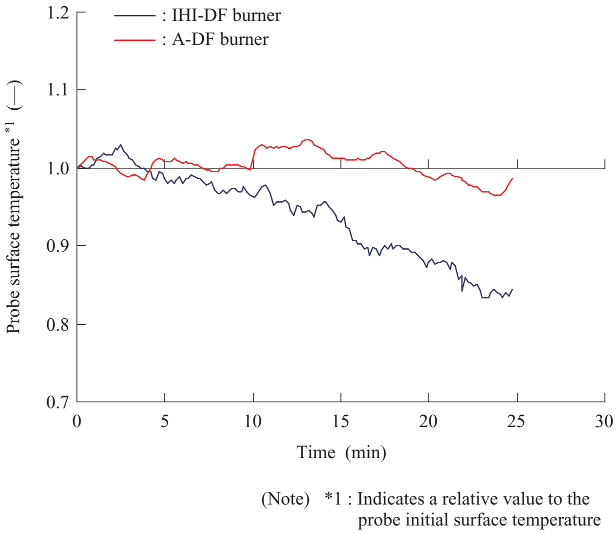


Fig. 2 Temperature trend of slagging probe

developed for practical use and the moisture content has been successfully reduced to approximately 10%. However, as a result of drying the volatile content exceeds 40%, and close attention must be paid to ignitability when handling such dried lignite coals. When transporting dried lignite coals to burners, ambient-temperature air that has not been preheated must be used to prevent self ignition. At the same time, the flow rate of the air must be as small as possible to prevent reductions in boiler efficiency. To satisfy these requirements, we have developed an ultra low A/C burner. This type of burner features a ring-shaped pulverized coal nozzle to assure ignition stability and burnout and supplies combustion air from both outside and inside the pulverized coal flow in order to efficiently mix the very highly concentrated pulverized coal flow, which is blown into the furnace, with the combustion air. **Figure 3** shows the conceptual diagram of the ultra low A/C burner.

Using the ultra low A/C burner, a combustion test on dried lignite coals was conducted and it was confirmed that they provide stable ignition and good burnout. **Figure 4** shows the appearance of the flames. Luminous flames were generated from the throat outlet and bright stable flames were observed across the entire visual field. **Figure 5** shows the NO_x emissions and the combustion efficiency under partial load. The air ratio increases in the burner under partial load, thereby increasing NO_x emissions. Dried lignite coals showed high combustion efficiency under all

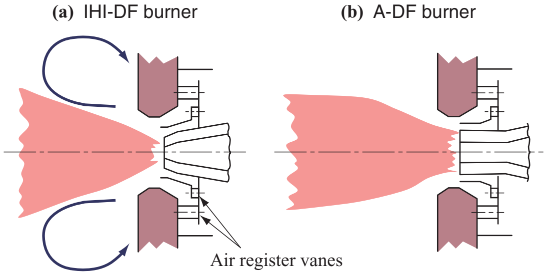


Fig. 1 Comparison of DF burner and Advanced-DF burner

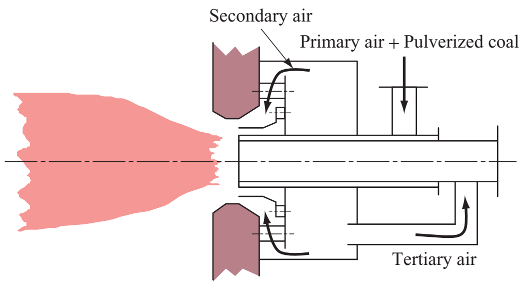


Fig. 3 Conceptual diagram of ultra low A/C burner

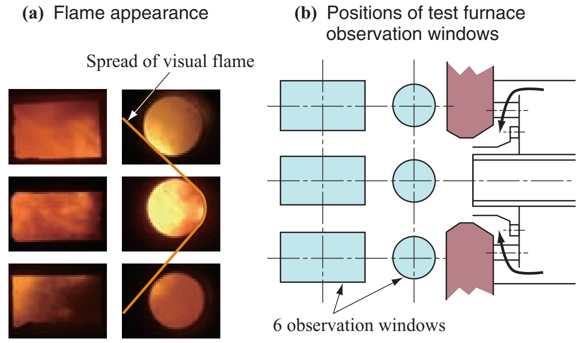


Fig. 4 Flame photograph of ultra low A/C burner

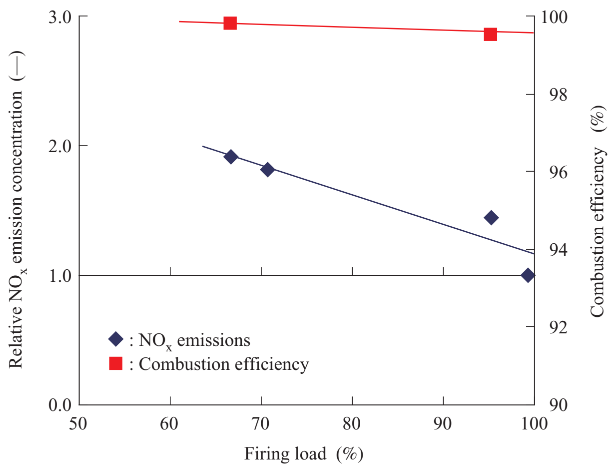


Fig. 5 Behavior of NO_x and combustion efficiency using ultra low A/C burner

loads and this is comparable to that of bituminous coals. The firing load was decreased to 50% during the test and stable combustion was confirmed.

3. Development of mills

Nuclear power generation systems generate power at a constant output (the so-called base load). On the other hand, pulverized coal fired boilers must have a high load change capability as a middle power source for covering changes in load. Efforts have been made to reduce CO_2 emissions by partially substituting coal with carbon-neutral woody biomass. To meet such needs, IHI has developed a high-performance mill featuring significantly improved low-load operation and load change capability. A woody biomass pulverizing mill was also developed.

3.1 High-performance roller mills

Pulverized coal fired boilers use coal of several tens of micrometers in size and then fire such pulverized coal in a suspended state inside the boiler furnace. Roller mills are commonly used as pulverizers due to their low power consumption. They pulverize coal between a roller and a rotating pulverizing table. To meet society's needs for load change capability and reduced minimum load, a method of controlling the table rotation speed has been adopted in response to changes in the coal feed rate for high-performance roller mills. The shape of the table was optimized and the table rotation speed control method was examined by conducting parametric pulverizing tests using a test mill owned by IHI. The pulverizing capacity at increased table speeds was evaluated using three types of coals with different Hardgrove Grindability Index (HGI) values. **Figure 6** shows the test results for two types of coal. It was observed that capacity increased by 10% when the table rotation speed was increased by 14% while using coal with an HGI of about 60. Capacity increased at a higher rate when using coal with a lower HGI.

A load change test was conducted by adjusting the table rotation speed in accordance with several different patterns and the results were compared with respect to dead times and also with respect to first-order lags. **Figure 7** shows the

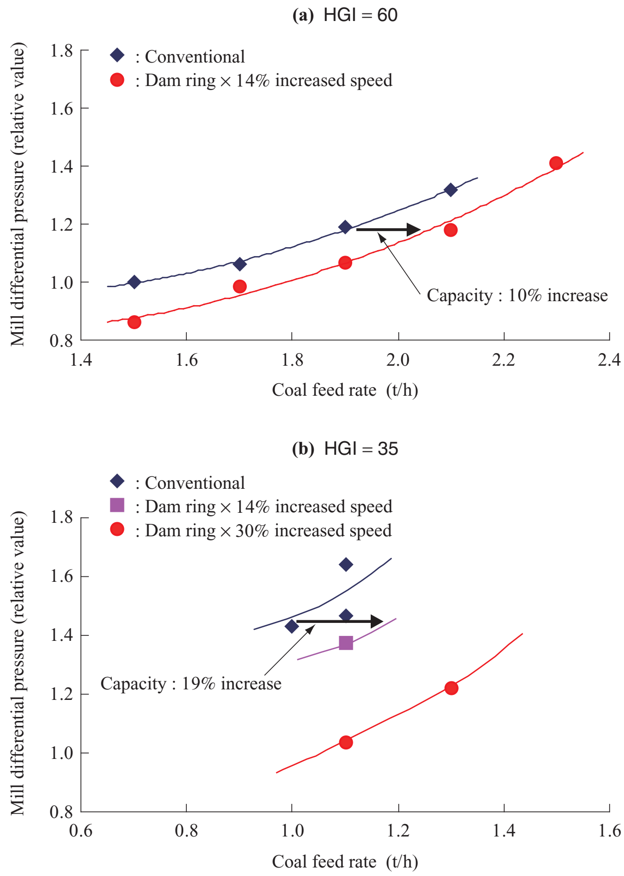


Fig. 6 Increase of pulverizing capacity by high-speed table rotation

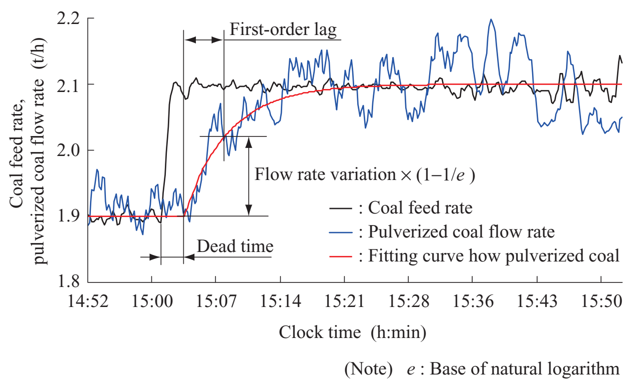


Fig. 7 Measurement result of pulverizer response for step load change

characteristics of the pulverized coal flow (an example of measuring how much the coal feed rate and flow rate of the pulverized coal change over time). The dead time and first-order lag were reduced by approximately 35% by selecting the best combination of table shape and table rotation speed control method.

3.2 Woody biomass pulverizing mill

Woody biomass is already in use at many pulverized coal power stations.[(4), (5)] When woody biomass is pulverized together with coal in a mill designed for pulverized coal fired boilers, the maximum mixing rate is approximately 5 cal%. To reduce CO_2 emissions from pulverized coal power stations, there is a great need for fire woody biomass to increase its mixing rates. To do this, the woody biomass must be pulverized separately before feeding it into the furnace for co-firing.

To understand the woody biomass pulverizing characteristics of the roller mill, pulverizing tests were conducted, first without modifying the roller mill and then by changing the shapes of the table and air port in order to increase woody biomass pulverizing capacity. Successful results were obtained and capacity was increased as shown in **Fig. 8**.

4. Numerical simulation

Enormous amounts of time and money are required to develop new products or technologies by conducting tests to examine each aspect of performance. It is impossible to make a full-sized model for testing performance prior to production, particularly in a case such as a large boiler for a thermal power station. Therefore, a numerical simulation is applied to realize efficient development. This section describes the combustion simulation, which is used to design the boiler furnaces, and the particle classification simulation, which is currently used to develop high-performance roller mills.

4.1 Furnace simulation

To precisely simulate the influences of burner structure and operating conditions on the state of thermal flow inside the furnace as well as to understand the performance of such furnace, a new technique was established to quickly analyze the entire area from the burner inlet to the furnace outlet.[(6)] The CFD code FLUENT was used to conduct the analysis. The pulverized coal firing model was created and it serves as the key to this analysis by reflecting data on the volatilization process and the char combustion process acquired from a test conducted using a drop tube furnace. The adopted technique calls for analyzing the burner and furnace separately in order to analyze the entire furnace and shorten the necessary calculation time. **Figure 9** shows the conceptual diagram for this technique, which links the burner and the furnace by inputting the data acquired at the burner nozzle outlet to the furnace analysis.

Figure 10 shows the gas temperature distribution inside the furnace as a result of the analysis conducted by changing the swirl intensity of the primary air and pulverized coal flow. **Figures 10-(a)** and **-(b)** show the results obtained under weak and strong swirl conditions, respectively. The positions in which the char combustion rate is 2×10^{-3} kg/s (referred to provisionally as ignition points) are indicated by the circles in the figure. A comparison of the weak and strong swirls indicates that the ignition points move farther from the burners under weak swirl conditions. This is because weak swirls strengthen the straight flow of pulverized coal and render it difficult to generate internal circulating flows. Note that the secondary air swirl intensity remained unchanged in this analysis.

Separating the analysis of the burner and furnace helped reduce the analysis time. The burner structure and operating conditions were reflected in the furnace analysis and used in the boiler design. In this way, the analysis was able to provide boilers with optimal specifications.

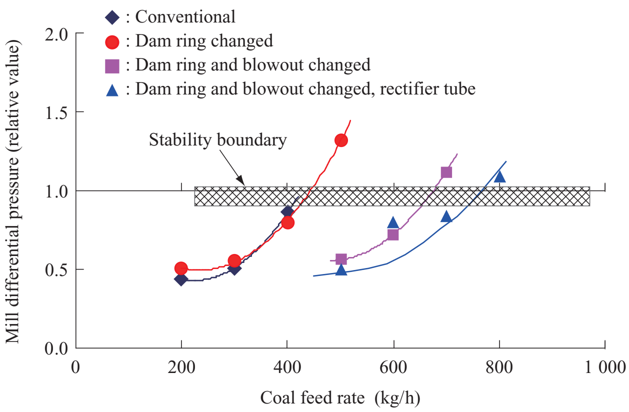


Fig. 8 Increase of pulverizing capacity of woody biomass pulverizing

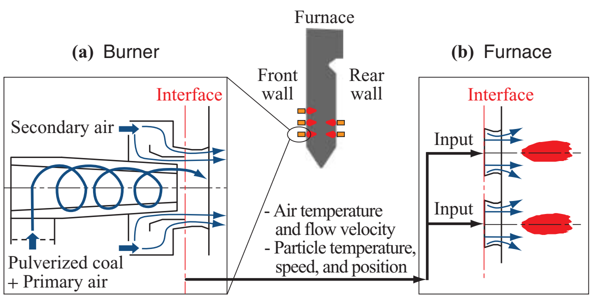


Fig. 9 Conceptual diagram of analytical method

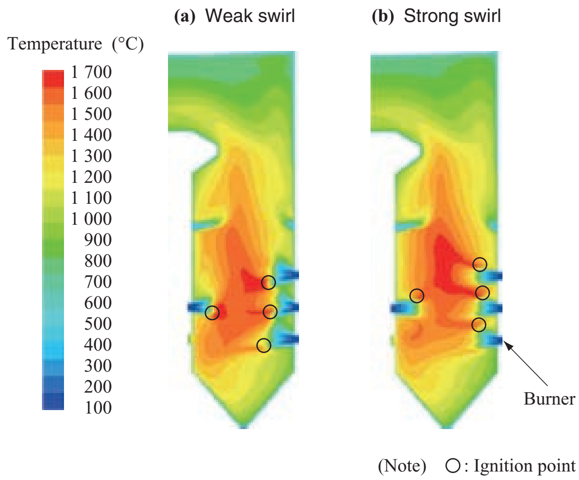


Fig. 10 Gas temperature magnitude

Figure 11 shows the pulverized coal particle trajectory on the cross-section of the burners. Different colors indicate the differences in unburned content rate. Particles under the weak swirl condition (**Fig. 11-(a)**) tend to move linearly in bunches. By contrast, particles under the strong swirl condition (**Fig. 11-(b)**) tend to disperse widely due to centrifugal force. This result indicates that the adjacent horizontal flows interfere with one another and the two central flames move closer to the center of the furnace as the two outer flames move closer to the side wall, particularly under the weak swirl condition.

4.2 Simulation of particle classification in mills

To reduce the unburned content in the pulverized coal fired boilers, the particle classification efficiency in mills must be improved. This affects the dynamic characteristics and size of the mills. Particle classification performance was evaluated by using numerical simulation to parametrically examine the shape and operating conditions. The CFD code STAR-CD was used for this analysis alongside the multi-frame method to simulate rotary movements in the flows around a rotational classifier. While conducting this simulation, the performance of the classifier was evaluated through a cold flow test using a test mill and the resulting data was used as simulation verification data. **Figure 12** shows the simulated pulverized coal particle trajectory inside the mill.

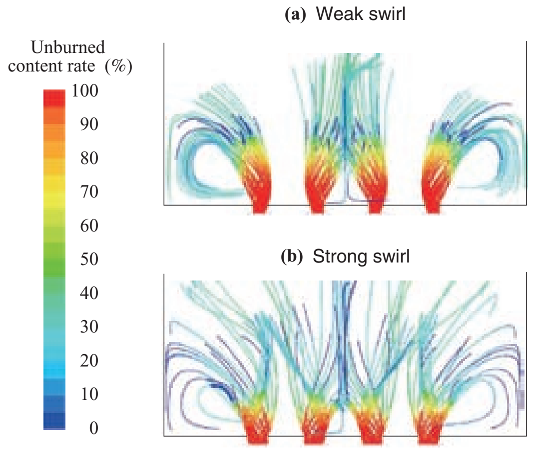


Fig. 11 Pulverized coal particle trajectory colored by burnout level

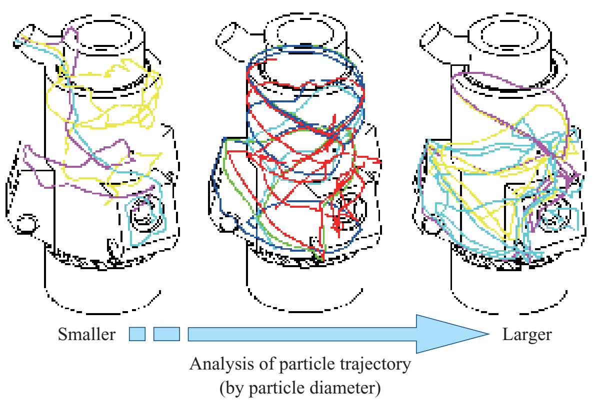


Fig. 12 Pulverized coal particle trajectory in roller mill

As described above, a numerical simulation and a cold flow test were combined to understand the flows inside the mill, and then the shape and operating conditions of the classifier were examined in order to improve classification efficiency.

5. Large-scale coal combustion test facility and advanced development

IHI decided to construct a CCTF in addition to its existing test facilities in order to meet future market needs and increase the speed of development. The CCTF is equipped with a flue gas treatment system as well as an oxygen supply system in the same system configuration as that of pulverized coal power stations. Thus, this will be the world's largest test facility and will enable integrated performance evaluations of furnace and environmental facilities as well as oxygen combustion to be conducted. Exhaust gas from the CCTF will be introduced into CO_2 chemical absorption equipment and then subjected to various tests. **Table 1** shows the equipment of the CCTF and **Fig. 13** offers an aerial view.

It is planned to use the CCTF for developing pulverizers and burners, which are important equipment in boiler plants, as well as for designing and planning furnaces. Pulverized coal generated by the pulverizer is supplied to the burners. Two types of combustion methods are available: the indirect combustion method in which pulverized coal is collected in pulverized coal bins before combustion and the direct combustion method in which pulverized coal is supplied directly to a burner. The pulverizer structure was examined and designed to facilitate service life evaluation and vibration evaluation as well as to acquire data during operation. The thermal flow state inside the furnace is determined by the arrangement of the furnace and the pulverized coal burners, and this affects the heat absorption of the furnace, which is an important element for the boiler. The burner can be set in different positions within the CCTF in order to make it possible to acquire various kinds of data when burners are in different positions. Such data will be

Table 1 CCTF equipment

Equipment	Test
Furnace, pulverizer, burners, flue gas treatment system, and oxygen supply system	Large-scale coal combustion tests and oxygen combustion tests conducted with full-sized equipment

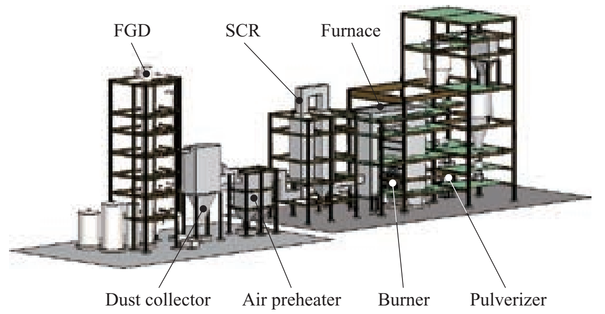


Fig. 13 Bird's-eye view of CCTF

used in future furnace designs. The CCTF is equipped with a flue gas recirculation line and oxygen storage equipment in order to enable evaluation of oxygen combustion characteristics to help realize a low-carbon society.

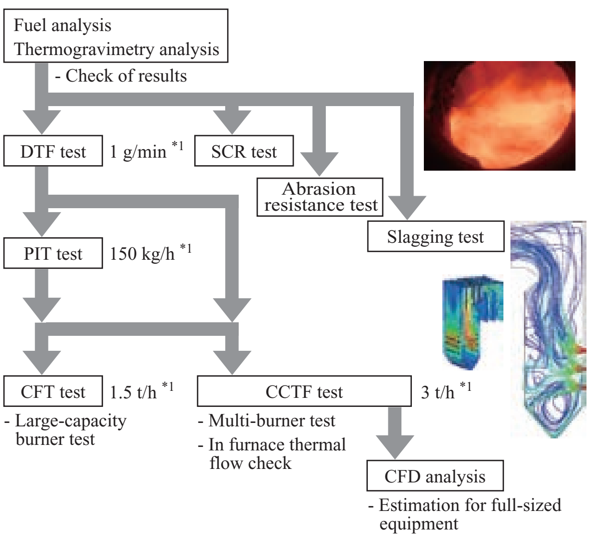
The CCTF described above can be combined with various other combustion test facilities owned by IHI and numerical analysis techniques to facilitate efficient technology development. This combustion technology development process is shown in **Fig. 14**.

Each facility and its intended use in burner development are described below. First, a fuel analysis and a thermogravimetry analysis are conducted in order to understand the properties of the fuel to be used. Then, tests on combustion, NO_x reduction, abrasion resistance and slagging are carried out within a Drop Tube Furnace (DTF) and other test equipments as necessary to acquire the design data to be applied to full-sized equipment. The data from the volatile content release process and the char combustion process in the reducing atmosphere are used to create pulverized coal combustion models for use in the numerical analyses described below.

Next, a Perpendicular Industrial Combustion Test Furnace (PIT) of 150 kg/h is used to optimize the burner structure. At this time, numerical analyses are performed to specify, change and check the detailed structure and operating conditions of the test burner, narrowing down the burner structures to be tested. After that, a large-capacity burner test is conducted by using the Demonstration Combustion Test Furnace (CFT) to check the burner performance as a single unit.

Conventionally, the subsequent evaluation steps are conducted by using numerical analyses. In the future, performance evaluation will be conducted by using the CCTF, which enables multi-burner tests as needed. CCTF measurement data will be used as the comparison verification data for numerical analyses, thereby improving the analysis techniques to more precisely estimate the heat flow state inside the furnace in order to optimize burner arrangement.

By applying the optimal test devices and numerical analyses (including CCTF) throughout every step of the development process, combustion performance will be able to be understood and evaluated to a higher degree of accuracy in a shorter period of time.



(Notes) - DTF : Drop Tube Furnace
- PIT : Perpendicular Industrial Combustion Test Furnace
- CFT : Demonstration Combustion Test Furnace
- CCTF : Coal Combustion Test Facility
- CFD : Computational Fluid Dynamics
- SCR : Selective Catalytic Reduction
*1 : Scale of each test (firing rate)

Fig. 14 Development process of combustion technologies

6. Conclusion

This paper details our latest combustion equipment technologies for burners and pulverizing mills used in pulverized coal fired boilers, which have very low environmental impact. To realize a low-carbon society and energy security as well as to reduce power generating costs, expectations for higher efficiency combustion technologies with low environmental impact are increasing. By combining testing using large-scale coal combustion test furnaces and other large- and small-sized testing facilities with advanced numerical analysis techniques, IHI is increasing the pace of technology development and flexibly responding to market needs.

IHI will continue to accelerate the development of combustion technologies for pulverized coal fired boilers, including mills and burners, to quickly develop technologies and products that respond to the diverse demands of the market.

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