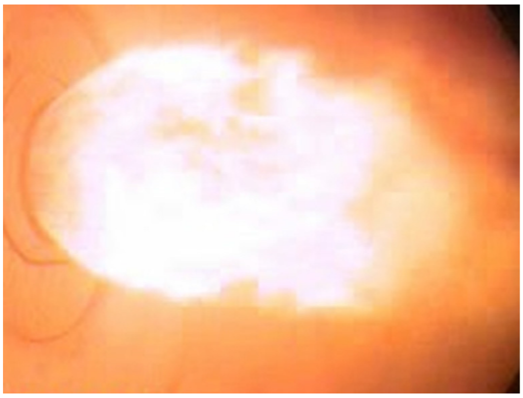
High-fidelity Combustion Simulation for Pulverized Coal Combustion Boilers



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The efficient development of a low-NOx, low-unburned component combustion method applicable to various kinds of fuel for coal combustion boilers requires simulation technology capable of predicting multiphysics including pulverized coal combustion, gaseous combustion and radiative heat transfer with high accuracy. Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has utilized measurement results obtained in from small-scale basic combustion experiments to actual-scale burning tests for actual equipment performance-matched implementation of model development/ verification. This has gradually enabled combustion simulation technology to be applied to the development of various burners.

1. Introduction

MHPS has been engaged in the development of a low-NOx, low-unburned component combustion method applicable to various kinds of fuel to comply with more stringent environmental regulations over coal combustion boilers, as well as to satisfy the need for cheaper fuel costs. In particular, our possession of combustion equipment compatible with both opposed firing and circular U-firing systems allows us to answer a variety of customer requests. For the efficient development of these combustion systems, it is indispensable to select an optimal burner shape/burner arrangement/boiler furnace geometry based on numerical simulations in advance.

Before merging to become MHPS, the thermal power sectors of both parties (Mitsubishi Heavy Industries, Ltd. and Hitachi, Ltd.) have respectively developed their own combustion simulation technologies able to predict boiler performance including NOx concentration and unburned components with high accuracy. The integration of these technologies has come to enable a high-fidelity combustion simulation contributive to the further improvement of product performance and reliability. This paper summarizes the combustion simulation technology and introduces actual cases of its application to burner development.

2. Overview of simulation

2.1 Simulation technology development strategy

Within a tens of meters-tall huge coal combustion boiler furnace, multiscale/multiphysical analysis technology is required since several phenomena including complex flowing of gas containing pulverized fine powder coal (with an average grain size of approximately 40 microns), pulverized coal combustion and radiative heat transfer from combustion gas to water pipes occur at the same time. In the case of pulverized coal combustion in particular, it is difficult as a rule to

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analytically predict the combustion state, not only because it is accompanied by the processes of moisture evaporation from pulverized coal as the temperature rises, combustible gas release from volatiles and its burning, and fixed carbon (char) combustion, but also because one kind of coal differs from another in composition and the process of burning. Hence, MHPS and the Research & Innovation Center of Mitsubishi Heavy Industries, Ltd. measured the reaction rates of many different kinds of coal, using a tandem-type staged DTF[1], which simulated a high-temperature environment inside the boiler furnace as shown in **Figure 1**. The results were incorporated in an analysis program, thereby realizing high-precision analysis. Furthermore, using large combustion test equipment as shown in **Figure 2**, we verify the accuracy of analytical programs, achieving higher reliability.

In the following sections, char combustion, NOx reaction, and gaseous combustion models important for the prediction of pulverized coal combustion boiler performance are explained.

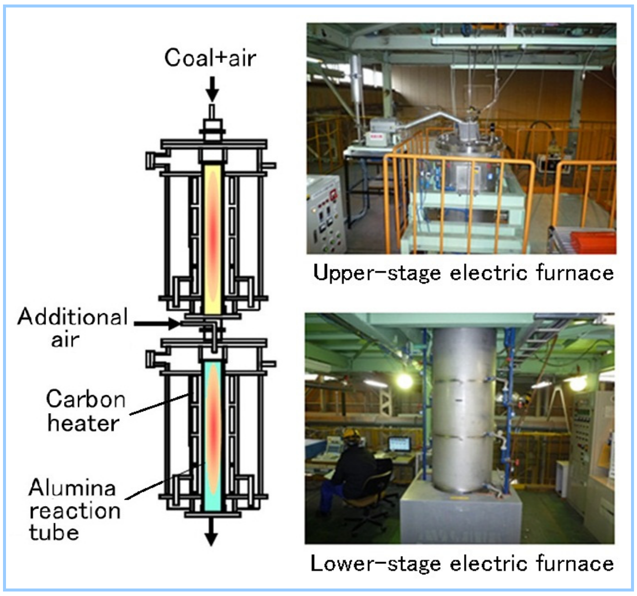

Figure 1 Tandem-type staged DTF

Figure 2 Example of large combustion test equipment (Operation started in 2014)

2.2 Char combustion model

When pulverized coal is heated, a devolatilization reaction takes place to release combustible gas known as “volatile.” After that, char which is the remaining solid component reacts with surrounding oxygen and other gases. This reaction is referred to as char combustion. The reaction time of char combustion is of the order of a few seconds, longer than approximately 50 milliseconds of devolatilization reaction time, and this indicates that it is char combustion that dominates solid burning in the downstream of a boiler furnace. To reduce unburned fuel losses in the boiler for higher-efficiency combustion, this char combustion must be predicted accurately. It is also important to design optimal boiler furnace geometry so as to secure the necessary reaction time matching the characteristics of the coal used.

The growing demand for burning brown, sub-bituminous and other low-grade coals to reduce fuel costs has come to necessitate a char combustion model compatible with the characteristics of not only bituminous coal, but also a wide variety of coal types. To deal with this, we developed a char combustion model taking into account the difference with different kinds of fuel in air ratios, temperatures, particle diameters, residence time, and other conditions for operating the boiler. This model characteristically takes into account not only char oxidation reaction with oxygen, but also char gasification reaction with carbon dioxide or water vapor, and also models the effects of contained moisture. To develop this model, we measured combustion characteristics under a variety of burning conditions using DTF, and developed a database for combustion experiments.

Figure 3 shows the results of prediction concerning the components remaining unburned when brown coal was fired. If the reaction rate of brown coal is predicted with that of a bituminous coal, unburned components are underestimated, but the combustion database-based determination of reaction rate resulted in improved accuracy of prediction.

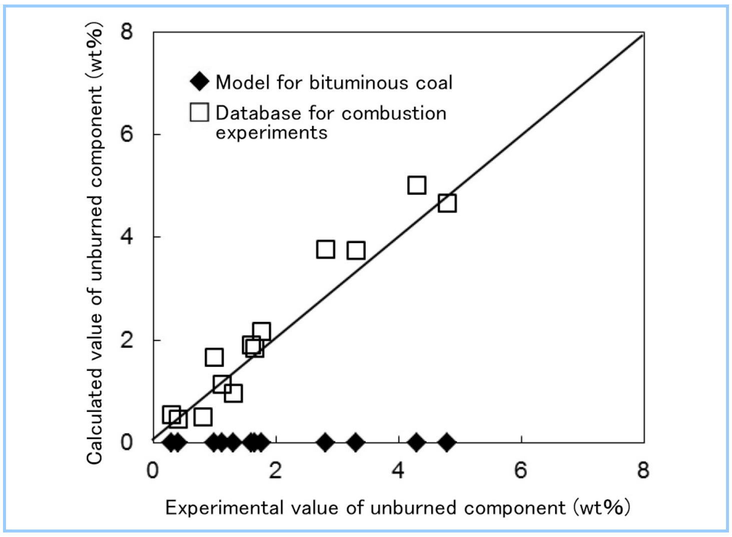

Figure 3 Prediction accuracy for unburned components of brown coal

2.3 NOx reaction model

Pulverized coal combustion boilers employ a low-NOx burner and/or a two-stage combustion process, thereby reducing NOx emissions. For NOx reduction, it is important to promote a NOx reduction reaction in the low-oxygen region from the furnace's burner section to the air input for second-stage combustion. As shown in **Figure 4**, it is found from fundamental researches at MHPS that a NOx reduction reaction with hydrocarbon radicals is important for NOx reduction. Since the concentration of hydrocarbon radicals greatly differs for different kinds of coal, we developed a model to predict this from basic DTF tests. **Figure 5** shows the NOx model accuracy in the DTF system. The analytical accuracy was found to be high against various test data for different fuels in terms of temperature, air ratio, coal type, and coal grain size. Using the developed NOx model, a NOx reduction method for actual boilers is under examination.

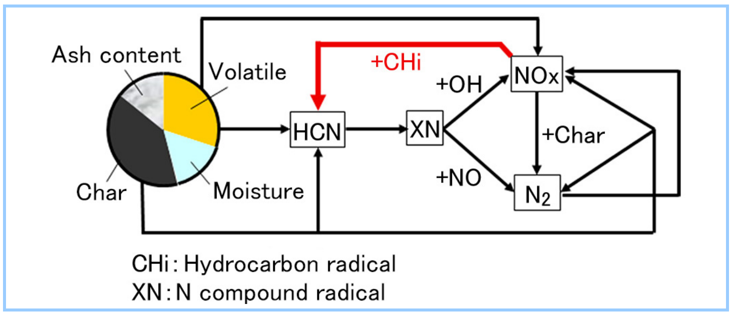

Figure 4 NOx reaction model

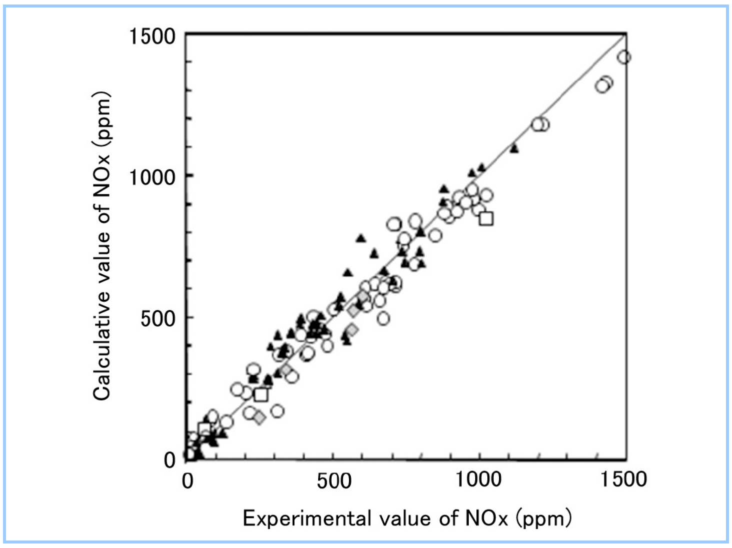

Figure 5 Prediction accuracy of NOx model

2.4 Gaseous combustion model

The reaction with combustible gas released from pulverized coal is calculated as a reactive phenomenon in the gaseous phase. MHPS uses two types of gaseous combustion models in a different way: one is a well-used eddy dissipation model mainly to determine equipment design in the steady state and its operating policy, and the other is a coal flamelet model(2) to examine unsteady-state phenomena such as ignition and flameout. Here, the coal flamelet model calculate a diversity of burning states dependent upon the composition of combustible gases released from several fuel components (such as volatiles and char) with reference to a composition database as shown in **Figure 6**. Using this model, the ignition characteristics are under examination for low-grade coal containing a large amount of moisture such as brown coal and sub-bituminous coal.

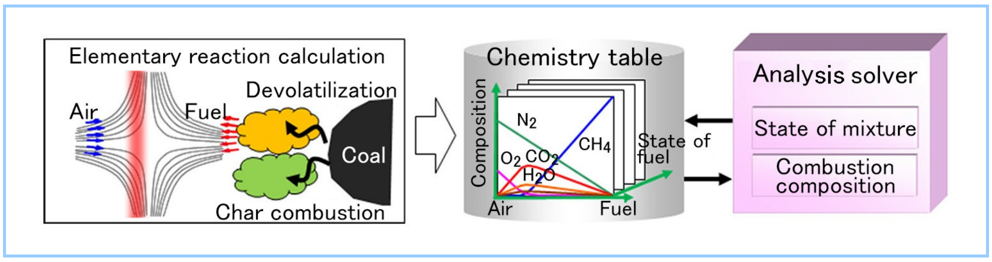

Figure 6 Outline of coal flamelet model

3. Cases of application to burner development

3.1 M-PM burner development

Since coal contains more N as a fuel component than gas and oil, causing a large amount of NOx, its low-environmental load operation is required. Low-NOx combustion can also save ammonia consumption for denitration equipment. MHPS has utilized combustion simulation to locate NOx generation in the existing A-PM burner(3). In this research, M-PM burner combustion was additionally simulated. **Figure 7** presents an M-PM burner case of temperature, O_2, and NOx distributions. The burner is located along the middle horizontal line on the left side of each distribution. The outer circumferential high-temperature/high-oxygen zone in the flame to cause NOx occurrence narrowed to reduce the amount of NOx generated there. In addition, NOx formed in the middle of the flame was reduced rapidly within the flame. It could be assured from this result that a new concept for the reduction in the amount of NOx in an M-PM burner has become reality. Thus in selecting a burner shape, an attempt is made to shorten the period of development, based on the combustion analysis prior to burning tests. As for the accuracy of test-furnace NOx analysis, both of A-PM and M-PM burners have achieved 15% or less.

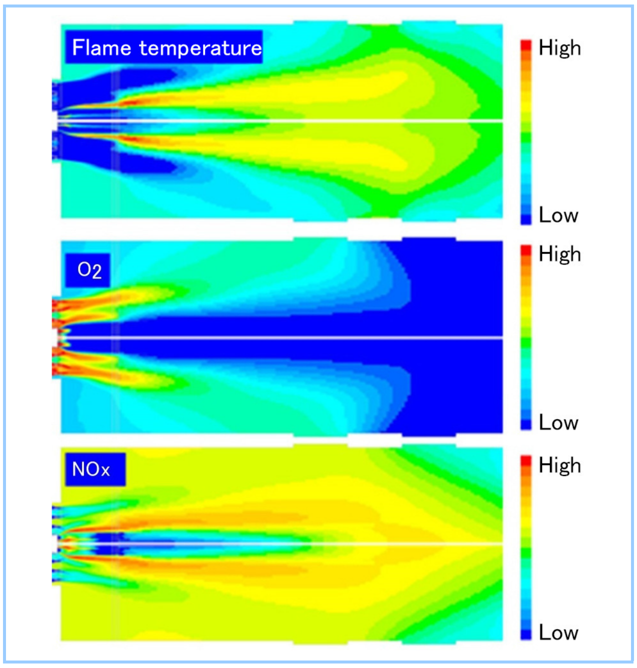

Figure 7 Results of M-PM burner analysis

3.2 Brown coal combustion burner development

Brown coal has, due to its abundant deposits and cheap price, been increasingly used worldwide in recent years. However, brown coal has the problem of poor ignition property against stable burning because of its high moisture content. Hence, the range of stable burning was determined for brown coal combustion burners by means of combustion simulation. **Figure 8** shows the stable combustion range of a brown coal combustion burner. The same figure also gives the analytical results (temperature distribution) of stable and unstable combustion states and flame photos taken during combustion tests. The test finding that combustion becomes unstable when the burner load factor is small could be reproduced by combustion analysis.

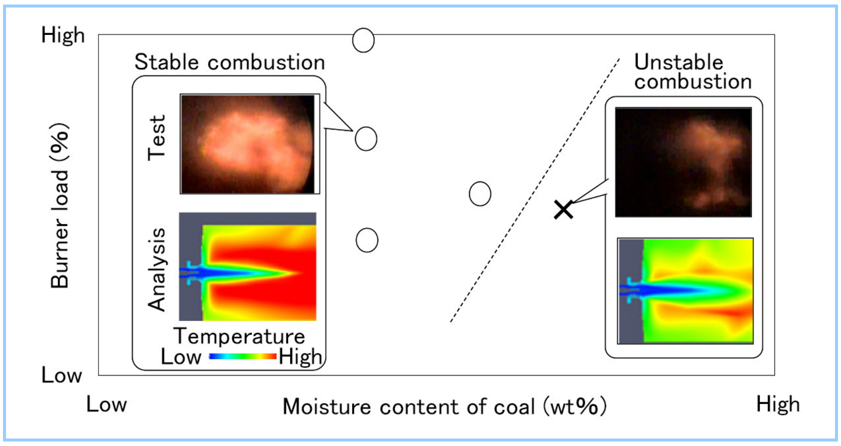

Figure 8 Stable combustion range of brown coal combustion burner

4. Conclusion

Combustion simulation technology to predict the fired condition in a pulverized coal combustion boiler with high accuracy was developed and compared with experimental data. We improved the prediction accuracy of unburned components by including the effects of contained moisture and gasification reaction of char with carbon dioxide and/or water vapor. In addition, modeling of the NOx reduction reaction with combustion-derived hydrocarbon has enabled high-accuracy prediction of NOx concentration. Furthermore, the high-fidelity flamelet gas combustion model was enhanced for the pulverized coal combustion field, indicating that the prediction of combustion instability far difficult for conventional analytical technology has become possible.

Cases where this simulation technology was actually applied to the development of a low-NOx M-PM burner, as well as a burner for high-moisture content brown coal, were explained to prove that the prediction by the simulation of a combustion performance improvement method could bring higher efficiency to burner development.

Toward the future, we intend to proceed with the integration of the two premerger parties' simulation technologies for their evolution into further advanced technologies in concurrence with the preparation of a huge database through the consolidation of existing basic test data and actual equipment data, the additional acquisition of basic combustion data, and verification using the large combustion test equipment which started operation in 2014.

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