Development of Computer Program for Combustion Analysis in Pulverized Coal-fired Boilers

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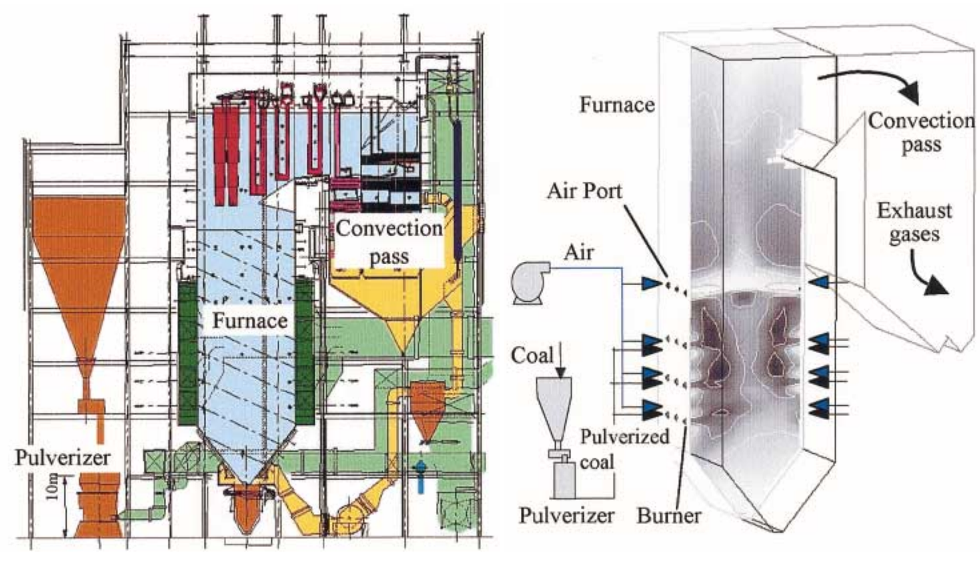
OVERVIEW: The requirements in the design of a pulverized coal-fired boiler, (1) the complete combustion of the fuel, (2) the minimal release of environmental pollutants, and (3) the uniformity of steam temperature at the water wall outlet. To attain a design that can both satisfy these requirements over the range from partial load to full load and achieve economical operation, techniques for analyzing flow, combustion and heat transfer inside the furnace are required. To meet that need, we have developed a computer program for analyzing the combustion of pulverized coal, radiation heat transfer, and changes in flow rate distribution and temperature within the water wall tubes by simulation. Concerning the combustion of pulverized coal, we formulated a devolatilization model, a char combustion model, and an NO_X and CO reaction model on the basis of fundamental experiments on the combustion of coal particles. Concerning radiant heat transfer between the flame and the water wall tubes, a radiative property model of the gas-particle mixture is incorporated and the heat transport rate is calculated by the discrete transfer (DT) method, which is highly accurate but requires a small computational load. In addition, to analyze the two-phase flow in the water wall tubes, we developed an algorithm that can be applied to an arbitrary flow path network. Comparison of the results calculated by this program with data on furnace operation under various coal and load conditions confirmed that the furnace exit gas temperature can be predicted to within ± 30°C. This technology can be used in the redesigning of existing plants as well as in the design of new 1,000-MW class boilers.



(a) Boiler side view

(b) Example of calculated results (gas temperature distribution)

Fig. 1— Combustion Analysis for a Pulverized-Coal-fired Boiler.
A means of predicting the state of combustion is indispensable in the design of a furnace, which is the heart of the boiler. This analysis program calculates the combustion state from the amount of fuel entering from the burners and the amount of air entering from the air ports.

INTRODUCTION

THERE is a need to improve the performance of pulverized coal-fired boilers in terms of efficiency, reliability, and effect on the environment. Specifically required are (1) reduction of unburned components in the ash, (2) reduction of NO_x and CO in the exhaust gases, and (3) uniformity in furnace exit steam temperature, without extreme peaks in the heat flux distribution to the walls. Because there is interaction among phenomena such as flow within the furnace, combustion, and heat transfer within the water wall tubes, to design a boiler that satisfies these requirements in any operating state requires techniques for conducting an overall analysis of these phenomena within the furnace. For that purpose, we developed a computer program that can conduct such an analysis on the basis of a physical model that is based on the results of fundamental experiments on the combustion of coal particles and burner performance experiments.

Here, we describe the feature of the model used by that program and present the results of experiments that were conducted with actual boiler.

PROGRAM FUNCTIONS AND STRUCTURE

This program calculates the gas velocity, temperature distribution, and gas composition distribution within the furnace and the heat flux on the water wall and the flow rate and temperature in the water tubes, given formatted data on the boiler dimensions, water wall tube geometry and arrangement, connection state and boundary conditions such as fuel and air flow rates, water flow rate, and pressure. The program consists of a combustion calculation module and a module for calculating flow distribution in the water wall tubes. The combustion calculation module analyzes the gas flow, coal-air reactions, and radiation heat transfer phenomena. The heat flux distribution of the water wall is determined by means of the combustion analysis. The water wall tube flow distribution calculation module accepts as input the heat flux that is output by the combustion analysis and analyzes the changes in flow rate and temperature for each water tube.

COAL COMBUSTION MODEL

The flow rate and temperature distribution within the furnace are obtained by solving the conservation equations for the mass, momentum, and energy of the air and combustion gases. The coal particles are assumed to be accompanied by the gas phase, and so their distribution is determined by solving the transport equation in the same way as for the various gas components. The coal particles comprise water and volatile matter, char, and ash. The reaction rate constants of these components are given as temperature and oxygen concentration functions, and the changes in each component are calculated. The numerical calculations are performed by SIMPLE method (semi-implicit method for pressure-linked equations). In the vicinity of the burner, overlaid grids are employed, because it is capable of setting up a particularly detailed grid and so increases the accuracy of calculations for areas in which there are sharp changes in state.

This program incorporates models for predicting combustion efficiency and the concentrations of gases such as NO_x and CO. Those respective models were developed on the basis of data from fundamental experiments in which the type of coal, SR (stoichiometric ratio) and temperature were varied. This model made it possible to predict NO_x concentration, which had previously been difficult to accomplish. Examples of the calculated results are presented in Fig. 2.

In the two-stage combustion method, NO_x is reduced to N_2 in fuel rich zone. To predict the NO_x

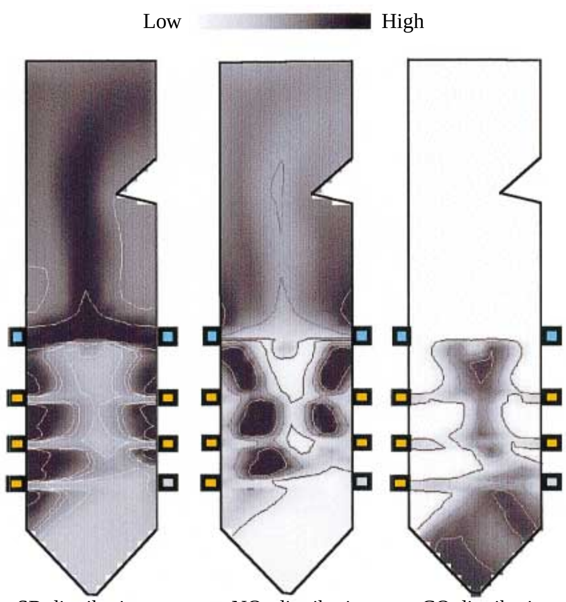


Fig. 2— Examples of Combustion Analysis Within the Furnace.
In the two-stage combustion method, the SR near the burner is precisely controlled so as to control the generation and release of gases that pollute the environment.

concentration, it is necessary to estimate the combustion rate and the gas composition in fuel rich zone. The coal reacts with CO_2 and H_2O to produce CO and H_2. This is called the gasification. Conventionally, in a pulverized coal-fired boiler, the oxidation reaction between char and O_2 is dominant and so the gasification reaction calculation is often omitted. Omitting that calculation creates an error of about 10% in the combustion rate in fuel rich zone. In this program, the accuracy of predicting the combustion rate in fuel rich zone and the gas composition were improved by new models for the oxidation and gasification[1].

Moreover, in the prediction of NO_x, it is necessary to estimate the CH and OH radical concentrations, which are very small components, as well as CO_2, H_2O, CO, H_2 and other high concentration gas components. This program incorporates a model that allows highly accurate calculation of radical concentrations, and so improves the accuracy of NO_x estimations. In the low SR regions that are formed within the furnace, NO_x concentration is decreased by reduction reaction with CH radicals (Fig. 2).

RADIATION HEAT TRANSFER MODEL

For large boilers, the heat transfer from the combustion gases in the furnace to the surrounding water wall is mostly radiation heat transfer. The heat flux distribution on the water wall affects the steam temperature distribution within the water wall tubes, and the heat transfer rate at the water wall determines the furnace exit gas temperature. For that reason, modeling of the radiation heat transfer is important in the furnace analysis.

In radiation heat transfer, the heat of high-temperature gas and particles (radiative media) is propagated in the furnace as electromagnetic waves. That electromagnetic wave is absorbed by the water wall at the boundary of the furnace, which results in the heat transfer.

For the analysis, modeling of the radiative media and that of radiative transfer are required.

A radiative medium is a substance that emits and absorbs electromagnetic waves. In pulverized coal combustion, radiation characteristics of the gas molecules (H_2O, CO_2) and particles (raw coal, char, fly ash, soot) are modeled. For the gas molecules, the “Weighted Sum of Gray Gases,” which is a kind of optical database, is employed. The properties of the solid particles, on the other hand, are given by the Mie scattering theory. The theory involves the particle diameter, wavelength of the electromagnetic wave, and an optical property of the particle material (complex refractive index). Also, although geometrical optics theory and Rayleigh scattering theory are also used, they are respectively approximations of Mie scattering at the upper and lower limits of particle size to reduce the computation time.

For the modeling of radiative transfer, the DT method (a kind of ray-tracing method) is employed.[2] With that method, it is possible to obtain a solution that is quite consistent with the strict solution with a practically small computational load. As an example of that, the results of calculations of radiative transfer in a one-dimensional system (a radiative gas between two flat plates of different temperature) are shown in Fig. 3. The solution obtained by the DT method is the same as the strict solution at various optical thicknesses (degrees of gas opaqueness).

FLOW CALCULATION MODEL IN WATER WALL TUBES

A detailed estimate of the temperature distribution in the water wall is important in optimizing the structure and improving the soundness in the design of the water wall of a pulverized coal-fired boiler furnace.

In the past, the accuracy of temperature estimations has been limited because a coarse mesh is conventionally used when evaluating the temperature

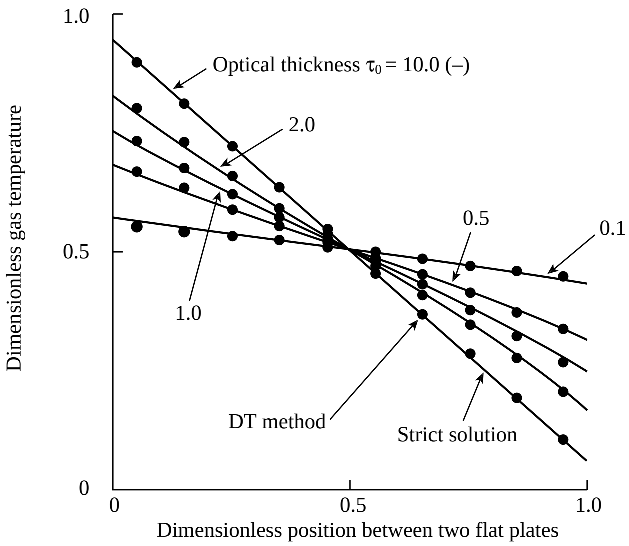


Fig. 3— Comparison of Strict Radiative Transport Solutions and Results of the DT Method.
The DT solutions are nearly the same as the strict solutions for a three dimensional system of complex shape as well as for the basic one-dimensional system shown here.

distribution. Moreover, it was not possible to deal with the changes in the combustion and heat flux distribution that accompany changes in the burner pattern and type of coal, so extra design margins were required.

The water wall of a 1,000-MW class boiler furnace, usually has approximately 2,000 water tubes and approximately 60 headers (flow collectors that feed flow into and out of the water tubes). These water tubes and tube collectors form a complex network of flow paths. Accordingly, to estimate the local temperature distribution, it is necessary to divide this entire flow path network into a mesh to find a solution. We were able to analyze this complex flow path network by applying a heat flow model that is used in the field of nuclear engineering and developing a new algorithm that is suitable for boilers. In this technique, the mass, momentum, and energy conservation equations are solved for an analysis mesh of all of the water tubes and tube collectors. The flow distribution of the water tubes is determined from the pressure loss in each water tube and the conservation of mass in the tube collectors. The water in the flow path network undergoes various phase changes, depending on the operating conditions, and may be a single-phase liquid, two-phase flow, superheated steam, compressed water, super-critical water, and so on. This analytical model can deal with all of these conditions, and steady-state or transient analysis is possible under a broad range of furnace operating conditions.

By integrating this newly developed model of flow in the water wall tubes with the earlier described coal combustion model and radiative heat transfer model, it is possible to understand in detail the thermal-hydraulic characteristics for each individual water tube.

COMPARISON WITH VALUES MEASURED IN AN ACTUAL PLANT

As described above, this program was constructed by combining the physical models that represent the phenomena of each elemental process. To verify the overall computational accuracy, the results of an analysis produced by this program were compared with data measured at an actual plant. The items that were compared were various and included the heat flux distribution, the unburned component in the ash, and the NO_x concentration in the gas. In particular, the values for the furnace exit gas temperature, which indicates the thermal balance in the gas, were shown to be consistent in the range from –23°C to +28°C. These values were calculated for different load conditions and types of coal of multiple plants and compared with the measured value.

A feature of this program is that it is possible to calculate the steam-side model continuously from the combustion model. Here, we describe the results of comparing the furnace heat absorption which represents the steam-side heat balance, and the furnace exit steam temperature.

The computations were performed for furnace heat absorption rate and furnace outlet steam temperature under rising load in a large-capacity, coal-fired, once-

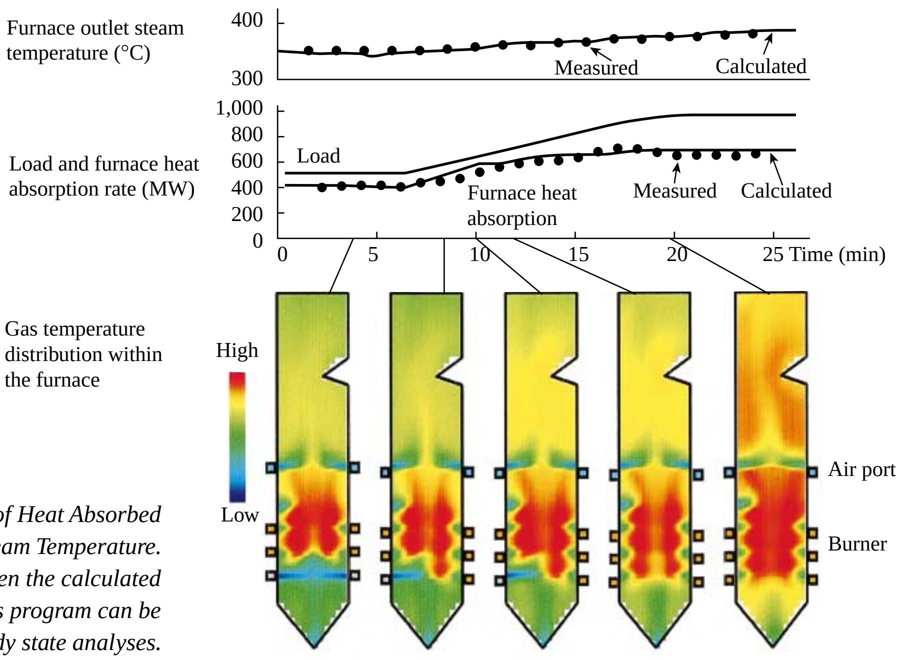


Fig. 4— Comparison of the Amount of Heat Absorbed by the Furnace and Steam Temperature.
There is good agreement between the calculated values and measured values. This program can be applied to both transient and steady state analyses.

through boiler and the results were compared with the measured values. The furnace heat absorption and furnace outlet steam temperature values for the process in which the load increased at 4%/min, the highest rate of increase in actual operation, are shown in Fig. 4. The calculated values are largely in agreement with the measured values, so the changes in the amount of heat absorbed by the furnace and the furnace outlet steam temperature can be predicted.

The above results confirm that this program is capable of calculating both the combustion-gas side and steam-side temperatures with good accuracy. This is the result of using physical models that faithfully represent the phenomena of each elemental process.

CONCLUSIONS

We have briefly described a computer program for analyzing the characteristics of a pulverized coal-fired boiler and validated its effectiveness by comparison with actual measured values.

This program can handle not only the furnace exit gas temperature and the steam temperature in the water wall tubes, which are heat transfer characteristics, but also the generation of small-quantity gas components such as NO_x. Because the models used in this program are based on physical phenomena, the program can be used to predict the general characteristics of boilers, such as NO_x concentration, unburned component, and steam temperature with changes in operating conditions such as load or type of coal.

This program is also used to design the latest plants by predicting plant performance. To further increase the reliability of the analysis program and to broaden its range of applications, we intend to continue with comparisons to the operating conditions of actual plant and with improvement in the program functions.

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