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Project Summary

Evaluation of Utility Boiler Radiant Furnace Residence Time/Temperature Characteristics: Field Tests and Heat Transfer Modeling

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This report describes an investigation of the adequacy of a modeling approach in predicting the thermal environment and flow field of pulverized-coal-fired utility boilers.

Two 420 MW_e coal-fired boilers were evaluated: a single-wall-fired unit and a tangentially fired unit, representing the two commonest boilers in the U.S. Extensive field measurements were conducted on each unit to determine detailed temperature, heat flux, gas species composition, and flow field data for a range of operating conditions.

Separate modeling approaches were used to predict boiler thermal performance and flow characteristics. A three-dimensional zone method of analysis was used to predict local and overall heat transfer, temperature profiles, and fuel burnout. Such predictive tools provide a sophisticated treatment of radiative heat transfer, but are decoupled from the furnace flow field. This input to the heat transfer code was obtained from detailed measurements in reduced scale isothermal physical flow models of the two boilers.

Comparisons between model predictions and the detailed field measurement data have demonstrated the viability of this approach in predicting furnace performance, and in extrapolating limited available data to alternate operating conditions. Overall thermal performance can, in general, be accurately predicted; however, the analysis has shown that the correct quantitative prediction of local temperatures and other properties requires an accurate specification of inhomogeneities in boiler input conditions, in the boiler flow field, and in the local distribution of wall ash deposits.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The injection of dry calcium-based sorbents into the furnace zone of coal-fired utility boilers (referred to as the LIMB process) offers the potential for a cost effective in-situ SO_2 control technology. However, the effectiveness of the process is very strongly dependent on the boiler thermal environment, particularly the temperature/time relationship experienced by the sorbent particles. For example, the ultimate reactivity of the sorbent material is very sensitive to the heating rate and to the peak temperature levels experienced by the particles. Hence, optimum sorbent activation requires injection at the appropriate thermal environment in the boiler. On the other hand, optimum sorbent reactivity must be accompanied by mixing and dispersion of the active sorbent particles in the furnace gases. Sulfation progresses most effectively in the temperature window 800-1200°C and requires residence times on the order of 1 sec. This provides further constraints on the effectiveness of the process. Such considerations indicate that a detailed knowledge of boiler thermal environment and the flow field is necessary for a given boiler application, both for predicting SO_2 removal potential, and in designing an effective sorbent injection system.

In order to generate the necessary boiler information, a purely experimental approach can be taken, where detailed in-furnace measurements of gas temperatures and velocities can be made for each individual coal-fired boiler of interest. However, such an approach requires many traverses to fully characterize the complex three-dimensional temperature and velocity fields typical of most utility boilers. Consequently the necessary measurement programs can be time-consuming and expensive. An alternative approach is to use a methodology based on state-of-the-art analytical or modeling techniques. Such a methodology, if authenticated, could offer a faster, less expensive, and more flexible approach than that provided by purely experimental methods.

This report summarizes an EPA-sponsored research program, the primary objective of which was to investigate the adequacy of a modeling approach in predicting boiler thermal environment and flow field. The program has included:

- Reviewing available furnace thermal prediction procedures and flow models, and selecting a suitable method to evaluate temperatures and flow fields in boilers.
- Field tests at two coal-fired utility boilers (wall-fired and tangentially fired, representing the two commonest boilers in the U.S.) to document thermal environment and flow characteristics.
- Modeling test cases with the selected heat transfer/flow model.
- Comparing model predictions with field data.
- Determining the adequacy and accuracy of such an approach for future predictive evaluations.

Heat Transfer and Flow Modeling Approach

In this study separate modeling approaches have been used to predict boiler thermal performance and flow field. A three-dimensional general boiler thermal analysis code was used to simulate test conditions for which extensive temperature, heat flux, and gas species composition data were obtained at two boilers. This heat transfer code is decoupled from the furnace flow field, but includes a sophisticated treatment of the radiative heat exchange process (mostly responsible for heat exchange in utility boilers) and a fully coupled solution of heat balances in a zonal description of the furnace enclosure. Since the furnace flow field is an input to the heat transfer code, it was obtained from isothermal physical flow modeling for the two boilers. Although there are purely analytical approaches to flow field prediction, many uncertainties, assumptions, and difficulties are associated with these approaches, such that fully mathematical solutions are available only for simple geometries. Consequently, reduced scale physical modeling is now the preferred approach.

The heat transfer model, used to predict the thermal behavior of the two test boilers in this program, was EER's three-dimensional General Boiler Thermal Analysis Code (GBTAC). This is just one of several available codes which are based on the zone method of analysis, and which are finding increasing application in the prediction and design of practical combustion systems. Such heat transfer codes allow predictions of local and overall heat transfer, temperature profiles, and fuel burnout in boiler combustion chambers and industrial furnaces dependent on actual furnace geometry, operating conditions, and fuel and wall deposit characteristics. All major fuel types can be considered. The EER code can also handle heat transfer in radiant superheater sections simultaneously coupled with the lower radiant furnace heat transfer calculations.

The furnace heat transfer model is decoupled from momentum balances. Thus, zonal balances of energy, volatile matter, char particles, and O_2 are based on a prescribed mass flux distribution for calculating convective transport over the volume zone boundaries. Such decoupling is typical of zone models, and allows concentrating the computational effort on an accurate simulation of radiative heat transfer This has been found necessary for reliable thermal performance predictions of large boiler furnaces.

In this present study the distribution of mass fluxes through the zone arrangement of the heat transfer model was obtained through observations and measurements in isothermal physical flow models.

Test Boilers

In this study, two coal-fired boilers (a wall-fired boiler, and a tangentially fired boiler) were evaluated. Each boiler was subjected to an intensive period of measurement, where detailed in-furnace probing was conducted to determine thermal conditions, flow field, and overall performance data as a function of a range of operating conditions. Reduced scale isothermal models were also constructed of each boiler for the experimental determination of the flow field, and for the subsequent specification of inputs for heat-transfer model evaluation.

The wall-fired boiler selected for this program was Duck Creek Unit 1, owned and operated by Central Illinois Light Company (CILCO). This 420 MW_e boiler, near Canton, IL, was built by Riley Stoker Corporation. The general arrangement of the boiler is shown in Figure 1. It is front-wall-fired, with boiler capacity representative of medium size wall-fired utility boilers. The NO_x emissions from this unit were reduced below the limit of 0.7 lb of $NO_x/10^6$ Btu* by retrofitting the original burners with low-NO_x burners. The fuel fired at this unit is a high volatile bituminous coal which contains approximately 4% sulfur, and flue gas desulfurization is achieved by a wet scrubber.

The second boiler was the 420 MW_e tangentially fired Unit 5 of the Conesville Generating Station near Conesville, OH, owned and operated by American Electric Power Corporation. Figure 2 illustrates the overall arrangement of the boiler. This unit is considered representative of medium size tangentially fired boilers.

Heat Transfer Analysis

Detailed flow and heat transfer analyses have been conducted for a wide range of furnace operating conditions for both the Duck Creek and Conesville boilers. In general, the major test cases were chosen to correspond with those selected for the field measurement program in order to provide a basis for direct comparison of measured and predicted results. However, a number of additional cases were also established to evaluate the sensitivity of model predictions to certain model inputs and assumptions. Tables 1 and 2 list the test cases for the Duck Creek and Conesville boilers, respectively. For each of these cases the modeling procedures were used to make predictions for the three-dimensional distributions of temperature, velocity, volatile combustion, unburnt fixed carbon, O_2 concentration, incident and net heat fluxes, and wall surface temperature. These results, compared to measured values, were used to

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* 1 lb/10^6 Btu = 0 43 kg/GJ

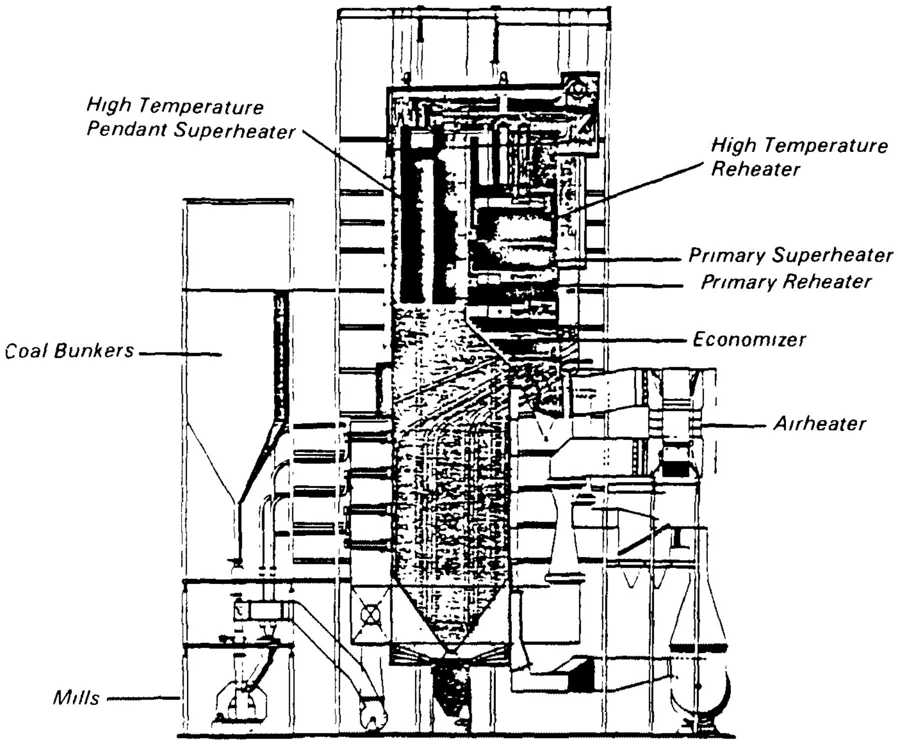


Figure 1 General arrangement of Duck Creek Unit 1 boiler

test the accuracy and sensitivity of the model predictions

Many previous studies for coal-fired boiler furnaces using EER's furnace heat transfer and combustion model have shown that the accuracy of the predictions obtained from this model depends on a prescription of mass flux distribution and on a variety of other model input data. Since one goal of the project was to establish the amount and type of input data necessary to establish reliable time/temperature predictions, the formulation of additional input data received considerable attention in this study. Certain groups of key input data are difficult to specify. One such group relates to the distribution of ash deposits on the furnace heat transfer surface, and the specification of their thermal resistance and emissivity. A second important subset of inputs relates to the distribution of air and fuel flows to individual burners (and hence local stoichiometries), which is particularly important when overfire or underfire air is employed for NO_x emission control.

An example of the importance of correct specification of the distribution of input flows can be found in the comparison between analyses for Cases 1 and 3 for the Duck Creek boiler. Case 1 represents predictions based on minimal information of actual boiler operation, while Case 3 represents a more realistic situation where input flows and stoichiometries have been modified based on a detailed analysis of field data. Predicted temperature distributions for these cases are presented in Figure 3. The dramatic effect on the temperature field is clearly evident, particularly the strong temperature stratification caused by the underfire air jets originating in the lower furnace. Predicted Case 3 profiles of local gas temperatures and actual field measurements are compared in Figure 4.

Considering the difficulties inherent to temperature measurements in full scale pulverized-fuel-fired boiler furnaces and the many unavoidable model assumptions and simplifications, the overall agreement between measured and predicted profiles of the gas temperatures is satisfactory. Maximum local differences between calculated and predicted values occur at elevations in the upper furnace and very close to the side walls, where steep temperature gradients are encountered. Most of the local differences between predicted and experimental values originate from asymmetrical effects of actual furnace operation which are not covered by the model since symmetry between west and east furnace half was presumed. The asymmetrical effects caused by the non-uniform secondary air damper settings (which were changed almost daily) are especially noticeable in measured near-rear-wall temperature profiles at burner level elevations.

Predicted and measured O_2-concentration profiles are in general directly inverse to corresponding temperature profiles; i.e., a low oxygen concentration predicted or measured locally is associated with a local high temperature value and vice versa. This leads to the conclusion that the temperature profiles in the Duck Creek furnace are not governed by furnace heat transfer alone but to a considerable degree by mixing of underfire air with the flame zone products, and also by interburner flow mixing due to the inhomogeneous firing pattern. Considering that the furnace model used for the current anslysis is primarily a (radiative) heat transfer model, the agreement between measured and predicted O_2-concentration profiles is again reasonable. It is believed that a better agreement can only be achieved by use of a finer computational grid and by more exact modeling of main flow development and turbulent exchange using expensive fluid dynamics models.

Similar comparisons between predicted and measured results were also obtained for the Conesville boiler, where a strong impact of the assumed local distribution of stoichiometries on flame zone temperatures and O_2 profiles was observed. Figure 5 compares the profiles predicted without and with the assumption of inhomogeneous air distribution to the corners of each burner level. In the case of non-uniform corner stoichiometries, the air flow from the rear wall corners was reduced resulting in an increase of near-rear-wall gas temperatures of up to 100 K and more. The effect is particularly strong for low load at elevation 18.1 m. Compared to the measured data, the change to non-homogeneous corner stoichiometry improved the predictions at some locations, and at other locations the discrepancies increased. However, the corner air distribution assumed in Cases 3 and 5 was somewhat arbitrary. Due to such operational uncertainties, even the most sophisticated computer model will probably not yield better agreement for local profiles than that obtained in the current study.

For the Conesville boiler study, discrepancies of the measured and predicted

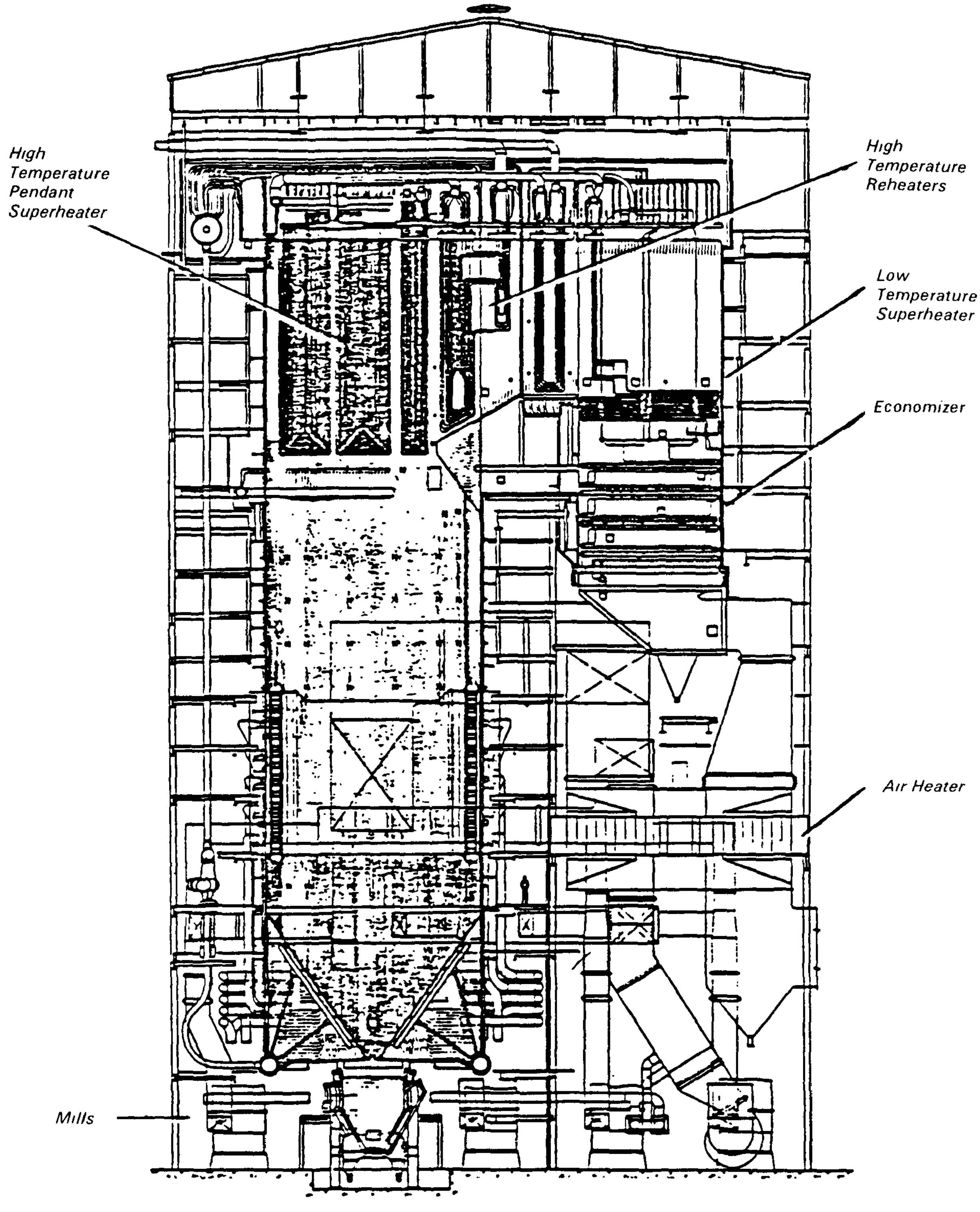


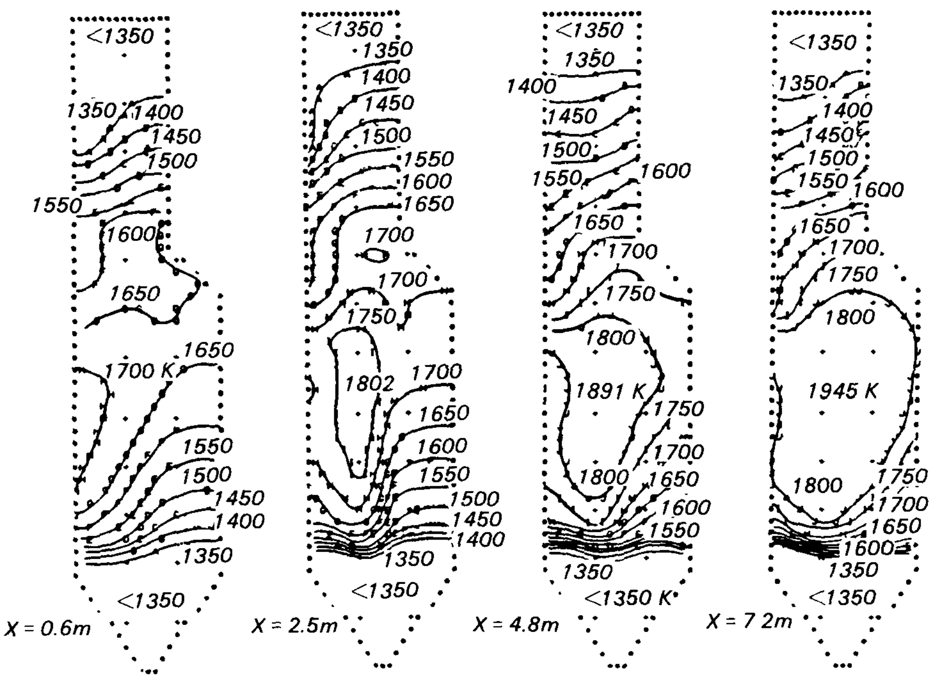
Figure 2. General arrangement of Conesville Unit 5 boiler

Table 1. *Case Description of Duck Creek Heat Transfer Analysis*

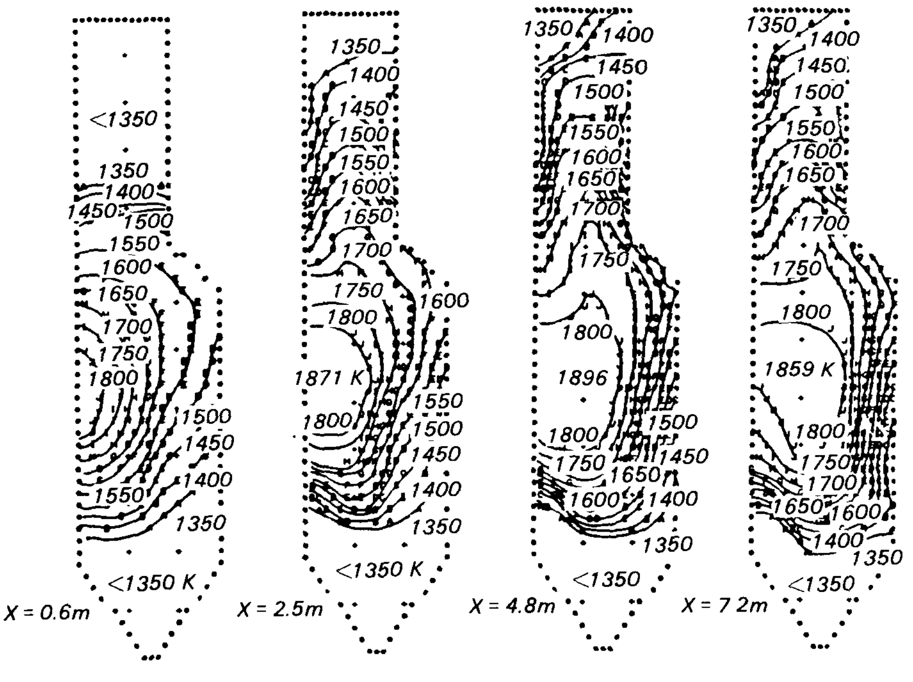
Case No.	Load	Test Condition	Mills in Operation	Excess Air	UFA	Burner Level Stoichiometry	Flow Field Prescription	Superheater Deposits	Water Cooled Wing Walls
	%	—	—	%	%	—	—	—	—
1	100	N/A	A,B,C	18.4	25	Uniform	Initial Corrected for UFA	Medium	No
2	100	1,5	A,B,C	18.4	25	Non-Uniform	Corrected from Case 1 (Flow Field I)	Medium	No
3	100	1,5	A,B,C	18.4	25	Non-Uniform	Corrected from Case 2 (Flow Field II)	Medium	No
4	100	1,5	A,B,C,	18.4	25	Non-Uniform	Corrected from Case 3	Heavy	No
5	100	N/A	A,B,C	18.4	25	Non-Uniform	Corrected from Case 2	Medium	Yes
6	60	Preliminary	A,B	22.8	0	Uniform	Corrected from Initial Flow, Ash Hopper Recirc.	Light	No
7	60	4	A,C	20.1	0	Non-Uniform	Corrected from Initial Flow, Ash Hopper Recirc.	Medium	No
8	60	4	A,C	20.1	0	Non-Uniform, Increased Flame Length	Corrected from Case 7	Heavy	No
9	60	4	A,C	20.1	25	Non-Uniform Increased Flame Length	Corrected from Case 8	Heavy	No

Table 2. *Case Description of Conesville Heat Transfer Analysis*

Case No.	Load %	Test Condition	Burner Level in Operation	Excess Air, %	OFA %	Burner Level Stoichiometry	Corner Stoichiometry	Flow Field Prescription	Furnace Wall Deposit Pattern
1	100	N/A	B,C,D,E	18.8	8.3	Uniform	Uniform	Initial	Uniform,
2	100	1	B,C,D,E	21.2	18.9	Non-Uniform	Uniform	Upgraded; Corrected for Burner Level Stoichiometry	Non-Uniform, Pattern I
3	100	1	B,C,D,E	21.2	18.9	Non-Uniform	Non-Uniform	Corrected from Case 2 for Corner Burner Stoichiometry	Non-Uniform, Pattern II
4	45	5	C,D	47.3	59.4	Non-Uniform	Uniform	Corrected from Case 2	Non-Uniform, Pattern I
5	45	5	C,D	47.3	44.2	Non-Uniform	Non-Uniform	Corrected from Case 2	Non-Uniform, Pattern II
6	45	5	C,D	47.3	59.4	Non-Uniform	Uniform	Set-up from Scratch	Non-Uniform, Pattern I
7	100	3	B,C,D,E	25.0	18.9	Non-Uniform	Non-Uniform	Corrected from Case 3	Non-Uniform, Pattern II



(a) Case 1: Gas temperatures (K) 100% load, uniform burner level load and stoichiometry, 25% UFA.



(b) Case 3: Gas temperatures (K) 100% load, non-uniform burner level load and stoichiometry, flow field II, 25% UFA.

Figure 3. *Comparison of predicted temperature distributions for Cases 1 and 3 for the Duck Creek boiler.*

temperature profiles in the upper furnace are believed to be mainly due to differences in the velocity profiles. The influence of flow field is demonstrated in Figure 6. This figure compares temperature profiles predicted for 45% load at the radiant superheater inlet plane using two different flow field prescriptions: the standard presumed one (Case 4) and an upgraded one based on field measurements (Case 5). All other model inputs were kept constant. The upgraded flow field clearly yields a closer agreement with measured temperature profiles, and illustrates the strong influence of this parameter.

In addition to the flow field, the thickness and conductivity (thermal resistance) of ash deposits on boiler walls and other heat transfer surfaces, as input to the model, can have a large impact on heat transfer predictions. Usually these are specified based on observation of the distribution of deposit thickness and surface texture in the boiler, with appropriate model parameters assigned based on experience and standard numerical values. Sensitivity studies based on such assumptions have been conducted and show clearly that, if local properties (e.g., temperature and heat flux) are to be correctly predicted, local variations in deposit thermal resistance must also be considered. Figure 7 shows that an increase of the conductivity to thickness ratio of the ash deposits at the superheater surface zone layers $k = 14$ and 15 from 0.160 to 0.400 kW/m^{2}K resulted in considerable improvement of the incident heat flux distribution predicted in the upper furnace for both load conditions.

In addition to the prediction of local properties, averaged properties at various boiler elevations are also of interest in the sorbent injection problem. Of particular interest is the temperature/time profile through the sulfation temperature window, since this is a main parameter that impacts SO_2 removal. As shown in Figure 8, the optimum model predictions represent quite well the measured averaged temperature distributions through the boilers. Such agreement indicates also that overall furnace performance (e.g., mean exit temperature, furnace heat absorption) can be predicted accurately if model inputs are correctly specified. Corresponding mean time/temperature profiles predicted for Duck Creek full load Cases 1, 2, and 3 are presented in Figure 9, and show the impact of the various flow and stoichiometry distribution assumptions. In spite of the different model

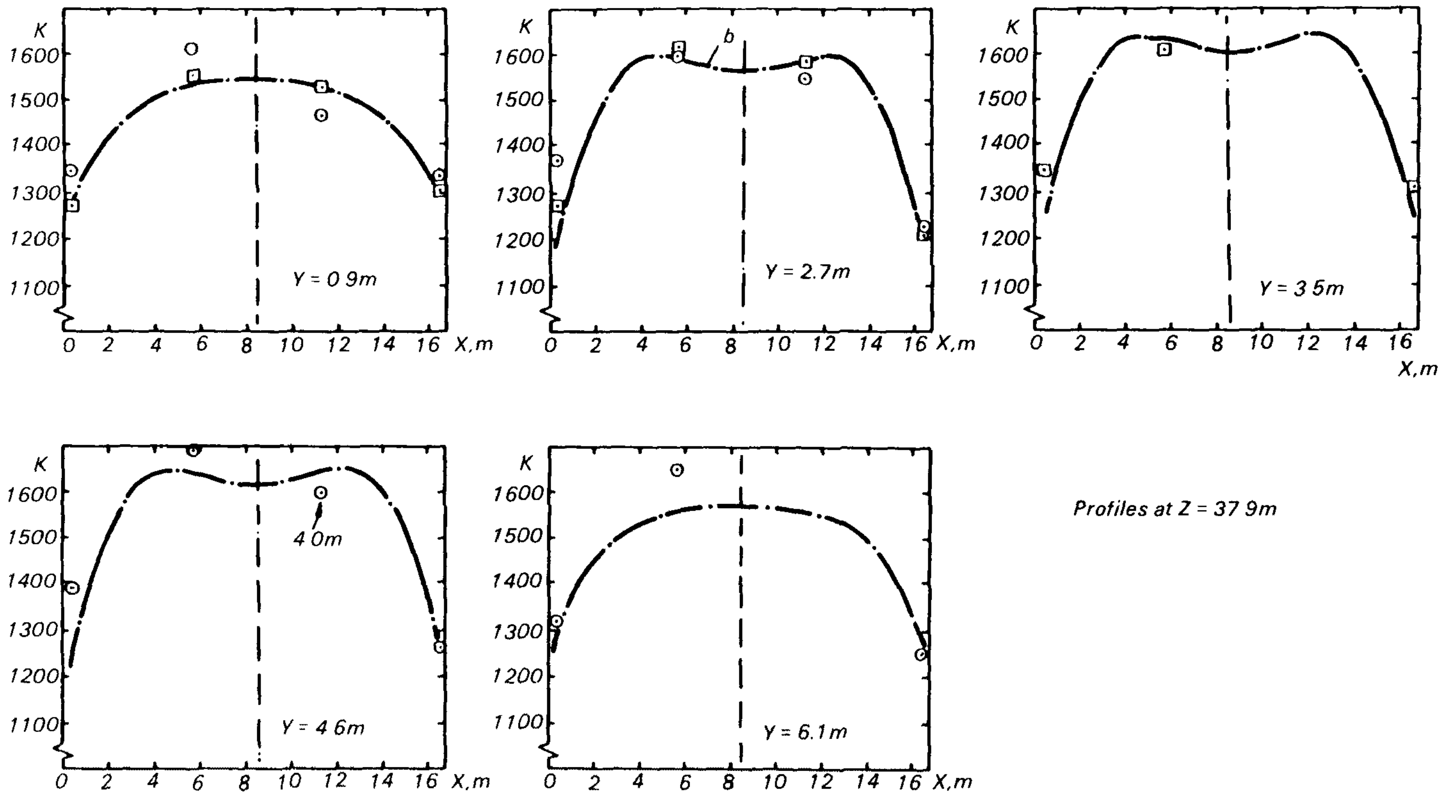


Figure 4. *Comparison of measured and predicted gas temperature profiles at 100% load. (⊡ meas Phase I. ⊙ meas. Phase II, ●—● pred. Case 3)*

input conditions utilized in the three cases and in spite of considerably different profiles predicted for furnace hopper and flame zones, lower furnace exit temperatures (calculated at platen superheater inlet plane) differ only by 35 K. The most realistic model predictions are probably achieved in Case 3. In this case, an average quench rate of 394 K/s is calculated in the upper furnace The other quench rates predicted are 331 K/s for Case 2, and 341 K/s for Case 1.

Conclusion

Detailed heat transfer analyses for a wall-fired boiler and a tangentially fired boiler have been conducted for a range of furnace operating conditions using a state-of-the-art heat transfer model. Predictions have been compared with corresponding measurement data obtained in extensive field trials on the two test boilers. In general, the study has shown that good agreement between predicted and measured overall thermal performance parameters (furnace exit temperature, peak radiative heat flux, carbon burnout, etc.) can be achieved if the fuel and air flows into the furnace, and the insulating effect of wall deposits are properly described.

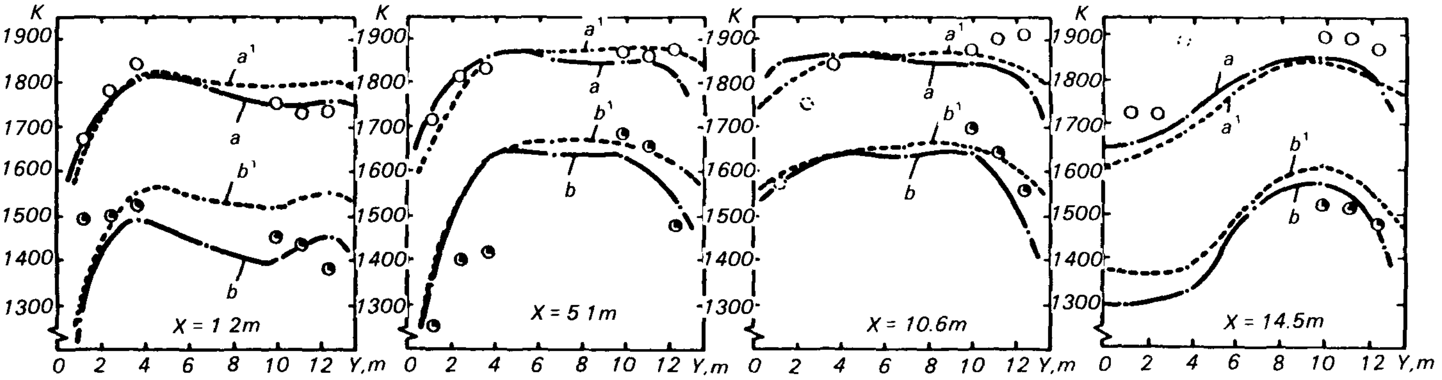
Quantitatively correct predictions of profiles of local temperatures and other furnace variables have, however, proven to be more difficult to achieve. The analyses have shown that a reasonable agreement with measured data can be obtained only if the inhomogeneities in the input conditions are correctly prescribed, and the flow field incorporated into the heat transfer model is a good representation of the flow field in the actual boiler. This appears to be particularly true when the boiler furnace is operated under staged combustion conditions, and strong inhomogeneities in the distribution of stoichiometry result. The prediction of local properties is also affected by the ability to correctly describe the local distribution and properties of wall ash deposits, although this is less critical than the flow field specification.

Due to the sensitivity of absolute model predictions to accurate prescription of operating conditions and model parameters, some model verifications are always required especially when the model is used to support actual design of sorbent injection systems for existing boilers. The three methods of model verification are:

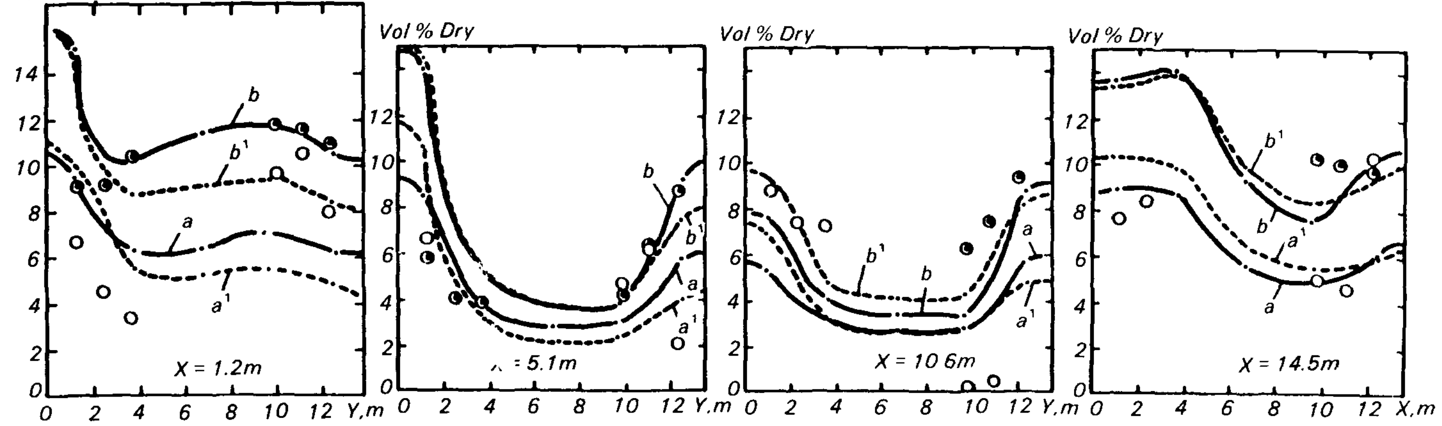
- Comparison with design performance based on manufacturer performance calculations.
- Comparison with actual overall performance data, which requires a short field test.
- Detailed performance comparison including comparison with extensive temperature, concentration profile, heat flux, and velocity measurements.

The comparison of model predictions with design performance is only recommended if no other boiler performance data are available. The most desirable and most efficient approach to model verification is by using a combination of control room data and results of an abbreviated field test. Detailed in-furnace measurements are only necessary in exceptional cases, such as boilers with operational problems. The high expense of the detailed measurements must be weighed against their value to model verification.

Some of the weaknesses of the current model can be eliminated, and the accuracy of absolute performance predic-



Gas Tedmperature (K) Profiles at Z = 26.2m



O_2 Concentration (Vol %, Dry) Profiles at Z = 26 2m

Figure 5. *Impact of non-uniform corner stoichiometry on gas temperature and O_2 profiles predicted for 100 and 45% load (100% load. ○ meas., ⁘ uncertain data pt., a •—• pred Case 2, uniform corner stoichiometry, a¹ •---• pred. Case 3, non-uniform corner stoichiometry; 45% load: ◑ meas., b -·- pred. Case 4, uniform corner stoichiometry, b¹ ..... pred Case 5, mon-uniform corner stoichiometry.*

tions can still be increased. A particular area where improvement can be obtained for coal-fired boilers is more accurate characterization of thermal properties of fly ash and ash deposits, including physical structure, optical properties, wave length, and temperature. This is also important for the LIMB process since sorbent injection can affect these properties. Similarly, the furnace flow prescription could be replaced by advanced fluid dynamics calculations which include prediction of turbulent exchange and the effects of buoyancy (totally neglected in the current study). An increase in accuracy of local temperature profile predictions of roughly 20-40 K is expected from such a modification. A fluid dynamics model does not make physical flow modeling unnecessary since physical models are very useful for validating numerical flow models under isothermal conditions.

In spite of the limitations of the current model, with respect to absolute accurate performance predictions, the present model applications carried out for two boiler furnaces have undoubtedly shown its usefulness for analysis of furnace performance and its potential for optimization of the LIMB process. The major advantage of the model employed is also its ability to extrapolate limited measurement and performance data from baseline conditions to a variety of other operating conditions.

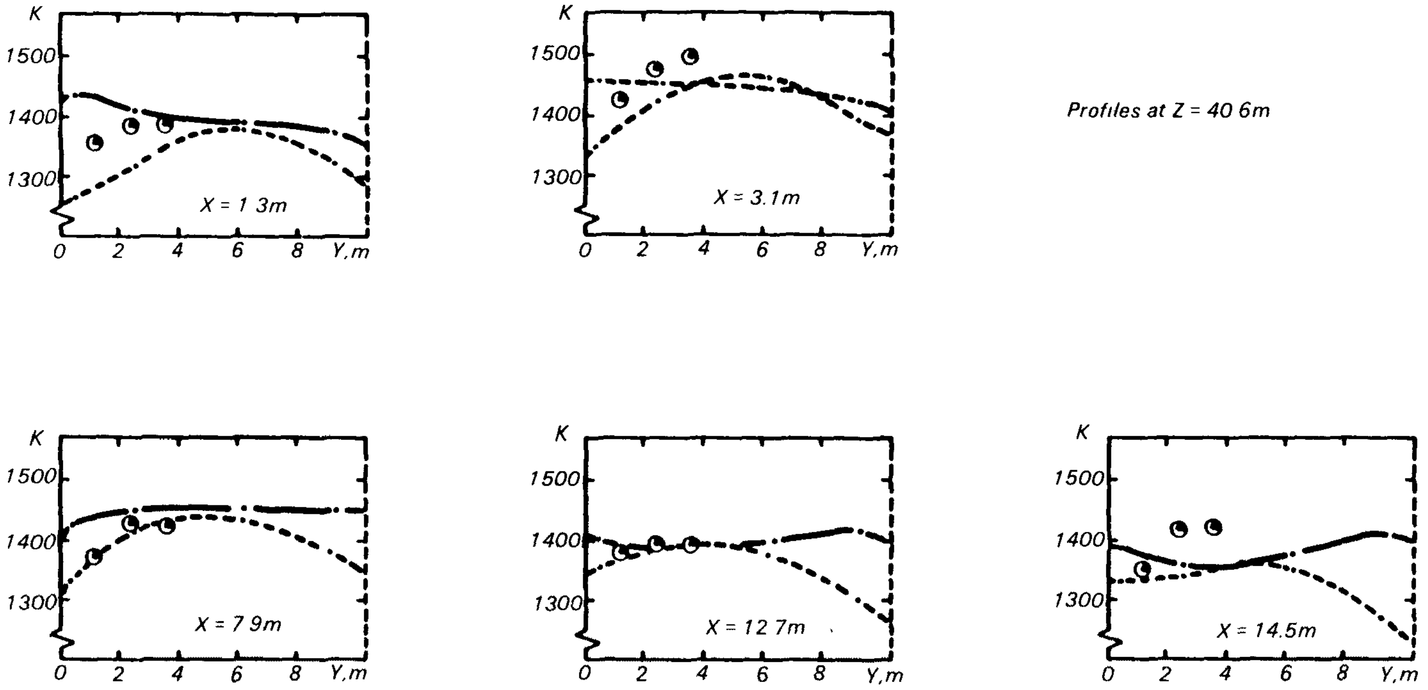
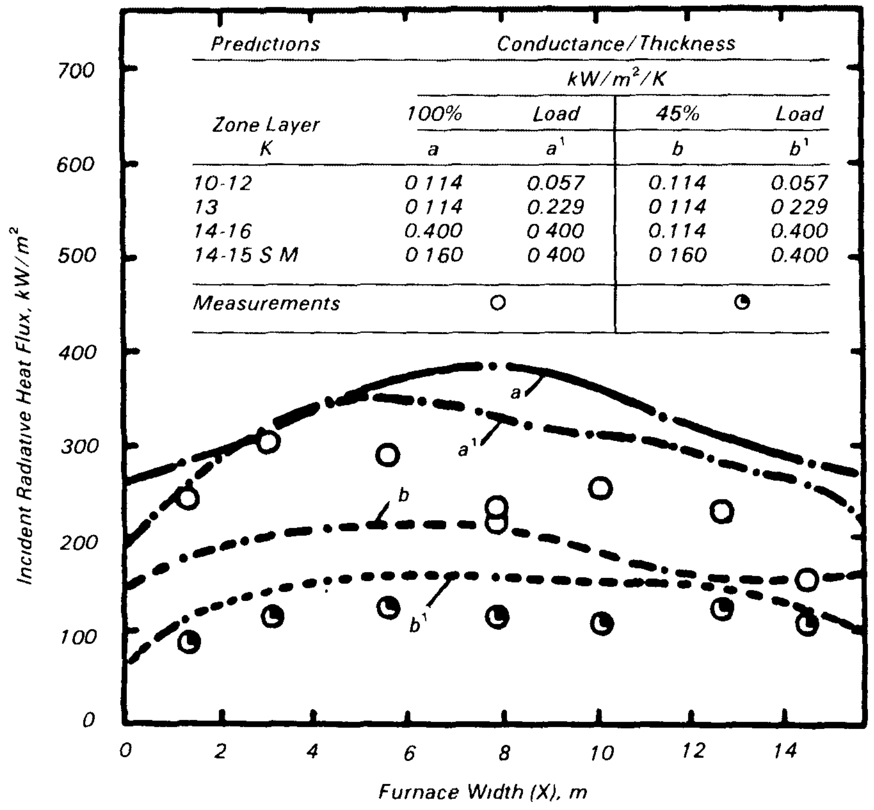
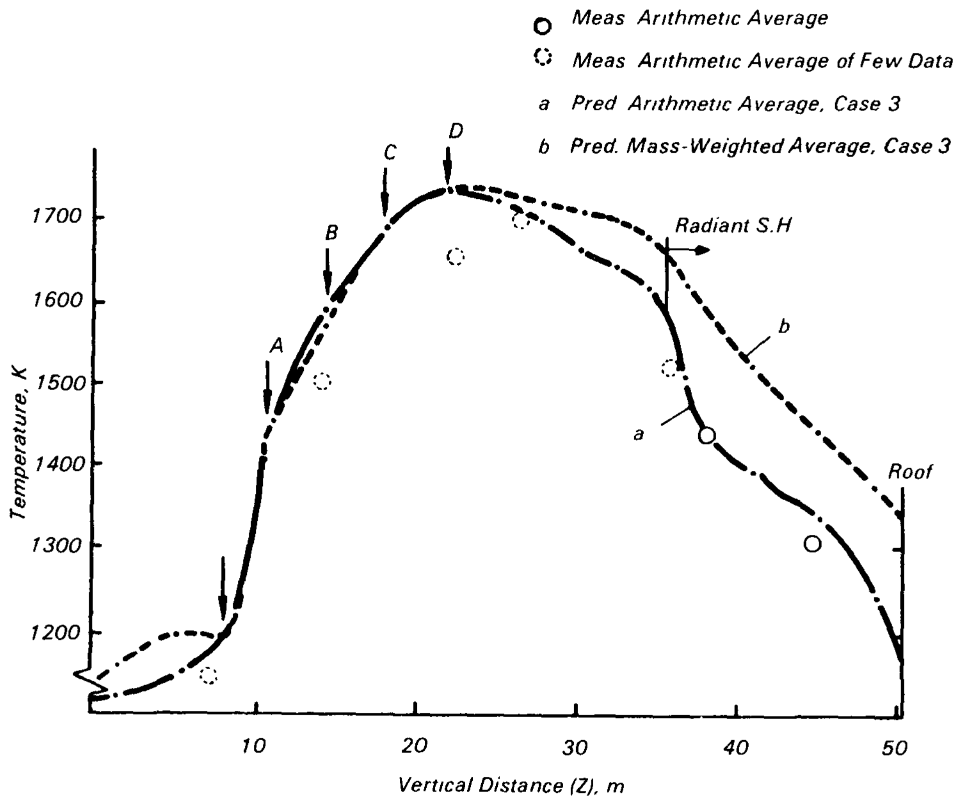


Figure 6. Impact of flow distribution in upper furnace (elevation Z = 40 6m) on temperature profiles predicted for 45% load (◔ meas , •—• pred Case 4, original flow field
•---• pred Case 6, modified flow field)

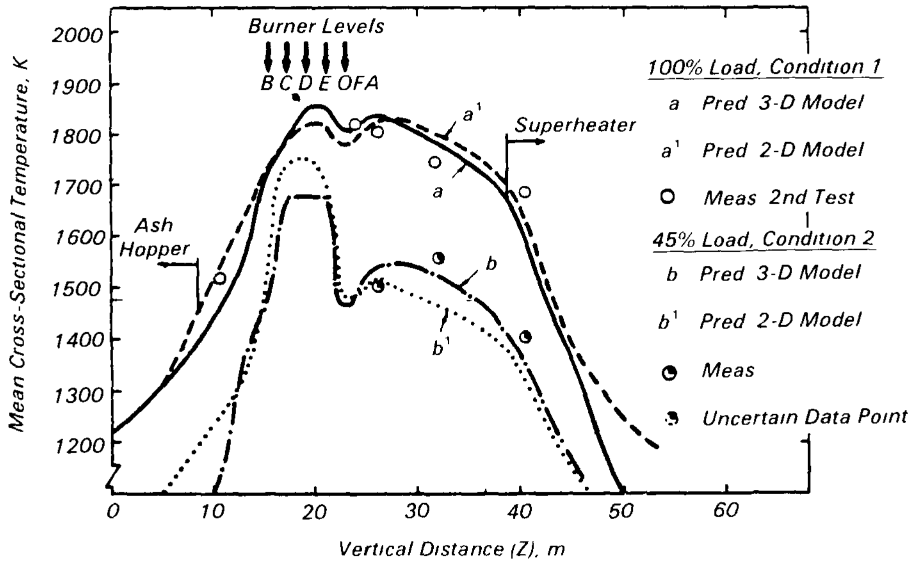


Predictions	Conductance/Thickness			
	kW/m²/K			
Zone Layer	100%	Load	45%	Load
K	a	a¹	b	b¹
10-12	0 114	0.057	0.114	0.057
13	0 114	0.229	0 114	0 229
14-16	0.400	0 400	0.114	0.400
14-15 S M	0 160	0 400	0 160	0.400
Measurements	○		◔	

Figure 7. Impact of deposits in upper furnace on radiative heat fluxes incident on front wall at elevation Z = 40 6m



(a) Duck Creek, 100% Load and Flow Field II



(b) Conesville

Figure 8. *Mean temperature profiles along the furnace predicted for the Duck Creek and Conesville boilers and comparison with measurements*

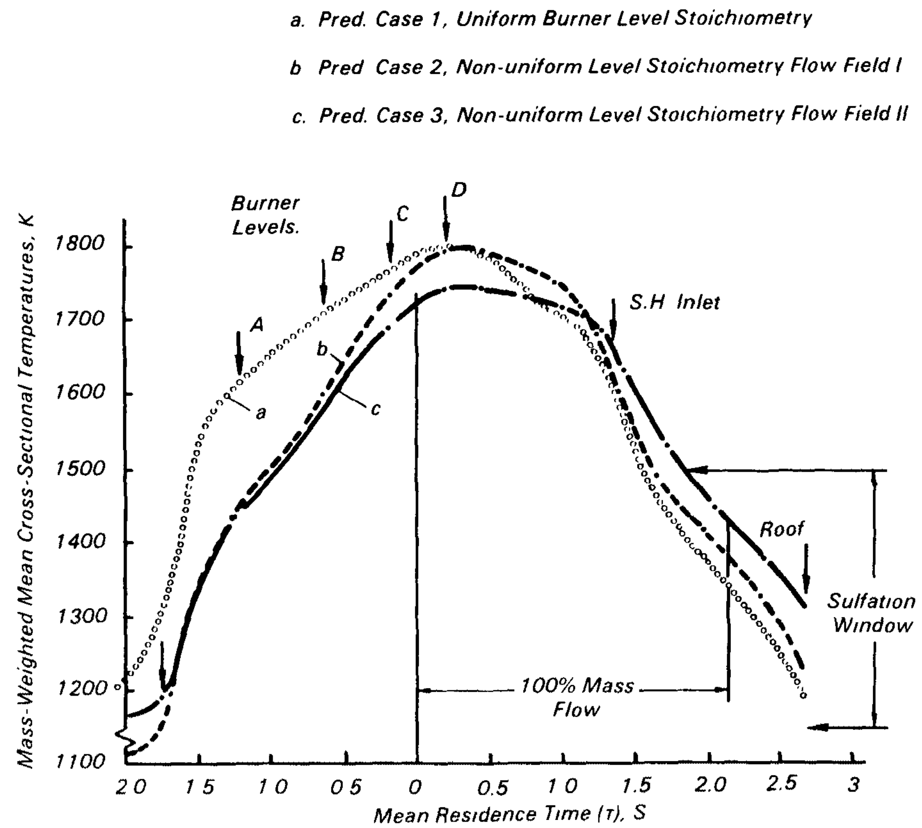


Figure 9. Dependence of mean time/temperature profiles predicted for 100% load on burner level stoichiometry and flow field assumption (Duck Creek).

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The complete report entitled "Evaluation of Utility Boiler Radiant Furnace Residence Time/Temperature Characteristics: Field Tests and Heat Transfer Modeling," (Order No. PB 87-213 112/AS; Cost: $36.95, subject to change) will be available only from:

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