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SPECTRAL RADIATIVE HEAT TRANSFER IN COAL FURNACES USING A HYBRID TECHNIQUE

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ABSTRACT

A hybrid technique has been developed to solve three-dimensional spectral radiation transport equations for absorbing, emitting and anisotropically scattering media. An optimal mix of computational speed and accuracy is obtained by combining the discrete ordinate method (S_4), modified differential approximation (MDA) and P_1 approximation for use in different range of optical thicknesses. The technique is used in conjunction with a char burnout model and spectroscopic data for H_2O , CO_2 , CO , char, soot and ash to determine the influence of ash composition, ash content and coal preparation on furnace heat absorption.

NOMENCLATURE

a_1	anisotropic scattering coefficient	G	incident radiation
I	intensity	q	heat flux
$\hat{s}$	beam direction	β	extinction coefficient
ϵ	emissivity	ω	scattering albedo
Ω	solid angle	ϕ	scattering phase function

Subscripts

b	black body	m	medium-originated radiation
s	surface-originated radiation	w	wall

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1. INTRODUCTION

Thermal radiation is the principle mode of heat transfer in industrial and utility furnaces burning pulverized coal fuel. The radiative transfer is due to both band emission from CO_2 and H_2O and continuous emission from the various types of particles (coal, char, soot and ash) which occur in the flame. The relative contribution of gaseous molecules and combustion particles to radiative heat transfer has been a source of controversy in literature [1,2,3]. The issue is important because differences in heat transfer characteristics of different coals are mostly associated with the different types of particles that are generated during combustion. There are at least three aspects to this issue: 1) radiation transport by combustion particles suspended in the gas, 2) reflectance and transmittance of layer formed by deposition of ash particles on furnace walls, and 3) insulating behavior of ash deposits. This paper is concerned primarily with the first aspect although the other two do enter through boundary conditions. It emphasizes the method of solving radiation transport equation and its application to coal furnaces. The subject of radiation properties of coal flames (i.e., absorption and scattering coefficients) has been addressed in a companion paper [4].

In a recent paper, a modified differential approximation (MDA) for solving the radiation transport equation (RTE) was described [5]. MDA was shown to be sufficiently accurate for all optical thicknesses, but computationally slow in the optically thin and thick limits. This paper presents an advanced hybrid technique which improves the computational speed without incurring loss in solution accuracy.

With respect to the application of model to coal furnaces, the following are the principal objectives.

a) Establish the need of conducting heat transfer calculations on a spectral basis.

b) Resolve the relative contributions of char, soot and ash to overall furnace heat absorption.

c) Determine the sensitivity of heat transfer to particle size distributions (i.e., coal grind/micronization), ash content (i.e., coal cleaning/beneficiation), moisture in coal (i.e., coal-water slurry), and ash buildup on furnace walls.

2. RADIATION HEAT TRANSFER

For a three-dimensional absorbing, emitting and scattering rectangular enclosure the radiation transport equation (RTE) is

$$\nabla \cdot (\hat{s}I) + \beta I = (1 - \omega)\beta I_b + \frac{\omega\beta}{4\pi} \int_{4\pi} I(\vec{r}, \hat{s}') \phi(\hat{s}, \hat{s}') d\Omega' \quad (1)$$

where I is the spectral radiation intensity in the beam direction $\hat{s}$, β and ω are respectively the spectral extinction coefficient and scattering albedo, I_b is the Planck function, ϕ is the scattering phase function and Ω denotes the solid angle. The boundary conditions for diffusely reflecting walls are

$$I(\vec{r}, \hat{s}) = \epsilon I_b + \frac{(1 - \epsilon)}{\pi} \int_{\hat{n} \cdot \hat{s} < 0} |\hat{n} \cdot \hat{s}| I(\vec{r}, \hat{s}') d\Omega'. \quad (2)$$

Three of the many methods of solving RTE are the differential approximation (P_1),

modified differential approximation (MDA), and the discrete ordinate method (S_4). Of the three methods, P_1 approximation is computationally the fastest but is accurate only in the optically thick limit. MDA is accurate for all β but has shown slow convergence in the optically thin and thick limits. S_4 is also accurate for all β but is computationally the slowest particularly for large β . We have developed a hybrid scheme within which P_1 approximation is used for $\beta > \beta_{\max}$, MDA for $\beta_{\min} < \beta < \beta_{\max}$ and S_4 for $\beta < \beta_{\min}$. Typically, $\beta_{\min}$ and $\beta_{\max}$ are respectively of the order of 0.05 m^{-1} and 2.0 m^{-1} . Although not specifically required, the scattering phase function is assumed to be linearly anisotropic of the form,

$$\phi(\hat{s}, \hat{s}') = 1 + a_1(\hat{s} \cdot \hat{s}') \quad (3)$$

3. P_1 APPROXIMATION

Governing equations for P_1 approximation may be derived by expanding the radiation intensity in terms of a truncated series of spherical harmonic functions or by employing the lowest order moment method [6]. For a linearly anisotropic phase function and diffusely reflecting walls, the method reduces to determining the incident radiation G from

$$\nabla \cdot \left(\frac{1}{\beta_1} \nabla G \right) - 3(1 - \omega)\beta G = -12\pi(1 - \omega)\beta I_b \quad (4)$$

subject to wall boundary conditions

$$-\frac{\gamma}{3\beta_1} \hat{n} \cdot \nabla G + G = 4\pi I_{bw} \quad (5)$$

where

$$\beta_1 = \beta(1 - \omega_1) \quad (6)$$

$$\omega_1 = a_1 \omega / 3, \text{ and} \quad (7)$$

$$\gamma = 2/3(2/\epsilon - 1) . \quad (8)$$

Equation (4) is solved numerically by using a cell-centered finite difference technique.

4. MODIFIED DIFFERENTIAL APPROXIMATION

Following Modest [7], the radiation intensity I is decomposed into two parts: one, I_s , that may be traced to emission from the enclosure walls, and the second, I_m , that may be traced to emission from the medium. The two components of intensity are governed by the following equations.

$$\nabla \cdot [\hat{s} I_s(\vec{r}, \hat{s})] + \beta I_s(\vec{r}, \hat{s}) = 0 \quad (9)$$

$$\nabla \cdot [\hat{s} I_m(\vec{r}, \hat{s})] + \beta I_m(\vec{r}, \hat{s}) = (1 - \omega) \beta I_b + \frac{\omega \beta}{4\pi} \int_{4\pi} I(\vec{r}, \hat{s}') \phi(\hat{s}, \hat{s}') d\Omega' \quad (10)$$

I_s field, given by equation (9), accounts for radiation emitted by the furnace walls after attenuation by medium absorption and scattering, and for wall reflection. It is solved by the discrete ordinate method (S_4) subject to the following wall boundary condition [5].

$$I_s(\vec{r}, \hat{s}) = \epsilon I_b(\vec{r}) + \frac{(1-\epsilon)}{\pi} \int_{\hat{n} \cdot \hat{s} < 0} |\hat{n} \cdot \hat{s}| I_s(\vec{r}, \hat{s}') d\Omega' \quad (11)$$

Following Modest [7], whereas I_s with its origin from the radiation emitted by the wall has highly irregular angular distribution, I_m with its origin linked to medium emission is expected to be near isotropic. Thus, equation (10) describing I_m can be simplified by applying the P_1 approximation. For a linearly

anisotropic phase function, the following equation for incident radiation G_m may be derived:

$$\nabla \cdot \frac{1}{\beta_1} \nabla G_m - 3(1 - \omega)\beta G_m = -12\pi(1 - \omega)\beta I_b - 3\omega\beta \left[1 + \frac{a_1}{3(1 - \omega_1)}\right] G_s \quad (12)$$

For a diffusely reflecting surface, G_m admits Marshak's boundary condition for a cold surface.

$$-\frac{\gamma}{3\beta_1} \hat{n} \cdot \nabla G_m + G_m = -\frac{\gamma\omega_1}{1 - \omega_1} \vec{q}_s \cdot \hat{n} \quad (13)$$

Equation (12) is solved numerically for G_m by using a cell-centered finite difference technique [5]. As pointed out by Modest, MDA reduces to the correct limit for optically-thin as well as optically-thick mediums. In the thin limit, the medium emission related contribution to heat transfer becomes vanishingly small. In the thick limit, the MDA solution converges to the P_1 approximation.

5. DISCRETE ORDINATE METHOD

In the S_4 method, RTE is solved for twenty-four ordinate directions and the integrals are replaced by the quadrature summed over the ordinate directions [8]. For a discrete direction Ω_ℓ defined by directional cosines μ_ℓ , ξ_ℓ , and η_ℓ , RTE is written as:

$$\mu_\ell \frac{\partial I^\ell}{\partial x} + \xi_\ell \frac{\partial I^\ell}{\partial y} + \eta_\ell \frac{\partial I^\ell}{\partial z} + \beta I^\ell = (1 - \omega)\beta I_b + \frac{\omega\beta}{4\pi} S_\ell \quad (14)$$

where S_ℓ is the source term for in-scattered radiation.

$$S_\ell = \sum_{\ell'=1}^{N'_\ell} w_{\ell'} \phi_{\ell\ell'} I^{\ell'} \quad (15)$$

$$w_{\ell'} = \pi/4 \quad (16)$$

The finite-difference form of S_4 solution is developed by integrating RTE over

a control volume. For positive directional cosines,

$$I_p^\ell = \frac{\mu_\ell A I_i^\ell + \xi_\ell B I_j^\ell + \eta_\ell C I_k^\ell + \alpha[(1 - \omega)\beta I_b + S_\ell]V_p}{\mu_\ell A + \xi_\ell B + \eta_\ell C + \alpha\beta V_p} \quad (17)$$

where A, B and C are cell face areas, V_p is the cell volume, I_i , I_j and I_k are intensity at cell faces, and α is an interpolation parameter for linearly relating the intensity at cell center (I_p) to face intensities. The overall solution is developed by visiting the finite-difference grid in the direction of the beam. More details of the solution procedure are given in Carlson and Lathrop [9].

6. FURNACE MODEL

The foregoing hybrid method of solving RTE has been incorporated into a computer code FURN3D [10]. Other elements of the computer code include a heat balance model which also determines char burnout kinetics and traces the evolution of char particle size distribution. Convective heat transfer is calculated on the basis of a specified heat transfer coefficient. A separate report describes the formalism for calculating spectral extinction coefficient and scattering albedo of the cloud containing CO_2 , H_2O , CO , char, soot and ash [4]. Briefly, the spectral absorption coefficients of participating gases are estimated from a band model. Mie theory for homogeneous spherical particles is invoked for determining radiation cross-sections of combustion particles. A dispersion relation, derived from experimental data on efficiency factors, is employed for estimating optical constants of char. Complex refractive indices of soot are approximated by an oscillator model formulated for soot produced from hydrocarbon fuels. Experimental data and correlations of Goodwin [2] are used to estimate optical constants of ash in terms of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO and MgO composition.

Particle size distributions are represented in terms of histograms containing forty size bins. Detailed spectral calculations are conducted by dividing the infrared spectrum into thirty-seven wavebands. RTE is solved for each waveband and spectral integration performed to obtain total divergence of radiation heat flux as a source term to the heat balance equations.

7. MODEL VALIDATION

The main models comprising FURN3D have been compared with experimental data, where available, and with other analytical formulations. The hybrid scheme of solving RTE has been compared for speed and accuracy with P_1 , P_3 , S_4 , S_6 , S_8 and zone-method solutions of other investigators [5]. The formalism for determining radiation properties of products of coal combustion has been calibrated against wide band models and the experimental data for char, soot and ash [4]. Butler and Webb [11] have reported measurements of local gas temperatures and radiation heat flux in an 80 MWe corner-fired coal boiler. We have analyzed the 7.5 m x 7.7 m x 25 m furnace using a 15 x 15 x 51 grid and the reported proximate and ultimate analyses of coal and coal/ash size distributions. Figure 1 depicts the spectral variations in the optical constants determined from the reported SiO_2 , Al_2O_3 , FeO , CaO and MgO contents of ash. Figure 2 exhibits the absorption and scattering cross-sections of the combustion gas in the hopper zone, flame zone and the heat absorption zones of the furnace. Figures 3 and 4 compare the computed temperature and heat flux profiles against the averaged data. The comparison is considered favorable considering the difficulties associated with making measurements in field tests on industrial-size boilers and the apparent inconsistencies in data.

8. FURNACE HEAT TRANSFER

A number of parametric calculations have been performed on a 915 MWt (net heat input exclusive of sensible heat in combustion air), 12.7 m x 12.7 m x 47.6 m furnace fired with a low-volatile bituminous coal (Pocahontas No. 3), high-volatile bituminous coals (Illinois No. 6 and Utah) and a sub-bituminous coal (Wyoming). Table 1 presents the proximate, ultimate and ash analyses of these coals. A 15 x 15 x 51 grid is used for numerical solution of RTE. For heat balance purposes, the furnace is divided into a 7.5 m high hopper zone, a 9.3 m high burner belt zone, and five heat absorption zones. It is assumed that 10% of volatile matter is transformed into soot and that volatile matter and soot are completely combusted in the burner zone. The furnace uses 20% excess air preheated to 573 K. Calculations show that char particles smaller than 50 μm in diameter complete burnout within the burner belt zone. Thus, soot and most char particles are confined to the burner zone whereas ash particles are uniformly dispersed in the furnace. Unless specified otherwise, the wall emissivity is taken as 0.7, anisotropic scattering coefficient as 1.0, apparent wall temperature as 1080 K, char mass median diameter (mmd) as 50 μm , ash mmd as 7.5 μm , soot mmd as 0.1 μm , and convective heat transfer coefficient as 15 W/m²K. A log normal distribution function with geometric standard deviation of 2.0 is used to express char, ash and soot particle size distributions (psd). Figure 5 captures the typical spectral variation of wall heat flux in different zones. Table 2 summarizes the results of parametric calculations. Some of the important conclusions drawn from these results are discussed below.

a) Soot particles, in spite of being present in the flame zone only, significantly enhance radiative heat transfer due to gas molecules. Soot

contribution is most pronounced when comparing heat transfer due to gas only with that due to gas and soot. Because of the band nature of gas absorption, luminous radiation emitted by soot particles in the flame zone reaches furnace walls adjacent to the absorption and hopper zones practically unattenuated. Depending upon gas composition and volatile matter content, soot contribution to heat transfer is calculated to vary in a narrow range of 14 and 16%.

b) Radiative heat transfer due to char particles is comparatively small, i.e., less than 3% of gas radiation. This is attributed to a large scattering cross-section of the char particles which serves to attenuate the radiation emitted by the gaseous molecules as well as the char particles themselves. As pointed out earlier [4], there is some uncertainty in the data base for char optical constants. Moreover, emission by char particles has been underestimated in the calculations presented in Table 2 since the black body emissive power is based on gas rather than particle temperature. During burnout, char particle temperature can be 50-150 K higher than the local gas temperature.

c) Ash contribution to heat transfer depends upon the mineral composition. For ash with a high iron content, such as in Illinois No. 6 coal (20.1% Fe_2O_3), incremental heat transfer associated with ash particles can be more than 15% of that due to gas molecules. For ash with intermediate iron content, such as in Wyoming coal (11% Fe_2O_3), contribution of ash particles is less than 2%. For a low iron ash, such as in Pocahontas No. 3 coal (4% Fe_2O_3), ash contribution to radiative heat transfer is negligible, i.e., less than 1%. For a very low iron ash, such as in Utah coal (1.2% Fe_2O_3), ash contribution to heat transfer can be negative. Thus, high iron ashes can be regarded as absorbing type and low iron ashes as scattering type.

d) Combined contributions of soot, char and ash particles to total heat transfer are non-additive, always less than the sum of individual contributions, and sometimes subtractive. For Illinois No. 6 coal containing high-iron ash the combined contributions of combustion particles is nearly 18% of heat transfer by gaseous radiation. For Wyoming coal with intermediate-iron ash, ash (and char) contribution to total heat transfer is negligible. For Pocahontas No. 3 coal containing low-iron ash, the combined heat transfer decreases if ash (and char) contribution is included with gas and soot even though individual contribution of ash (and char) is positive. Importance of scattering by ash particles is most evident with Utah coal for which ash is seen to decrease gas and soot radiation by more than 3%.

e) Overall heat transfer decreases by 5-10% with fine-grinding of coal to produce 10- μ m char psd and 3.5- μ m ash psd. Ash particles have a high scattering cross-section for infrared radiation. The macroscopic total cross-section of ash (and char) particles increases with fine grinding leading to higher scattering albedo for gas-particle mixture. A greater decrease in radiative heat transfer is observed with fine-grinding of Utah coal containing scattering type ash than with Illinois coal containing absorbing type ash. The radiation characteristics of the two types of micronized coals are quite different. With Illinois No. 6 micronized coal, ash (and char) is seen to enhance band radiation by 10% but to attenuate luminous gas-soot mixture radiation by about 2%. With micronized Utah coal, scattering by ash particles reduces band radiation by more than 7% and gas-soot radiation by more than 12%.

f) Consistent with the above explanation, the effect of cleaning coal to reduce ash content is to improve furnace heat absorption obtained from burning

finely-ground coals that contain scattering-type ash. Compared with the parent coal, the improvement in heat transfer upon cleaning Utah and Pocahontas coals is nearly offset by the decrease in heat transfer with fine-grinding. A different trend is observed for coals that contain absorbing type ash. Furnace heat transfer changes insignificantly with cleaning of micronized Illinois and Wyoming coals. For these coals the combined effect of cleaning and fine grinding is to reduce heat absorption by about 5%. This reduction is attributed to lower absorption cross-section of ash particles and higher scattering cross-section of char particles.

g) Ash buildup on furnace walls determines the surface emissivity as well as the effective temperature of surface exposed to the combustion gas. The deposit emissivity is known to be highly spectral and to depend upon the iron content of ash as well as the nature of the deposit (i.e., sintered or fused) [12]. The effective surface temperature is naturally a function of the deposit thickness and conductivity. Sensitivity of radiative heat transfer to surface emissivity and temperature is quantified in Table 2 for Illinois No. 6 coal. A decrease of 0.1 in emissivity from the base value of 0.7 reduces furnace heat absorption by nearly 3%. Similarly, heat transfer decreases by about 16% if the effective surface temperature is raised by 320 K.

h) At constant heat input, the effect of substituting coal with 50/50 coal-water slurry (CWS) is to reduce furnace heat absorption by about 21%. The reduction in heat transfer is due primarily to lowering of gas and flame temperatures and is in spite of enhanced emission with higher partial pressure of H_2O . Gas temperatures are lower with CWS because of latent heat of vaporization, slightly higher combustion gas throughput, and (mainly) larger

specific heat of moist gas.

i) Assumption of forward scattering results in 1.5% higher calculated heat transfer than isotropic scattering.

j) Necessity of performing spectral calculation is amply justified by the results summarized in Table 2. Parametric calculations show that a gray-medium assumption not only overestimates heat transfer but produces inconsistent results as well.

9. ASSESSMENT AND CONCLUSIONS

A comprehensive radiation transport model has been developed that is capable of resolving the effects of combustion particle size distribution, content and composition on furnace heat absorption. The model is somewhat unique in its ability to conduct detailed spectral calculations of radiative transfer in conjunction with a consistent data base for optical constants of char, soot and flyash. Sample calculations have been performed to determine the sensitivity of furnace heat transfer to coal grinding, coal cleaning, coal slurring, and coal ash composition. These show that the combined contribution of char, soot and ash can exceed 25% of gaseous heat transfer. Contributions of different types of particles are non-additive, always less than the sum of individual contributions, and sometimes subtractive. Ashes with high iron content can be classified as absorbing type and those with low-iron content as scattering type. Ashes rich in iron content enhance furnace heat transfer. Iron deficient ashes can reduce heat transfer; the reduction is more pronounced if the combustion gas contains a luminous radiation emitter such as soot particles. Coal micronization (fine grinding) generates fine ash particles that lead to diminishing of heat transfer.

Coal cleaning (reduction in ash content) results in enhancement of heat transfer for scattering-type ashes and in reduction if the ash is absorbing type. Generally, a coal micronization step precedes the cleaning operation. Thus, the effects of coal micronization and cleaning mutually offset each other for scattering-type ashes but reinforce each other for absorbing-type ashes. Sample calculations indicate that burning coal as a slurry reduces heat transfer. The contribution of char particles to heat transfer is found to be secondary to that of soot and ash particles. Char contribution may have been underestimated in the parametric study due to use of gas temperature to estimate char emission and the underlying uncertainty in char optical constants [4].

Importance of contribution of combustion particles to furnace heat absorption can be judged by the need expressed by furnace vendors to know the furnace exit temperature within 50°F (28°C). Table 2 shows that various parameters considered in this study affect the furnace exit temperature by more than 28°C. However, results are not as dramatic as construed in a previous publication [4] which showed a complete qualitative and quantitative difference in radiation properties of gas flames and coal flames. Smaller sensitivity of heat transfer to particles derives from the coupling of radiation transport to heat balance. The coupling serves to moderate the influence of higher radiation cross-sections on heat transfer with corresponding decrease in gas temperature. Such a coupling has been previously noted in a related problem [13,14]. It also explains the sensitivity of heat transfer to distribution of combustion particles as determined by Mengüç and Viskanta [3] on the basis of a fixed temperature profile.

Results in Table 2 provide sufficient justification for computer time and expense

incurred in carrying out detailed spectral calculations. These show that rather arbitrary results can be obtained with a gray-body assumption. Most investigations reported in coal literature including [3] treat the furnace as a gray medium and should be reviewed carefully. Similar conclusion applies to sensitivity studies based on improper or indeed ad-hoc variations in optical constants. In particular, studies based on optical constants that do not satisfy Kramer-Kronig relations are of limited validity [4].

Finally, results in Table 2 indicate that heat transfer is sensitive to ash buildup on furnace walls through effective surface temperature and surface emissivity. Thickness of ash deposit, together with deposit conductivity, determines the effective surface temperature. Deposit buildup on furnace walls as well as surface emissivity are function of ash composition. This factor has not been explicitly considered in Table 2. Thus, furnace heat transfer may be more sensitive to ash composition than reported in Table 2. Also, flyash does not have uniform composition as assumed here. The class of particles, rich in iron content, that are generated from combustion of pyrite (originally present as extraneous ash) is of particular interest from the standpoint of promoting heat transfer. Further study is recommended to address these remaining issues.

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Table 1. Coal and Ash Analyses

Coal	Illinois No. 6	Pocahontas No. 2	Utah	Wyoming
High Heating Value, MJ/kg	26.6	33.33	30.19	28.23
Proximate Analysis				
Moisture	5.8	3.3	3.3	10.3
Volatile Matter	43.8	18.7	47.2	47.0
Fixed Carbon	38.7	71.8	42.2	38.6
Ash	11.7	6.2	7.3	4.1
Ultimate Analysis, dry ash-free basis				
Carbon	80.5	89.4	80.7	79.3
Hydrogen	5.5	4.6	5.8	5.6
Sulfur	3.3	0.6	0.4	1.1
Nitrogen	1.6	1.3	1.4	1.8
Oxygen	9.1	4.1	11.7	12.2
Ash Analysis, % by wt				
SiO ₂	47.52	60.0	52.5	24.0
Al ₂ O ₃	17.87	30.0	18.9	20.0
TiO ₂	0.78	1.6	1.2	0.7
Fe ₂ O ₃	20.13	4.0	1.1	11.0
CaO	5.75	0.6	13.2	26.0
MgO	1.02	0.6	1.3	4.0
Na ₂ O	0.36	0.5	3.8	0.2
K ₂ O	1.77	1.5	0.9	0.5

Table 2. Parametric Study of Furnace Heat Transfer

Fuel Type	VM %	Ash %	MMD		Wall Temp K	Wall Emis	Exit Temp K	Heat Trans MW	Ash Composition				Comments
			Char µm	Ash µm					SiO2	Al2O3	CaO	Fe2O3	
Illinois No.6	43.8	11.7	50	7.5	1080	0.7	1490	482.4	47.5	27.9	5.7	20.1	pCO2 = 0.1379 atm
Ash, Char & Gas	-	11.7	50	7.5	1080	0.7	1516	469.0	47.5	27.9	5.7	20.1	pH2O = 0.08448 atm
Char & Gas	-	-	50	-	1080	0.7	1619	415.7	-	-	-	-	Qrel = 892.7 MW
Ash & Gas	-	11.7	-	7.5	1080	0.7	1512	471.1	47.5	27.9	5.7	20.1	res. time = 3.884 s
Soot & Gas	43.8	-	-	-	1080	0.7	1520	467.1	-	-	-	-	air flow = 359.9 kg/s
Gas only	-	-	-	-	1080	0.7	1630	409.9	-	-	-	-	hhv = 27.86 MJ/kg
Wyoming	47.0	4.1	50	7.5	1080	0.7	1515	465.6	24.0	20.0	26.0	11.	pCO2 = 0.1387 atm
Ash, Char & Gas	-	4.1	50	7.5	1080	0.7	1584	429.4	24.0	20.0	26.0	11.	pH2O = 0.09253 atm
Char & Gas	-	-	50	-	1080	0.7	1612	414.8	-	-	-	-	Qrel = 895.0 MW
Ash & Gas	-	4.1	-	7.5	1080	0.7	1592	425.1	24.0	20.0	26.0	11.	res. time = 4.049 s
Soot & Gas	47.0	-	-	-	1080	0.7	1517	464.6	-	-	-	-	air flow = 359.6 kg/s
Gas only	-	-	-	-	1080	0.7	1626	407.6	-	-	-	-	hhv = 28.23 MJ/kg
Pocahontas No.3	18.7	6.2	50	7.5	1080	0.7	1536	472.0	60.0	30.0	0.6	4.0	pCO2 = 0.1446 atm
Ash, Char & Gas	-	6.2	50	7.5	1080	0.7	1622	428.2	60.0	30.0	0.6	4.0	pH2O = 0.06874 atm
Char & Gas	-	-	50	-	1080	0.7	1625	426.4	-	-	-	-	Qrel = 895.1 MW
Ash & Gas	-	6.2	-	7.5	1080	0.7	1638	420.0	60.0	30.0	0.6	4.0	res. time = 3.86 s
Soot & Gas	18.7	-	-	-	1080	0.7	1516	482.1	-	-	-	-	air flow = 357.8 kg/s
Gas only	-	-	-	-	1080	0.7	1644	416.8	-	-	-	-	hhv = 33.032 MJ/kg
Utah	47.2	7.3	50	7.5	1080	0.7	1547	454.0	56.5	20.3	14.2	1.2	pCO2 = 0.1397 atm
Ash, Char & Gas	-	7.3	50	7.5	1080	0.7	1625	412.9	56.5	20.3	14.2	1.2	pH2O = 0.08448 atm
Char & Gas	-	-	50	-	1080	0.7	1617	417.4	-	-	-	-	Qrel = 894.9 MW
Ash & Gas	-	7.3	-	7.5	1080	0.7	1632	409.5	56.5	20.3	14.2	1.2	res. time = 3.74 s
Soot & Gas	47.2	-	-	-	1080	0.7	1519	468.5	-	-	-	-	air flow = 361.3 kg/s
Gas only	-	-	-	-	1080	0.7	1629	410.8	-	-	-	-	hhv = 29.77 MJ/kg
Illinois No.6	43.8	11.7	10	3.5	1080	0.7	1535	459.2	47.5	27.9	5.7	20.1	Micronized coal
Ash, Char & Gas	-	11.7	10	3.5	1080	0.7	1546	453.6	47.5	27.9	5.7	20.1	
Ash & Gas	-	11.7	-	3.5	1080	0.7	1552	450.7	47.5	27.9	5.7	20.1	
Wyoming	47.0	4.1	10	3.5	1080	0.7	1559	442.5	24.0	20.0	26.0	11.	Micronized coal
Ash, Char & Gas	47.0	4.1	10	3.5	1080	0.7	1583	430.1	24.0	20.0	26.0	11.	
Ash & Gas	47.0	4.1	10	3.5	1080	0.7	1609	416.4	24.0	20.0	26.0	11.	

Table 2. Parametric Study of Furnace Heat Transfer (Cont'd)

Fuel Type	VM %	Ash %	MMD μm		Wall Temp K	Wall Emis Temp K	Heat Trans MW	Ash Composition %Wt			Comments		
			Char	Ash				SiO2	Al2O3	CaO Fe2O3			
Pocahontas No.3	18.7	6.2	10	3.5	1080	0.7	1591	444.1	60.0	30.0	0.6	4.0	Micronized coal
Ash, Char & Gas	18.7	6.2	10	3.5	1080	0.7	1625	426.6	60.0	30.0	0.6	4.0	
Ash & Gas	18.7	6.2	10	3.5	1080	0.7	1666	405.9	60.0	30.0	0.6	4.0	
Utah	47.2	7.3	10	3.5	1080	0.7	1611	411.3	56.5	20.3	14.2	1.2	Micronized coal
Ash, Char & Gas	47.2	7.3	10	3.5	1080	0.7	1630	401.1	56.5	20.3	14.2	1.2	
Ash & Gas	47.2	7.3	10	3.5	1080	0.7	1667	381.7	56.5	20.3	14.2	1.2	
Illinois No.6	49.1	1.0	10	3.5	1080	0.7	1540	457.0	47.5	27.9	5.7	20.1	Cleaned coal
Wyoming	48.5	1.0	10	3.5	1080	0.7	1545	440.5	24.0	20.0	26.0	11.	Cleaned coal
Pocahontas No.3	18.7	1.0	10	3.5	1080	0.7	1556	461.8	60.0	30.0	0.6	4.0	Cleaned coal
Utah	50.5	1.0	10	3.5	1080	0.7	1553	450.6	56.5	20.3	14.2	1.2	Cleaned coal
Isotropic Sca.	43.8	11.7	50	7.5	1080	0.7	1504	475.1	47.5	27.9	5.7	20.1	Illinois No.6
Gray Medium	43.8	11.7	50	7.5	1080	0.7	1409	524.2	47.5	27.9	5.7	20.1	Illinois No.6
Ash, Char & Gas	43.8	11.7	50	7.5	1080	0.7	1407	525.0	47.5	27.9	5.7	20.1	
Char & Gas	43.8	11.7	50	7.5	1080	0.7	1376	540.5	47.5	27.9	5.7	20.1	
Ash & Gas	43.8	11.7	50	7.5	1080	0.7	1406	525.5	47.5	27.9	5.7	20.1	
Soot & Gas	43.8	11.7	50	7.5	1080	0.7	1377	540.2	47.5	27.9	5.7	20.1	
Gas only	43.8	11.7	50	7.5	1080	0.7	1375	541.4	47.5	27.9	5.7	20.1	
CWM(50/50)	24.3	1.0	10	3.5	1080	0.7	1499	399.5	24.0	20.0	26.0	11.	Illinois No.6
Illinois No.6	43.8	11.7	50	7.5	1080	0.8	1466	494.8	47.5	27.9	5.7	20.1	Wall emissivity
Illinois No.6	43.8	11.7	50	7.5	1080	0.6	1519	467.5	47.5	27.9	5.7	20.1	
Illinois No.6	43.8	11.7	50	7.5	1400	0.7	1616	417.2	47.5	27.9	5.7	20.1	Wall temperature
Illinois No.6	43.8	11.7	50	7.5	800	0.7	1430	513.2	47.5	27.9	5.7	20.1	

FIGURE CAPTIONS

- Figure 1. Spectral Variation in Ash Optical Constants.
- Figure 2. Absorption and Scattering Cross-Sections of the Combustion Gas.
- Figure 3. Comparison of Computed and Measured Gas Temperature Profiles.
- Figure 4. Comparison of Computed and Measured Heat Fluxes.
- Figure 5. Furnace Heat Absorption Pattern.

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