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INFLUENCE OF THE GRAY GASES NUMBER IN THE WEIGHTED SUM OF GRAY GASES MODEL ON THE RADIATIVE HEAT EXCHANGE CALCULATION INSIDE PULVERIZED COAL-FIRED FURNACES

by,

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The influence of the gray gases number in the weighted sum in the gray gases model on the calculation of the radiative heat transfer is discussed in the paper. A computer code which solved the set of equations of the mathematical model describing the reactive two-phase turbulent flow with radiative heat exchange and with thermal equilibrium between phases inside the pulverized coal-fired furnace was used. Gas-phase radiative properties were determined by the simple gray gas model and two combinations of the weighted sum of the gray gases models: one gray gas plus a clear gas and two gray gases plus a clear gas. Investigation was carried out for two values of the total extinction coefficient of the dispersed phase, for the clean furnace walls and furnace walls covered by an ash layer deposit, and for three levels of the approximation accuracy of the weighting coefficients. The influence of the number of gray gases was analyzed through the relative differences of the wall fluxes, wall temperatures, medium temperatures, and heat transfer rate through all furnace walls. The investigation showed that there were conditions of the numerical investigations for which the relative differences of the variables describing the radiative heat exchange decrease with the increase in the number of gray gases. The results of this investigation show that if the weighted sum of the gray gases model is used, the complexity of the computer code and calculation time can be reduced by optimizing the gray gases number.

Key words: *furnace, pulverized coal, simple gray gas model, relative difference,*
numerical simulation, weighted sum of gray gases model

Introduction

In numerical investigations of processes inside pulverized coal fired furnaces, the simple gray gas model (SGM) or weighted sum of gray gases model (WSGM) is used as the gas-phase radiative property model (RPM). When the SGM is used, a real gas is replaced by a gray gas. In the WSGM, a real gas is replaced by a mixture consisting of several gray gases plus a clear gas. The WSGM is used in numerical investigations of conventional combustion with air [1-3] and oxy-fuel combustion [4-6].

In the WSGM based on total radiative properties, the number of gray gases is usually not bigger than three. The emissivity of a real gas is represented by summing the terms, each of which is a product of the emissivity of a gray gas column and temperature-dependent weighting coefficient. The influence of the number of gray gases on the emissivity accuracy

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has been well documented [7-9]. The increase in the number of gray gases decreases the differences between the emissivity determined by the WSGM and the emissivity of a real gas.

The influence of the number of gray gases in the WSGM on the calculation of the radiative heat transfer were described for the WSGM based on the spectral radiative properties. Coelho [10] used the spectral line based WSGM with 3 and 20 gray gases to evaluate the performances of two radiation models for the calculation of wall fluxes and radiative heat sources inside a rectangular 3-D enclosure with fixed temperature and concentration distribution. The exact values were obtained by the ray tracing method and statistical narrow band model [11]. With some exceptions, an increase in the number of gray gases from 3 to 20 decreased the average and maximal relative errors. Park and Kim [12] used the regrouping technique to investigate the possibility of reducing the number of gray gases of the narrow band based WSGM. The exact values of the wall fluxes and average intensity of radiation inside the cubic 3-D enclosure with fixed temperature and concentration spatial distribution were found using the statistical narrow band model. Nine hundred gray gases were regrouped into 3, 5, 7, 10, 15, and 20 gray gases. The average and maximal relative errors generally decreased with the increase in the number of regrouped gray gases, and when the number of gray gases was bigger than five, the reduction of the average and maximal relative errors became unimportant. Results presented by Coelho [10] and Park and Kim [12] showed that the difference in radiative heat transfer calculations in 3-D enclosures with fixed temperature and concentration distributions decreased with increases in the number of gray gases.

The objective of this investigation was to find the influence of the number of gray gases in the WSGM based on the total radiative properties on the calculation of the radiative heat exchange inside pulverized coal-fired furnaces. For a selected pulverized coal-fired furnace, an in-house computer code which solved a set of equations of the reactive two-phase turbulent flow with radiative heat exchange and with thermal equilibrium between phases was used. The radiative properties of the gas-phase furnace medium were determined by the SGM and two WSGM: a combination of one gray gas plus a clear gas (WSGM1) and a combination of two gray gases plus a clear gas (WSGM2). The influence of the number of gray gases in the WSGM was found through analyses of the relative differences of the wall fluxes, wall temperatures, medium (*i. e.* flame) temperatures, and heat transfer rates through all furnace walls. The selected variables directly describe or affect the radiative heat exchange. The investigations were started under numerical conditions used previously, such as clean furnace walls with constant wall temperature [13]. After that, the effects of the ash deposit layer on the furnace walls with various levels of weighting coefficient approximation accuracies (WCAC) were included. This investigation showed that the optimization of the number of gray gases was possible not only for the narrow line and spectral line based WSGM but also for the WSGM based on total radiative properties.

The mathematical model and computer code, developed for tangentially-fired furnaces, were applied for the furnace of a utility boiler of 210 MWe. The furnace was parallelepiped-shaped with a hopper at the bottom and a contraction at the upper part. The furnace was 40.0 m high, 16.5 m wide, and 14.5 m deep. The furnace geometry with mass flow rates of coal and air as well as coal properties has been described earlier [14, 15]. In the following text, the method and results of the investigation and the conclusions are described.

Method of investigation

This investigation was based on the analyses of results obtained from numerical simulations. The description of the method of investigation includes descriptions of the mathematical model and radiative properties.

Mathematical model

The mathematical model of the process inside the furnace described the reactive two-phase turbulent flow with radiative heat exchange and with thermal equilibrium between phases. Only the main characteristics are described here, because the mathematical model was described in [13].

The gas phase is described by the time averaged differential equations of the conservations of momentum, enthalpy, gas-phase concentrations, and turbulent kinetic energy and its rate of dissipation in an Eulerian reference frame. The general form of the gas-phase equation is:

$$\frac{\partial}{\partial x_i}(\rho_g U_i \Phi) = \frac{\partial}{\partial x_i}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_i}\right) + S_\Phi + S_{\Phi,p} \tag{1}$$

where ρ [kgm^{-3}] is the gas-phase density, U_i [ms^{-1}] – the component of the gas-phase velocity vector, Φ – the general gas-phase variable, Γ_Φ [kgm^{-1}s^{-1}] – the transport coefficient for Φ, S_Φ – the source term, and $S_{\Phi,p}$ – the source term due to the particles presence. The set of equations is closed by the k-ε turbulence model. The equation for the pressure field is obtained from the continuity and momentum equations. The pressure field is solved by the SIMPLE algorithm.

The dispersed phase is described by the differential equations of motion and change of mass and energy in a Lagrangian reference frame. The motion of the particles is tracked along trajectories with a constant number of particles. The particle velocity vector is the sum of the convective and diffusion components. Heterogeneous reactions of coal combustion are modeled in the kinetic-diffusion regime. The combustion model is described in detail in [16].

The radiative heat exchange is determined by Hottel s zonal method of radiation, based on division of the furnace volume into volume zones and furnace walls into surface zones. For every pair of zones, direct exchange areas (DEA) and total exchange areas (TEA) are calculated. The wall heat flux of the surface zone s_i is the difference between the energy absorbed and lost:

$$q_{w,s_i} = \frac{\sum_{m=1}^{N_{vz}} G_m S_i \sigma T_{g_m}^4 + \sum_{n=1}^{N_{sz}} S_n S_i \sigma T_{s_n}^4 - A_{s_i} \epsilon_{s_i} \sigma T_{s_i}^4}{A_{s_i}}, \qquad i = 1, \dots, N_{sz} \tag{2}$$

where $G_m S_i$ [m^2] is the volume-surface TEA, $S_n S_i$ [m^2] – the surface-surface TEA, N_{vz} – the number of volume zones, N_{sz} – the number of surface zones, T_{g_w} [K] – the temperature of the volume zone g_m, T_{s_i} [K] – the temperature of the volume zone s_i, ϵ_{s_i} – the emissivity of the surface zone s_i, and A_{s_i} [m^2] – the surface area of the zone s_i. The sum of the first two terms in the numerator of eq. (2) is the heat transfer rate of the gained energy and the third term is the heat transfer rate of the energy loss because of the emission of radiation from the surface zone s_i. The heat transfer rate of the zone s_i is determined by multiplying the wall flux by the surface area: $\dot{Q}_{s_i} = q_{w,s_i} A_{s_i}$, and the heat transfer rate through all furnace walls is found by summing the heat transfer rates of all surface zones which represent the wall: $\dot{Q}_{fur} = \Sigma \dot{Q}_{s_i}$.

When the gas-phase radiative properties are modeled by the WSGM, the wall heat flux of the surface zone s_i is determined from the relation:

$$q_{w,s_i} = \frac{\sum_{m=1}^{N_{vz}} \overrightarrow{G_m S_i} \sigma T_{g_m}^4 + \sum_{n=1}^{N_{sz}} \overrightarrow{S_n S_i} \sigma T_{s_n}^4 - A_{s_i} \epsilon_{s_i} \sigma T_{s_i}^4}{A_{s_i}}, \qquad i = 1, \dots, N_{sz} \tag{3}$$

where $\overrightarrow{G_m S_i}$ [m^2] is the volume-surface directed flux area (DFA), and $\overrightarrow{S_n S_i}$ [m^2] – the surface-surface DFA, [9].

The flow field was solved on a fine numerical grid composed of N_{cv} control volumes. Discretization and linearization of the gas-phase equations are achieved using the method of the control volumes and hybrid difference scheme. The stability of the iterative procedure is provided by the under-relaxation method [17]. The thermophysical properties of the gas phase are determined from the equation of the state, tabulated values, and empirical relations.

The method of calculation of the ash deposit temperatures is as described previously [18]. The furnace walls consist of two layers: the metal wall layer (4.0 mm thick) and the ash deposit layer (l_{ash} = 0.3 mm). The dependence of the effective thermal conductivity of the ash deposit layer on temperature was adopted from reference [19] (the sample whose silica ratio was 62), whereas the thermal conductivity of the metal wall layer was that of carbon steel [20, 21]. For the clean furnace walls (l_{ash} = 0.0 mm), the wall temperature was constant (T_w = 615.0 K). The wall emissivity was 0.8.

Radiative properties

The absorption coefficients of the gray gases for the WSGM were determined according to the procedure described in [7]. The absorption coefficients for the SGM and for the WSGM1 were the same as described previously [22]: $K_{a,g}$ = 0.07 1/m for the SGM and $K_{a,gg,1}$ = 0.23 1/m for the WSGM1. The absorption coefficients in the WSGM2 were $K_{a,gg,1}$ = 0.014 1/m and $K_{a,gg,2}$ = 0.41 1/m. The weighting coefficients $a(T)$ were determined by fitting the expression for the gas-phase emissivity:

$$\epsilon_g = \sum_{j=0}^{N_{gg}} \left\{ a_j(T) \left[1 - \exp(-K_{a,gg,j} L_m) \right] \right\}$$ (4)

where L_m [m] is the mean beam length, and ϵ_g – the emissivity of the real gas, determined by Leckner's model [23]. The weighting coefficients were determind in the range of 600-2400 K.

The weighting coefficients were determined in the form of polynomials:

$$f(\theta) = \sum_{i=0}^{PD} b_i \theta^i$$ (5)

where b designates the polynomial coefficient (PC), and θ [K] is the scaled temperature, $\theta = T/1000$. Each weighting coefficient was represented by the polynomials of the third, fourth, and fifth degrees. The PC were determined by the least-squares method [24] and their values are given in tabs. 1-3.

Table 1. The PC for the third-degree polynomial

PC	WSGM1	WSGM2		
	a_1	a_0	a_1	a_2
b_0	0.4246901	0.5697576	0.3659433	$0.5638441 \cdot 10^{-1}$
b_1	0.4030451	−0.2523325	0.4457903	−0.1790605
b_2	−0.2618388	$0.8786959 \cdot 10^{-1}$	−0.3326472	0.2368749
b_3	$0.4089782 \cdot 10^{-1}$	$-0.1185714 \cdot 10^{-1}$	$0.5355004 \cdot 10^{-1}$	$-0.4040215 \cdot 10^{-1}$

Table 2. The PC for the fourth-degree polynomial

PC	WSGM1	WSGM2		
	a_1	a_0	a_1	a_2
b_0	0.4211020	0.5506869	0.3542198	$0.9787451 \cdot 10^{-1}$
b_1	0.4155114	-0.1856524	0.4883071	-0.3148701
b_2	-0.2749168	$0.7523689 \cdot 10^{-2}$	-0.3849145	0.3936820
b_3	$0.4617232 \cdot 10^{-1}$	$0.2803175 \cdot 10^{-1}$	$0.7975415 \cdot 10^{-1}$	-0.1163087
b_4	$-0.7187912 \cdot 10^{-3}$	$-0.6941916 \cdot 10^{-3}$	$-0.4577278 \cdot 10^{-2}$	$0.1304861 \cdot 10^{-1}$

Table 3. The PC for the fifth-degree polynomial

PC	WSGM1	WSGM2		
	a_1	a_0	a_1	a_2
b_0	0.4338731	0.5323954	0.3532075	0.1183176
b_1	0.3548622	-0.1002886	0.4885568	-0.4074541
b_2	-0.1689990	-0.1385942	-0.3776072	0.5503041
b_3	$-0.3947450 \cdot 10^{-1}$	0.1441626	$0.6850880 \cdot 10^{-1}$	-0.2407334
b_4	$0.3164140 \cdot 10^{-1}$	$-0.5023798 \cdot 10^{-1}$	$0.1312308 \cdot 10^{-1}$	$0.5975788 \cdot 10^{-1}$
b_5	$-0.4607931 \cdot 10^{-2}$	$0.6104515 \cdot 10^{-2}$	$-0.1025669 \cdot 10^{-2}$	$-0.6645514 \cdot 10^{-2}$

The values of the weighting coefficients were set by means of weights [25] in the range of 750-1850 K, which was the expected temperature interval of the coarse numerical grid. The WCAC were determined by the root-mean-square error:

$$\chi = \sqrt{\frac{\sum_{i=1}^{N_{dp}} \left[a(T_i) - f(T_i) \right]^2}{N_{dp}}} \qquad (6)$$

where N_{dp} is the number of discrete points. Values of χ are given in tab. 4.

For the same furnace and for the conditions of thermal equilibrium between phases, it was already found that the results of numerical investigations agreed with

Table 4. Values of χ

PD	WSGM1	WSGM2		
	a_1	a_0	a_1	a_2
3	$0.37436 \cdot 10^{-3}$	$0.39216 \cdot 10^{-3}$	$0.35216 \cdot 10^{-3}$	$0.37577 \cdot 10^{-3}$
4	$0.11992 \cdot 10^{-3}$	$0.17851 \cdot 10^{-3}$	$0.13799 \cdot 10^{-3}$	$0.14780 \cdot 10^{-3}$
5	$0.48344 \cdot 10^{-4}$	$0.53011 \cdot 10^{-4}$	$0.56928 \cdot 10^{-4}$	$0.79235 \cdot 10^{-4}$

the experimental data for the medium total extinction coefficient between 0.2 and 2.0 1/m and for the scattering albedo between 0.0 and 0.5 [13]. As the gas-phase absorption coefficient was found to be $K_{a,g} = 0.07$ 1/m, it was concluded that the values of $K_{t,m}$ were determined by the radiative properties of the dispersed phase. In this investigation, the values of the total extinction coefficients of the dispersed phase were as follows: $K_{t,p} = 0.5$ 1/m ($K_{a,p} = 0.25$ 1/m, $K_{s,p} = 0.25$ 1/m) and $K_{t,p} = 2.0$ 1/m ($K_{a,p} = 1.0$ 1/m, $K_{s,p} = 1.0$ 1/m).

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The influence of the number of gray gases was found by comparing the relative differences of the numerical simulation results when WSGM1 (on one side) and SGM or WSGM2 (on the other side) were used. The relative differences of the variables were determined as the ratio of the absolute difference and the value of the variable obtained when the WSGM1 was used:

$$\delta_{\text{RPM}} = \frac{\left| \eta_{\text{RPM}} - \eta_{\text{WSGM1}} \right|}{\eta_{\text{WSGM1}}} 100.0 \qquad (7)$$

where the symbol η stands for the medium temperature T_{m}, wall heat flux q_{w}, and wall temperature T_{w} (only for $l_{\text{ash}} = 0.3$ mm), and the subscript RPM means SGM or WSGM2. The average values of the relative difference were determined on the basis of the relative difference of all control volumes or surface zones:

$$\overline{\delta}_{\text{RPM}} = \frac{1}{N} \sum_{i=1}^{N} \delta_{\text{RPM},i} \qquad (8)$$

where N stands for N_{cv} (for T_{m}) or N_{sz} (for q_{w} and T_{w}). The results also include the relative differences of $\dot{Q}_{\text{fur}}$.

Results and discussion

The coarse numerical grid was composed of volume zones of cubic shape with edge dimensions of 1.0 m. Volume zones composed the coarse numerical grid: $40 \times 14 \times 16$. The total numbers of volume and surface zones were $N_{\text{vz}} = 7956$ and $N_{\text{sz}} = 2712$, respectively. The DEA of the close zones were determined using correlations [9]. TEA were calculated using Hottel and Sarofim's method of original emitters of radiation [7]. Leaving fluxes were calculated using the method of LU decomposition [26]. TEA and DEA were corrected using the generalized Lawson's smoothing method [27]. The DFA were determined as defined in [9]. The fine numerical grid was obtained by dividing each volume zone into a number of control volumes. The grid-independent solution was achieved for the numerical grid containing 620136 control volumes. The grid-independent solution and agreement of the numerical results with the experimental data have been previously described [13]. All results were obtained after 4000 iterations. The results are presented in tabs. 5-11.

Table 5. Average and maximal values of the relative differences [%], $K_{\text{t,p}} = 0.5$ 1/m and $l_{\text{ash}} = 0.0$ mm

RPM	Average		Maximal	
	q_{w}	T_{m}	q_{w}	T_{m}
SGM	2.06	0.51	13.38	35.63
WSGM2	1.36	0.46	7.66	47.10

Table 6. Average and maximal values of the relative differences [%], $K_{\text{t,p}} = 2.0$ 1/m and $l_{\text{ash}} = 0.0$ mm

RPM	Average		Maximal	
	q_{w}	T_{m}	q_{w}	T_{m}
SGM	2.09	0.45	9.82	56.60
WSGM2	0.81	0.25	11.43	27.24

Table 7. Relative differences of the heat transfer rates, $l_{\text{ash}} = 0.0$ mm

$K_{\text{t,p}}$ [m^{-1}]	$\dot{Q}_{\text{fur}}$ [MW]	δ_{SGM} [%]	δ_{WSGM2} [%]
0.5	216.75	0.04	0.54
2.0	201.350	1.10	0.05

The average values of the relative differences decrease with the increase in the number of gray gases for both values of the total extinction coefficient of the dispersed phase. The

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Table 8. Average and maximal values of the relative differences [%], $K_{t,p}$ = 2.0 1/m and l_{ash} = 0.3 mm

RPM	Average			Maximal		
	q_w	T_m	T_w	q_w	T_m	T_w
SGM	1.90	0.28	0.32	7.62	56.62	1.32
WSGM2	0.62	0.22	0.09	5.80	47.68	1.37

Table 9. Average and maximal values of the relative differences [%] with the weighting coefficient approximated by the polynomial of the fourth degree, $K_{t,p}$ = 2.0 1/m and l_{ash} = 0.3 mm

RPM	Average			Maximal		
	q_w	T_m	T_w	q_w	T_m	T_w
SGM	1.78	0.44	0.29	10.38	56.71	2.21
WSGM2	0.11	0.26	0.14	7.83	30.82	1.97

Table 10. Average and maximal values of the relative differences [%] with the weighting coefficient approximated by the polynomial of the fifth degree, $K_{t,p}$ = 2.0 1/m and l_{ash} = 0.3 mm

RPM	Average			Maximal		
	q_w	T_m	T_w	q_w	T_m	T_w
SGM	2.06	0.35	0.32	13.55	56.72	1.34
WSGM2	1.20	0.30	0.16	10.52	23.25	2.35

Table 11. Relative differences of the heat transfer rates for the polynomials of the third, fourth, and fifth degrees, $K_{t,p}$ = 2.0 1/m and l_{ash} = 0.3 mm

PD	$\dot{Q}_{fur}$ [MW]	δ_{SGM} [%]	δ_{WSGM2} [%]
3	192.73	1.33	0.0073
4	193.63	0.86	0.11
5	192.98	1.20	0.29

maximal values of T_m (for $K_{t,p}$ = 0.5 m^{-1}) and q_w (for $K_{t,p}$ = 2.0 m^{-1}) increase with the increase in the number of gray gases for different values of $K_{t,p}$. For $K_{t,p}$ = 2.0 m^{-1}, the values and relative differences of $\dot{Q}_{fur}$, given in tab. 7, decrease with the increase in the number of gray gases. Therefore, that value of the total extinction coefficient of the dispersed phase was chosen for the rest of the investigation. The average and maximal relative differences for the furnace walls covered by the ash deposit layer, given in tab. 8, decrease with the increase in the number of gray gases, except for T_w, for which a small increase in the maximal value is obtained.

In tabs. 5-8, the weighting coefficients are approximated by the third-degree polynomial. Tables 9-11 show the average and maximal values of the relative differences of the selected variables for two levels of the WCAC and the relative differences of $\dot{Q}_{fur}$ for three levels of the WCAC. The average values of the relative differences of the selected variables and the relative differences of $\dot{Q}_{fur}$ decrease with the increase in the number of gray gases for every level of the WCAC, but the character of dependence on the approximation accuracy is changeable. An increase in the maximal values of the relative differences was obtained only for T_w and for the polynomial of the fifth degree.

The results of this investigation show that there are conditions of numerical investigations for which the relative differences of the variables describing the radiative heat exchange inside the pulverized coal fired furnace decrease with the increase in the number of gray gases in the WSGM. For example, both $K_{t,p}$ = 0.5 1/m and $K_{t,p}$ = 2.0 1/m provide agreement with experimental data and either can be used for numerical investigations [13]. The decrease in the average values of the relative differences of the selected variables and heat transfer rates through all furnace walls with the increase in the number of gray gases is obtained only for $K_{t,p}$ = 2.0 m^{-1}. For that value of $K_{t,p}$, a decrease in the relative differences of the selected variables and $\dot{Q}_{fur}$ is obtained when the effects of the existence of the ash deposit layer on the furnace walls are included with three levels of the WCAC. A small increase in the maximal values of the relative difference of T_w is of small importance, because the average

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values are obtained on the basis of the variables in all control volumes (or surface zones), whereas the maximal values of the relative differences represent the ratio of variables in one control volume (or surface zone).

The decrease in the differences is achieved at the expense of the computer code complexity and computational efficiency. For example, in the case of the computer code used in this investigation, three approximating polynomials for WSGM2 are needed instead of one (for WSGM1) and also a larger number of the data files for the TEA storage is needed for WSGM2 (77 files per gray gas are needed). The increase in the computational time from 60 (for WSGM1) to 84 hours (for WSGM2), using the Intel Core i3 processor, is also important. This analysis indicates the existence of the optimal number of gray gases in the WSGM, for which the increase in the computer code complexity and computational time is not justified by the improvement of the results.

Conclusions

The influence of the number of gray gases in the WSGM based on the total radiative properties on the calculation of the radiative heat exchange inside the pulverized coal fired furnace was discussed in the paper. A computer code which solved the set of equations of the mathematical model describing the reactive two-phase flow with radiative heat exchange inside the pulverized coal fired furnace was used. Gas-phase radiative properties were determined by the SGM and two combinations of the WSGM: a combination of one gray gas plus a clear gas and a combination of two gray gases plus a clear gas. The investigation was carried out for two values of $K_{t,p}$: for clean furnace walls and furnace walls covered by an ash layer deposit with three levels of WCAC. The influence of the number of gray gases was analyzed through the average and maximal values of the wall fluxes, wall temperatures, medium temperatures, and heat transfer rates through all furnace walls. The investigation showed that there were conditions of numerical investigation for which the relative differences of the variables describing the radiative heat exchange (including the $\dot{Q}_{fur}$) decreased with the increase in the number of gray gases in the WSGM. The results of this investigation show that if the WSGM is used as the gas-phase RPM, the complexity of the computer code and calculation time can be reduced by optimizing the number of gray gases.

Acknowledgment

Nomenclature

A – surface area, [m²]
a – weighting coefficient, [–]
b – polynomial coefficient, [–]
$\overline{G_iS_j}$ – volume-surface total exchange area, [m²]
$G_i\vec{S}_j$ – volume-surface directed flux area, [m²]
K_a – absorption coefficient, [m⁻¹]
K_s – scattering coefficient, [m⁻¹]
K_t – total extinction coefficient, [m⁻¹]
k – turbulent kinetic energy, [m²s⁻³]
L_m – mean beam length, [m]
l_{ash} – thickness of the ash deposit layer, [m]

N_{cv} – number of control volumes, [–]
N_{dp} – number of discrete points, [–]
N_{gg} – number of gray gases in the WSGM, [–]
N_{vz} – number of volume zones, [–]
N_{sz} – number of surface zones, [–]
$\dot{Q}$ – heat transfer rate, [W]
q – heat flux, [Wm⁻²]
$\overline{S_iS_j}$ – surface-surface total exchange area, [m²]
$S_i\vec{S}_j$ – surface-surface directed flux area, [m²]
S_Φ – source term for the gas-phase variable Φ
T – temperature, [K]

U_i – time-averaged velocity component, [ms^{-1}]
x_i – co-ordinate in general index notation, [m]

Greek symbols

Γ – transport coefficient, [kgm^{-1}s^{-1}]
δ – relative difference, [%]
ϵ – total emissivity, [–]
ε – rate of dissipation of the turbulent kinetic
     energy, [m^{2}s^{-3}]
θ – scaled temperature, [K]
ρ – gas-phase density, [kgm^{-3}]
σ – Stefan-Boltzmann constant, [Wm^{-2}K^{-4}]
Φ – gas-phase variable
χ – root-mean-square error, [–]

Subscripts and superscripts

g   – gas phase
gg   – gray gas
g_i – volume zone
fur   – furnace
m   – medium

p   – particle, dispersed phase
s_i – surface zone
w   – wall
Φ – related to general variable Φ

Abbreviations

DEA   – direct exchange area
DFA   – directed flux area
PC   – polynomial coefficient
PD   – polynomial degree
RPM   – radiative property model
SGM   – simple gray gas model
TEA   – total exchange area
WCAC   – weighting coefficient approximation
     accuracy
WSGM   – weighted sum of the gray gases
     model
WSGM1   – WSGM, combination of one gray gas
     plus a clear gas
WSGM2   – WSGM, combination of two gray
     gases plus a clear gas

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