INFLUENCE OF THE TEMPERATURE FLUCTUATIONS ON THE FLAME TEMPERATURE AND RADIATIVE HEAT EXCHANGE INSIDE A PULVERIZED COAL-FIRED FURNACE

by

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In this paper, influence of the temperature fluctuations, (as a version of turbulence-radiation interaction), on the flame temperature and radiative heat exchange inside the pulverized coal-fired furnace was investigated. The radiative heat exchange was solved by the Hottel zonal model. The influence of the temperature fluctuation was studied for three values of the extinction coefficient of the flame: 0.3 m^{-1}, 1.0 m^{-1}, and 2.0 m^{-1}. The investigation was conducted for the relative temperature fluctuations obtained by solving the transport equation for the temperature variance, and for four constant values of the relative temperature fluctuations (0.0, 0.1, 0.15, and 0.2). The maximal values of the mean temperature fluctuations and relative temperature fluctuations were obtained in the region close to the burners. The decrease of the flame temperature of about 100 K was obtained in the hottest region, for every extinction coefficient. An increase in the mean wall flux was found to be on the order of several percents, compared to the case without the temperature fluctuations. When the temperature variance was calculated, the mean relative temperature fluctuations were approximately 15%, for every extinction coefficient. The mean wall fluxes increased and flame temperature at the furnace exit plane decreased with the increase in the relative temperature fluctuations. The selected indicators of the furnace operation, such as the mean wall flux and mean flame temperature at the furnace exit plane, obtained for the calculated temperature variance, were close to the values predicted for the constant relative temperature fluctuation of 15%.

Key words: *furnace, pulverized coal, numerical investigation, turbulence-radiation interaction, temperature fluctuation, flame temperature, wall flux*

Introduction

The process inside the pulverized-coal fired furnace includes a turbulent two-phase flow with chemical reactions and radiative heat exchange. The spatial distributions of the physical quantities (temperature, velocities, species concentrations, thermophysical properties,

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wall fluxes, *etc.*) inside the furnace can be determined by numerical simulations, which are based on the solution of a set of partial differential equations describing turbulent two-phase flow, combustion, and radiative heat transfer. Usually, the solution is based on time-averaged (or averaged in other way, for example, Favre-averaged) values of the physical quantities. An improvement of the numerical simulations can be made including the turbulent fluctuations into iterative processes of calculation, such as interactions of the turbulence with radiation and combustion. This paper describes the effects of the turbulence-radiation interaction (TRI) on the numerical simulation results. Theoretical considerations indicate an increase of the radiation emission caused by the turbulent fluctuations [1-3].

Influence of the flow field fluctuations on the thermo-fluid variables was investigated for the laboratory flames of gaseous fuel and gas-fired furnaces [4-9]. For the laboratory flames, the effects of the TRI were considered for several levels of complexity: no TRI, which excludes the effects of the TRI, full TRI, which includes fluctuations of all involved physical quantities, and partial TRI, which neglects fluctuations of some physical quantities. Li and Modest [4] investigated turbulent jet methane flame. The TRI effects were taken into account for three optical thicknesses: 0.237, 0.474, and 0.948. The peak flame temperature decreased and net radiative heat loss increased with an increase in optical thickness. The biggest temperature drop was 117 K. Habibi *et al.* [5] investigated influences of the TRI for Sandia Flame D and Delft Flame III, considering full TRI, no TRI and several partial TRI. The maximal decreases of the peak temperatures of 60-70 K for the full TRI were obtained for Sandia Flame D, and 60-100 K for Delft Flame III. Coelho [6] investigated the effects of the TRI for methane/air jet flame for three cases: no TRI, partial TRI, and full TRI. The full TRI case showed the best agreement with the benchmark results. The partial TRI case provided the biggest values of the radiation intensity and smallest values of the temperatures. The no TRI case provided the smallest values of the radiation intensities and the biggest values of the temperature.

For the gas-fired furnaces, the method proposed by Snegirev [10] was followed. To solve the radiative heat transfer with turbulent fluctuations (for gas-fired furnaces), it is necessary to find the time-averaged values of the absorption coefficient and intensities, as well as the temperature variance. The solution is simplified by using optically thin fluctuation approximation, which excludes the correlation of the absorption coefficient and incident intensity fluctuations [1]. Then, the correlation between the absorption coefficient and blackbody intensity is to be solved. The solution requires the temperature variance, solved from the corresponding transport equation and derivative of the absorption coefficient with respect to time [10]. Yi *et al.* [7] investigated methane combustion in O_2/CO_2 atmosphere in axisymmetric furnace and obtained the drop of peak temperature of 13 K when included the TRI effects. Centeno *et al.* [8] investigated influence of the TRI for axisymmetric non-premixed methane-air flame. They obtained drop in peak flame temperature by 51 K and increase in radiative heat transfer rate by 32% when included the TRI effects in the calculation. Yang *et al.* [9] investigated methane combustion with air in different O_2/CO_2 atmospheres. When the TRI effects were taken into account, the biggest temperature drop of 44.4 K was obtained for air combustion. The temperature drop increased with increase in O_2 concentration in the O_2/CO_2 environment. On the other hand, the net radiative heat loss was the smallest for the air combustion (2.84%) and almost constant for the O_2/CO_2 environment ($\approx$ 7.0%).

For the pulverized-coal flame, the radiative properties include extinctions coefficient, scattering albedo, and scattering phase function. The radiative transfer equation for the absorbing, emitting, and scattering medium is given by Coelho [2]. It seems that the method of solution could be similar to that of the non-scattering medium. Investigations of the TRI effects on the operation of pulverized-coal fired furnaces are rare. The absorption coefficient for the pulverized coal flame is bigger than that for the gaseous fuel flame [11, 12] because of the presence of particles (char and fly ash particles). In this investigation, the flame was considered a gray medium, which reduced the process of TRI into temperature fluctuation (also a version of partial TRI). The objective of this investigation was to find an influence of the temperature fluctuations on the flame temperature level and radiative heat exchange inside the pulverized coal-fired furnace. The effects of the temperature fluctuations were taken into account by calculating the temperature variance for four constant values of relative temperature fluctuations: 0.0, 0.1, 0.15, and 0.2. The investigation was conducted for three representative values of the extinction coefficient of the flame: 0.3 m^{-1}, 1.0 m^{-1}, and 2.0 m^{-1}.

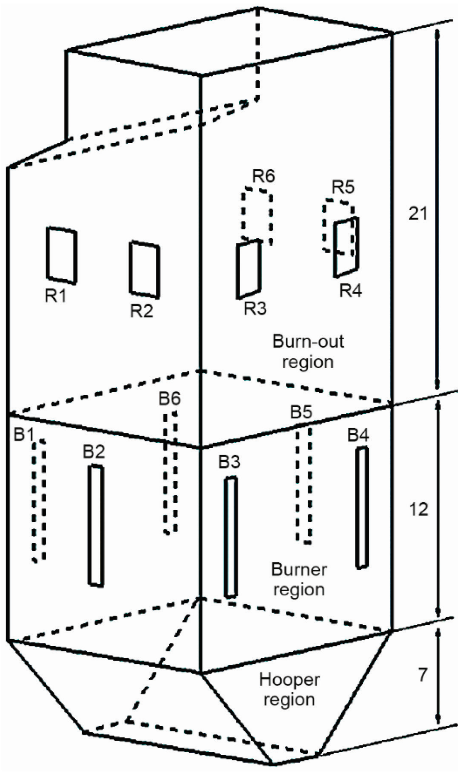

Figure 1. The furnace configuration and burner arrangement

The furnace of 210 MW monobloc thermal unit (A2 TENT, located in Obrenovac, Serbia) was selected for the investigation. The furnace is tangentially fired by Kolubara lignite and equipped with six jet burners (four tiers each), five of which are in operation (B1-B5), and six recirculation openings (R1-R6). Every burner is connected to one recirculation opening and one fan mill. The mill uses the hot recirculated combustion products and primary air for coal drying. The recirculated gases, primary air, and evaporated moisture constitute the transport fluid for the pulverized coal. Mass flow rates (per one burner assembly) of coal, primary air, and secondary air are 14.72 kg/s, 13.29 kg/s, and 34.12 kg/s, respectively. The temperatures of primary and secondary air are 438.0 K and 543.0 K, respectively. The furnace configuration and burner arrangement are shown in fig. 1. The furnace is 40.0 m high, 15.5 m wide, and 13.5 m deep. The mean beam length of the furnace is 10.56 m. Proximate and ultimate analyses of coal were described [13].

In the following text, mathematical model of the process inside the furnace, results and conclusions are described.

Mathematical model of the process

Mathematical model of the process inside the furnace described the two-phase reacting flow with radiative heat exchange. The model, based on the time-averaged physical quantities, was presented in [14-16]. The main difference of the model in this investigation is in the calculation of the wall fluxes and radiative energy source, which are found using the temperature fluctuations. The gas phase was described by the time-averaged partial differential conservation equations of momentum, enthalpy, component concentrations, turbulent kinetic energy and rate of turbulent kinetic energy dissipation in the Eulerian reference frame. The set of equations was closed by the k-ε model of turbulence. The pressure field was solved by the SIMPLE algorithm. (In the description of the mathematical model, capital letters of the variables designate the time-average quantities. The overbar sign, for the flame temperature, is used to emphasize the time-average value.)

For the gray medium with homogeneous radiative properties, the black emissive power (time-averaged, $\overline{E}_\mathrm{b} = \sigma\overline{T^4}$) with included effects of the temperature fluctuations and evaluated at the temperature of the volume element is [1]:

$$\overline{E}_\mathrm{b}(T_\mathrm{f}) = \sigma\overline{T}_\mathrm{f}^4\left(1+6\frac{\overline{T_\mathrm{f}'^2}}{\overline{T}_\mathrm{f}^2}\right) = 6\overline{T}_\mathrm{f}^4(1+6\xi^2) \tag{1}$$

where $\overline{T}_\mathrm{f}$ [K] is the (time-averaged) temperature, $\overline{T_\mathrm{f}'^2}$ [K^2] – the temperature variance, ξ [–] – the relative fluctuation, and σ [WK^{-4}m^{-2}] – the Stefan-Boltzmann constant. The term T'_f [K] designates the temperature fluctuation (defined by $T'_\mathrm{f} = T_\mathrm{f} - \overline{T}_\mathrm{f}$). The ratio $\xi = (\overline{T_\mathrm{f}'^2})^{1/2}/\overline{T}_\mathrm{f}$ [–] represents the relative temperature fluctuation, whereas the positive square root of the temperature variance $(\overline{T_\mathrm{f}'^2})^{1/2}$ [K] represents the mean temperature fluctuation [17].

The temperature is solved from the enthalpy equation:

$$\mathrm{div}(\rho\vec{\mathrm{U}}c\overline{T}_\mathrm{f}) = \mathrm{div}[\Gamma_H \mathrm{grad}(c\overline{T}_\mathrm{f})] + \vec{\mathrm{U}}\mathrm{grad}P + S_{H,\mathrm{com}} + S_{H,\mathrm{rad}} \tag{2}$$

where ρ [kgm^{-3}] is the gas-phase density, $\vec{\mathrm{U}}$ [ms^{-1}] – the gas-phase velocity vector, c [Jkg^{-1}K^{-1}] – the specific heat, Γ_H [kgm^{-1}s^{-1}] – the turbulent diffusivity for enthalpy, $S_{H,\mathrm{com}}$ [Wm^{-3}] – the source term due to combustion, and $S_{H,\mathrm{rad}}$ [Wm^{-3}] – the radiative source term. The enthalpy equation is solved for the thermal equilibrium between gas and dispersed phases [15]. Radiative heat exchange is solved using the zonal model of radiative heat exchange. It is based on division of the furnace walls and furnace space into the surface and volume zones. For each pair of zones, direct and total exchange areas are calculated. The radiative source term is:

$$S_{H,\mathrm{rad},i} = \frac{\sum_{m=1}^{M} G_\mathrm{m}G_i\overline{E}_{b,\mathrm{m}} + \sum_{n=1}^{N} S_nG_iE_{b,n} - 4K_\mathrm{e}(1-\omega)V_i\overline{E}_{b,i}}{V_i} \tag{3}$$

where G_mG_i [m^2] is the volume-volume total exchange area, S_nG_i [m^2] – the surface-volume total exchange area, M – the total number of the volume zones, N – the total number of the surface zones, V [m^3] – the volume, K_e [m^{-1}] – the total extinction coefficient, and ω [–] – the scattering albedo. The zonal model of thermal radiation was applied through the continual correction of the total exchange areas method [18]. The method is based on the correction of the total exchange areas, in accordance with the values of the surface zone emissivities and the summation principle. The numerator of eq. (3) is the net radiative loss $Q_{\mathrm{rad},i}$ [W], which can be summed over the furnace regions to obtain the net radiative loss of the region.

The wall flux of the surface zone s_i is determined:

$$q_{\mathrm{w},i} = \frac{\sum_{m=1}^{M} G_\mathrm{m}S_i\overline{E}_{b,\mathrm{m}} + \sum_{n=1}^{N} S_nS_iE_{b,n} - \epsilon_{w,i}\, E_{b,i}}{A_i} = \frac{Q_i}{A_i} \tag{4}$$

where S_nS_i [m^2] is the surface-surface total exchange area, M – the total number of the volume zones, N – the total number of the surface zones, ϵ_w [–] – the wall emissivity, A [m^2] – the surface area, and Q [W] – the heat transfer rate. The total radiative exchange in the furnace was obtained by summing all of the heat transfer rates for the surface zones that represents the solid walls: $Q_t = \Sigma Q_i$, and the mean wall flux was obtained by $q_{w,m} = Q_t/A_{fw}$, where A_{fw} [m^2] is the total surface area of all the furnace walls.

The temperature variance is solved from the equation given by Snegirev [10]:

$$\operatorname{div}\left(\rho\vec{U}\overline{T}_f'^2\right) = \operatorname{div}\left[\Gamma_{\overline{T}_f'^2}\operatorname{grad}\overline{T}_f'^2\right] + 2.0\left(\frac{\mu}{\Pr}\nabla\overline{T}_f\nabla\overline{T}_f - \rho\frac{\varepsilon}{k}\overline{T}_f'^2\right) \tag{5}$$

where μ [kgm^{-1}s^{-1}] is the turbulent viscosity, $\Gamma_{\overline{T}_f'^2}$ [kgm^{-1}s^{-1}] – the turbulent diffusivity for temperature variance, Pr [–] – the turbulent Prandtl-Schmidt number, k [m^{2}s^{-2}] – the turbulent kinetic energy, and ε [m^{2}s^{-3}] – the rate of the turbulent kinetic energy dissipation. The temperature variance is set to zero at the boundaries [10].

Dispersed phase is described by the differential equations of motion and change of mass and energy in Lagrangian reference frame. Motion of the particles is tracked along trajectories with constant flow of particles. Particle velocity vector is the sum of the convective and the diffusion component. Heterogeneous reactions of coal combustion are modeled in the kinetic-diffusion regime. Details of the combustion model can be found in [16].

Heat transfer rates through the furnace waterwalls are determined for the two-layer wall, composed of the metal wall 4.0 mm thick, and an ash deposit layer 0.6 mm thick. Along one side of the two-layer wall there is a flow of two-phase steam of boiling water, and hot furnace medium along the other side. Temperature of the water-steam mixture is determined according to the pressure in the waterwalls. Temperature of the inner surface of the metal wall is determined using the equation of the convective heat transfer between the metal wall and water-steam mixture, whereas the temperatures of the outer surface of the metal wall are determined using the 1-D steady-state heat conduction equation. The thermophysical properties of the furnace wall, such as thermal conductivity and emissivity with their temperature dependance, can be found in [19-22].

The thermophysical properties of the gas-phase are determined from the equation of state, tabulated values, and empirical relations. Discretization and linearization of the gas-phase equations are achieved by the control volume method and hybrid differencing scheme. Stability of the iterative procedure is provided by the under-relaxation method [23].

Results and discussion

Radiative heat exchange was solved on the coarse numerical grid composed of the cubical volume zones, having the edge dimension of 1.0 m. The furnace volume was divided into 7956 volume zones and furnace walls were divided into 2712 surface zones. Flow field was solved on the fine numerical grid which was obtained by dividing every volume zone into 64 control volumes. The fine numerical grid contained 620136 control volumes. Agreement with experimental data and the grid independence study were already shown [15]. Direct exchange areas of the close zones were determined using Tucker's correlations [24]. Total exchange areas were calculated by the method of original emitters of radiation [25]. Improvements of the values of total exchange areas were accomplished by using the generalized Lawson's smoothing method [26].

Figures 2 and 3 show the mean temperature fluctuation and relative temperature fluctuation. The differences in the flame temperatures can be explained by the net radiative losses. Net radiative losses for the furnace regions, with and without the effects of the temperature fluctuations are given in tab. 1. It is clear that the temperature fluctuations increase the net radiative losses in the burner region, and therefore the temperature decrease is the biggest in that region. The maximal values of the net radiative losses are expected, as the source term of eq. (5) contains the temperature gradient, which is the biggest in the burner region.

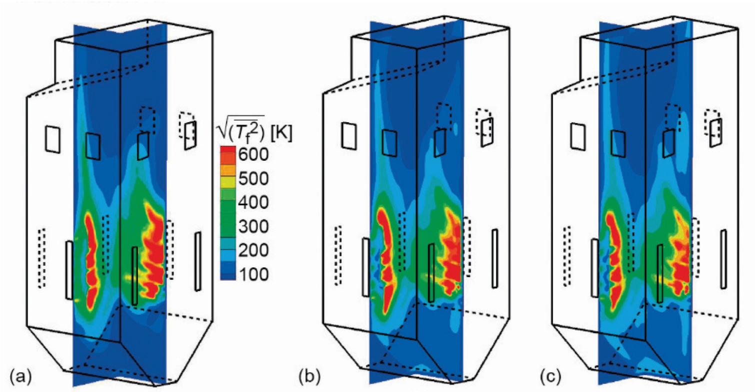

Figure 2. The mean temperature fluctuation; (a) K_e = 0.3 m^{-1}, (b) K_e = 1.0 m^{-1}, and (c) K_e = 2.0 m^{-1}

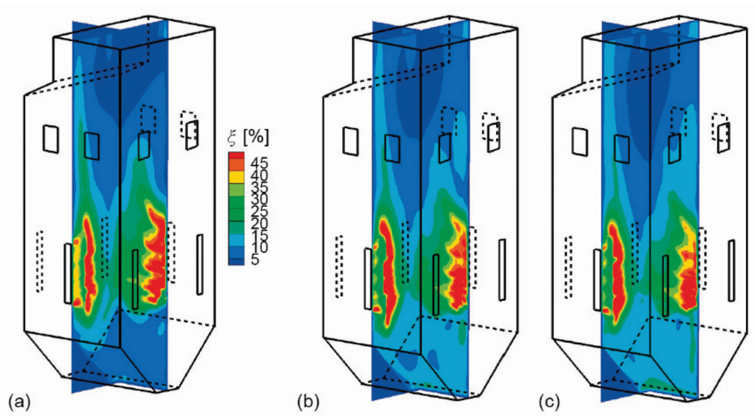

Figure 3. The relative temperature fluctuation; (a) K_e = 0.3 m^{-1}, (b) K_e = 1.0 m^{-1}, and (c) K_e = 2.0 m^{-1}

Table 1. Net radiative loss Q_{rad} [MW] with the effects of the temperature fluctuations/net radiative loss without the effects of the temperature fluctuations

K_e [m^{-1}]	Hopper region	Burner region	Burn-out region
0.3	14.54/17.26	92.29/64.67	93.90/100.23
1.0	21.13/22.23	70.03/50.32	96.27/98.70
2.0	22.97/23.42	60.30/43.18	95.79/95.36

Figures 2 and 3 show that the mean and relative temperature fluctuations depend very little on the flame extinction coefficient. The (arithmetic) mean values of the relative temperature fluctuations were 15% for every extinction coefficient.

Figures 4 and 5 show the influence of the temperature fluctuations on the flame temperatures. It is clear that lower temperatures were obtained in high temperature regions, because of the increased emission of the radiative energy. As the relative temperature fluctuation is maximal in the region close to the burners, the temperature drop is also the biggest in that area. The flame temperature is reduced approximately by about 100.0 K at the hottest region, for every extinction coefficient.

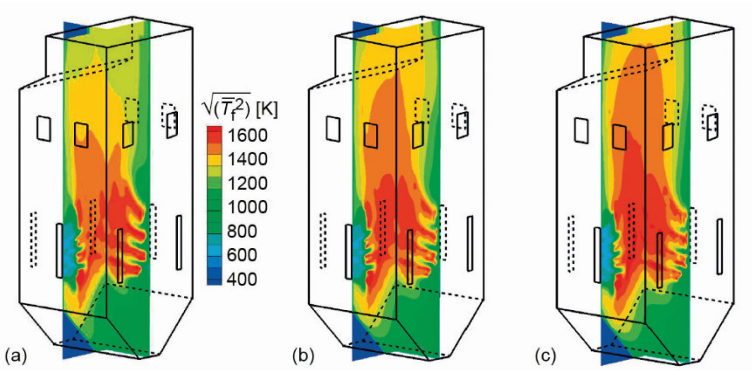

Figure 4. The flame temperature, (calculated without the effects of the temperature fluctuations); (a) K_e = 0.3 m^{-1}, (b) K_e = 1.0 m^{-1}, and (c) K_e = 2.0 m^{-1}

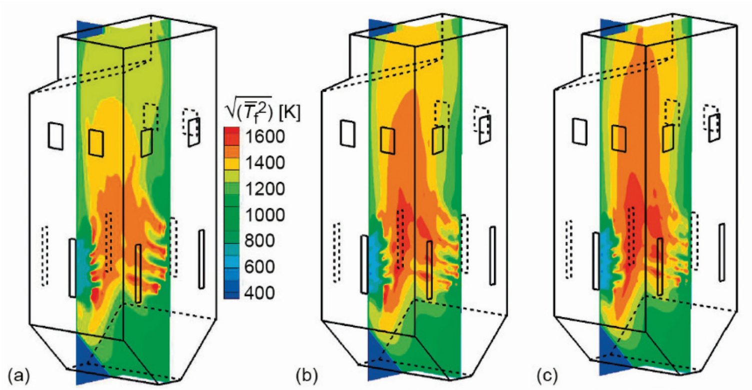

Figure 5. The flame temperature, (calculated with the effects of the temperature fluctuations); (a) K_e = 0.3 m^{-1}, (b) K_e = 1.0 m^{-1}, and (c) K_e = 2.0 m^{-1}

Table 2. The mean wall flux $q_{w,m}$ [kWm^{-2}]

	Relative temperature fluctuation				
K_e [m^{-1}]	0.0	0.10	0.15	0.20	ns*
0.3	70.63	72.61	75.44	79.03	77.41
1.0	66.75	68.96	71.40	75.22	72.69
2.0	63.52	65.39	68.11	71.43	69.78

* Determined in numerical simulation by eq. (5)

The values of the mean wall fluxes and (arithmetic) mean flame temperature at the furnace exit plane are given in tabs. 2 and 3. Table 2 shows an increase of the mean wall fluxes and decrease of the temperature with the increase in temperature fluctuations. The decrease of the flame temperature at the furnace exit plane is in accordance with the increase of the mean wall fluxes. When the relative temperature fluctuations were calculated, the increase of the mean wall fluxes can be estimated to be on the order of several percents. Tables 2 and 3 show that the selected indicators of the furnace operation, obtained for the calculated temperature variance (or relative temperature fluctuation), are close to the values obtained for the constant relative temperature fluctuation of approximately 15%. That value of temperature fluctuations can be used in the computer code if the indicators of the furnace operation are needed without the calculation of the temperature variance.

Table 3. The mean flame temperature [K] at the furnace exit plane

	Relative temperature fluctuation				
K_e [m^{-1}]	0.0	0.10	0.15	0.20	ns*
0.3	1304.0	1290.0	1279.0	1262.2	1284.7
1.0	1336.4	1324.8	1314.6	1297.5	1320.3
2.0	1346.5	1339.4	1325.7	1305.2	1329.8

* Determined in numerical simulation by eq. (5)

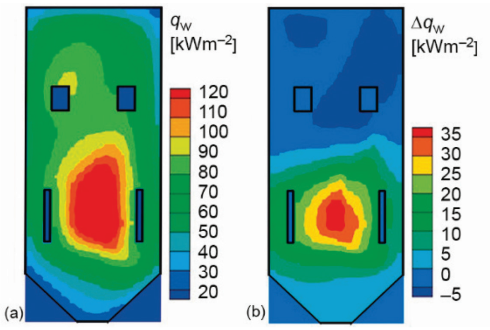

Figure 6. The wall fluxes at the front wall, K_e = 0.3 m^{-1}; (a) wall flux and (b) difference of the wall fluxes, and (c) K_e = 2.0 m^{-1}

Figure 6 shows the wall fluxes and the difference of the wall fluxes of the front furnace wall for the calculated temperature variance and constant temperature fluctuation of 15%, $\Delta q_w = q_{w,TRI} - q_{w,15}$. The differences of the wall fluxes are both positive and negative. The difference is positive in the lower part of the wall, which is close to the regions of the maximal relative temperature fluctuations, and negative in the upper part of the wall, where the relative temperature fluctuations are minimal. Figure 5 shows that the constant temperature fluctuation cannot be used for accurate determination of the wall fluxes distribution over the furnace walls, but only to find the mean wall flux.

As the temperature fluctuations reduce the flame temperature, they reduce the concentration of the thermal NO, whose formation is known to be temperature dependent [27]. That influence on the NO concentration is not considerable, as the thermal NO constitutes only small portion of the total NO. The influence of the temperature fluctuations on the temperature field in the pulverized coal-fired furnaces is similar to that obtained for the gas-fired furnaces. The results were obtained for the simplifications of the process inside the furnace and can be understood as an estimation of the influence of the temperature fluctuations on the physical quantities. The radiative properties of the pulverized coal flame are dominated by the gray particles, in the first place by the fly ash particles. That justifies the assumption of the gray medium. The radiative properties of the flame are considered homogeneous and non-fluctuating. As a consequence of the gray medium with homogeneous radiative properties, there is no correlation between the temperature fluctuation and absorption coefficient in eq. (1). Neglection of that correlation reduces the emission from the volume element. The level of the complexity of the TRI involved in the numerical simulation depends also on the radiation model itself.

Conclusions

The effects of the TRI on the flame temperature and radiative heat exchange inside the pulverized-coal furnace were considered in the paper. In the case of the homogeneous radiative properties, the TRI is reduced to the temperature fluctuations. The temperature fluctuations were found by solving the transport equation for the temperature variance. The investigation was conducted for three values of the extinction coefficient, for the calculated temperature variance, and four constant values of the temperature fluctuations. The results showed decrease of the flame temperature and increase of the total radiative exchange between the flame and furnace walls, when the temperature fluctuations became included in the calculation procedure. The flame temperature in the hottest area of the furnace decreased by approximately 100 K by the inclusion of the temperature fluctuations in the numerical simulations. The levels of the temperature drop were not influenced by the extinction coefficient. Estimated increase in the mean wall fluxes, representing an increase in radiative heat transfer between the flame and furnace walls, can be estimated to be on the order of several percents. The increase of the constant relative temperature fluctuations provided an increase of the mean wall fluxes and a decrease of the mean temperature in the furnace exit plane. The mean values of the relative temperature fluctuations were approximately 15%, for every considered value of the extinction coefficient. The indicators of the furnace operation, such as mean wall flux and mean flame temperature at the furnace exit plane, obtained for the calculated temperature variance and for the constant relative temperature fluctuations of 15%, were close. Comparison of the wall fluxes showed that the constant relative temperature fluctuations can be used only to find the mean wall flux and not for the accurate determination of the wall fluxes distribution.

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Nomenclature

A – surface area [m^2]
c – specific heat [$Jkg^{-1}K^{-1}$]
G_iS_j – volume–surface total exchange area [m^2]
k – turbulent kinetic energy [m^2s^{-2}]
K_e – extinction coefficient [m^{-1}]
M – total number of volume zones [-]
N – total number of surface zones [-]
Pr – turbulent Prandtl-Schmidt number ($= \mu/\Gamma$) [–]
q – wall flux [Wm^{-2}]
Q – heat transfer rate [W]
Q_{rad} – net radiative loss [W]
S – source term
S_iS_j – surface–surface total exchange area [m^2]
T – temperature [K]
$\bar{T}$ – time-averaged temperature [K]
T' – temperature fluctuation [K]
$\overline{T'^2}$ – temperature variance [K^2]
$(\overline{T_f'^2})^{1/2}$ – temperature rms (mean fluctuation) [K]
$\vec{U}$ – velocity [ms^{-1}]

Greek symbols

Γ – turbulent diffusivity [$kgm^{-1}s^{-1}$]
ϵ – emissivity [–]

ε – turbulent energy dissipation rate [m^2s^{-3}]
μ – turbulent viscosity [$kgm^{-1}s^{-1}$]
ξ – relative fluctuation [–]
ρ – density [$kg\ m^{-3}$]
σ – Stefan-Boltzmann constant [$Wm^{-2}K^{-4}$]
ω – scattering albedo [–]

Subscripts

f – flame
fw – all furnace walls
m – mean
t – total
w – wall

Acronym

TRI – turbulence-radiation interaction

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