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Radiative heat exchange inside the pulverized lignite fired furnace for the gray radiative properties with thermal equilibrium between phases

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ABSTRACT

The objective of the research was to find if an agreement of the results of a numerical investigation with experimental data could be achieved considering the two-phase medium in thermal equilibrium. Influence of the gray radiative properties on the radiative heat exchange inside pulverized lignite fired furnaces was investigated using the computational fluid dynamics (CFD) code based on a comprehensive mathematical model of the process. Radiative heat exchange was calculated using Hottel's zonal model. Heat transfer rates and wall fluxes increased for small values of the total extinction coefficient, $K_t < 0.2\ m^{-1}$; decreased for large values of K_t, $K_t > 2.0\ m^{-1}$; and were maximal for moderate values of K_t, $0.2 < K_t < 2.0\ m^{-1}$. Heat transfer rates and wall fluxes decreased with the increase of the scattering albedo, though the decrease was considerable only for $\omega > 0.5$. Agreement with the experimental data was obtained for the moderate values of the K_t and for scattering albedo $0.1 < \omega < 0.5$.

1. Introduction

Numerical simulations using the computational fluid dynamics (CFD) code for processes inside pulverized coal fired furnaces reveal spatial distributions of all physical quantities we are interested in. Radiative heat transfer is the main mode of heat transfer inside the furnaces. Transfer of energy by radiation from hot combustion products (or a medium) to furnace walls and within the combustion products depends on radiative properties of the medium and temperature field [1]. A medium inside pulverized coal fired furnaces consists of two phases: the gas phase and the dispersed phase (cloud of particles), which are usually considered in thermal non-equilibrium [2–4].

Average medium temperatures along the furnace cross-section and heat exchange can be obtained from numerical simulations using the advanced zonal computational method (AZCM) [5]. The boiler furnace (or the whole boiler) is divided into a relatively small number of zones which extend from one furnace wall to the other in both horizontal directions. The numerical simulations using the AZCM code provide agreement with the experimental data [5] or with the results of numerical simulations using the CFD code [6]. Temperatures of the medium at the zone outlet and heat exchange are found from the energy balance equation based on a two-phase mixture in thermal equilibrium. The AZCM is derived from the Russian normative method of boiler design which is applied for all types of furnaces [7].

Experimental evidence from the laboratory furnace showed considerable temperature difference between phases within the flame zone only [8]. Downstream from the flame zone, the temperature difference gradually diminished. Measurements carried out inside the furnace of the utility scale boiler showed a considerable difference of temperatures in the area of pendant superheaters only [9], which is usually not considered a part of the furnace. Binner et al. [10] performed experiments using a drop tube furnace and showed that temperature difference inside the flame zone is reduced for the combustion of coal with high moisture content.

The objective of this investigation was to find if the conditions of the two-phase medium in thermal equilibrium provided agreement of the results of numerical investigations using the CFD code with experimental data for pulverized lignite fired furnaces. It was

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Nomenclature

A	surface area (m^2)
A_r	parameter in Arrhenius relation ($m\ s^{-1}$)
B	zone edge (m)
c	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
c_p	specific heat capacity of gas at constant pressure ($J\ kg^{-1}\ K^{-1}$)
d	diameter (m)
D	molecular diffusivity ($m^2\ s^{-1}$)
E_a	activation energy ($J\ mol^{-1}$)
E_b	blackbody emissive power ($W\ m^{-2}$)
g_i	volume zone (–)
$\overline{G_iG_j}$	volume–volume total exchange area (m^2)
$\overline{G_iS_j}$	volume–surface total exchange area (m^2)
$\overline{S_iS_j}$	surface–surface total exchange area (m^2)
H	enthalpy ($J\ kg^{-1}$)
K_t	total extinction coefficient (m^{-1})
k_d	diffusion parameter of mass transfer ($m\ s^{-1}$)
k_r	reaction rate in kinetic regime ($m\ s^{-1}$)
L	length (m)
m	mass (kg)
M	total number of volume zones (–)
M_p	particle molar mass ($kg\ mol^{-1}$)
N	total number of surface zones (–)
N_p	number concentration of particles (kg^{-1})
P	pressure (Pa)
Q	heat transfer rate (W)
q	wall flux ($W\ m^{-2}$)
R	gas constant ($J\ mol^{-1}\ K^{-1}$)
s_i	surface zone (–)
S	source term (–)
Sh	Sherwood-number (–)
t	time (s)
T	temperature (K)
U_i	time-averaged velocity component ($m\ s^{-1}$)
V	volume (m^3)
x, y, z	Cartesian coordinates (m)

Greek symbols

ε	emissivity (–)
ρ	density ($kg\ m^{-3}$)
Γ	transport coefficient ($kg\ m^{-1}\ s^{-1}$)
Φ	general gas-phase variable (–)
X	oxidant molar concentration ($mol\ m^{-3}$)
ω	scattering albedo (–)
δ	relative difference (%)

Subscripts and superscripts

abs	absorbed
com	combustion
ed	experimental data
g_i	volume zone
H	enthalpy
f	furnace
inc	incident
rad	radiation
p	particle, dispersed phase
m	medium
nd	numerical simulation data
s_i	surface zone
w	wall
wpt	with pressure term
wopt	without pressure term
Φ	related to general variable Φ

Abbreviations

AZCM	advanced zonal computational method
CFD	computational fluid dynamics
DEA	direct exchange area
TEA	total exchange area
SGGM	simple gray gas model
WSGGM	weighted sum of gray gases model

expected that temperature difference between the phases inside such furnaces should be minimal because of the high moisture content of lignites. In our previous work, it was shown that radiative properties of the gas phase inside the pulverized lignite fired furnace can be modeled by the simple gray gas model (SGGM), which makes the medium inside the furnace the gray one [11]. It was also shown that the real scattering phase function can be replaced by the isotropic scattering phase function [12]. In that case, gray radiative properties of the medium are defined by the total extinction coefficient and scattering albedo. In this work, the influence of the total extinction coefficient and scattering albedo on the radiative heat transfer rates through the furnace walls and wall fluxes for a pulverized lignite fired furnace were investigated. Gray radiative properties were independently varied to find their influence on the radiative heat exchange.

Influence of the gray radiative properties on the wall fluxes was investigated for absorbing and emitting as well as absorbing, emitting, and scattering media in various enclosures [13–16] for nonradiative equilibrium and in cylindrical furnaces [17,18]. The temperature fields were uniform [13–16] or nonuniform [17,18], but always fixed. Gupta et al. [17] used the values of the total extinction coefficient from 0.25 to 1.25 m^{-1}. Marakis et al. [18] divided the cylindrical furnace into three parts and the radiative properties of each part were defined. The values of the total extinction coefficient were varied from 0.302 to 9.87 m^{-1} (determined from Ref. [18]). The temperature field was obtained from the experiment with natural gas firing. In all these investigations, the heat transfer rates and wall fluxes increased with the increase of the total extinction coefficient and decreased with the increase of the scattering albedo.

In this work, the influence of the gray radiative properties on radiative heat exchange was found using the CFD code based on a comprehensive mathematical model of the process. The temperature field was affected by the radiative properties of the medium. Radiative heat exchange was determined by Hottel's zonal method because of its ability to predict transfer of radiative energy accurately for every value of the total extinction coefficient. On the other hand, practical calculations are possible only for homogeneous medium. The total extinction coefficient was varied from the small value to the value determined by the condition of Tucker's correlations ($K_tB = 18.0$) [19], for several values of the scattering albedo. Tucker's correlations enabled application of higher values of the total extinction coefficient than in the previous studies.

Geometry of the furnace, flow rates of coal and air, and coal properties were described [11,12]. Briefly, the furnace height, width, and length are 40.0, 13.5, and 15.5 m, respectively. The furnace is equipped with six four-staged burners, five of which are in operation during the full load. In the following, the mathematical model