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Bed-to-wall heat transfer coefficient in a supercritical CFB boiler at different bed particle sizes

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ABSTRACT

The role of bed particle size in the heat transfer to membrane walls of a supercritical circulating fluidized bed (CFB) combustion system was studied. In this work, values of the heat transfer coefficient between the membrane walls and the bed include contributions of particle convection, gas convection, cluster convection, gas conduction and also radiation. The heat transfer conditions in the CFB combustor were analyzed for five sizes of bed inventory, with Sauter mean particle diameters of 0.219, 0.232, 0.246, 0.365 and 0.411 mm (Geldart group B). The operating parameters of a circulating fluidized bed combustor covered a range of 3.13–5.11 m s^{-1} for superficial gas velocity, 22.3–26.2 kg m^{-2} s^{-1} for the circulation rate of solids, 0.11–0.33 for the secondary to primary air ratio and 7.16–8.44 kPa pressure drop. Furthermore, the bed temperature, suspension density and the main parameters of cluster renewal approach were treated as experimental variables along the furnace height. To estimate the local bed to wall heat transfer coefficient, some experimental data from CFB boiler and some simple correlations were used. A simple semi-empirical method was proposed to estimate the overall heat transfer coefficient inside the furnace as a function of particle size and suspension density with an accuracy of 21%. Computationally obtained results were compared with the experimental data for CFB unit in a large-scale. It was observed that both bed particle sizes as well as the suspension density significantly influence heat transfer conditions.

1. Introduction

In the recent 20 yr the construction of circulating fluidized bed combustors has been developed with progressively increasing capacity of the CFB units. The use of circulating fluidized bed technology with regard to heat and power generation is the most popular one due to such factors as fuel flexibility, high efficiency, compact furnace size, good heat transfer characteristics, efficient combustion, adaptability to load change and also low emission of pollutants. Detailed information on the current status of circulating fluidized bed technology with time in different regions of the world was presented [1,2]. Heat transfer data from CFB units in a large-scale are rarely presented due to commercial reasons and measuring difficulties. Until now, only a limited number of studies [3–6] have treated the effect of bed particle size on the heat transfer coefficient at the wall surface in a laboratory scale at low furnace temperatures, from 338 to 673 K. Moreover, several experimental works on heat transfer inside the furnace chamber [7–16] were carried out in circulating fluidized beds with different mean particle diameters, at bulk temperature in the measurement section varying from 923 to 1173 K. These results obtained by different authors [3–16] confirm that larger particles give a lower overall bed-to-wall heat transfer coefficient. Moreover, the experimental studies in a laboratory scale were focused on the effects of suspension density [7,17–20] being a dominant factor influencing CFB heat transfer, superficial velocity and the circulation rate of solids [21–23], bed hydrodynamic parameter which effects the motion of solids (i.e. disperse phase and cluster phase) in the vicinity of wall, cluster formations [24,25]. Besides, there is a thicker radiation shield influencing a decrease in radiation flux and also gas gap thickness [8,26,27] having some influence on the radiation heat transfer as opposed to conduction heat transfer through a thin gas layer. Based on these literature data it was observed that geometry of the bed cross section and bed hydrodynamics strongly influence heat transfer conditions. Fluidized bed reactors of rectangular and square cross-sections are commonly employed in many industrial circulating fluidized bed applications [28–31] such as: oxy-fuel combustion systems, quenched reactors, external heat exchangers, reactors for surface coating and decoating, food

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Nomenclature

a	regression coefficient, –
A	cross-sectional area, m^2
A/D	analog-to-digital, –
b	regression coefficient, –
B	back-scatter fraction, –
c	specific heat, kJ (kg K)$^{-1}$
c_{sf}	cluster solid fraction, –
C_D	drag coefficient, –
CFB	circulating fluidized bed, –
d_p	mean bed particle size, mm
D_h	hydraulic diameter, m
e	emissivity, –
f	fractional of the wall covered by clusters, –
g	acceleration due to gravity, m s^{-2}
G_s	solids circulation flux, kg m^{-2} s^{-1}
G_{sh}	lateral solids flux, kg m^{-2} s^{-1}
h	bed-to-wall heat transfer coefficient, W (m^{-2} K^{-1})
H	height of furnace, m
H_{bed}	height of bed, m
h_c	cluster heat transfer coefficient, W (m^{-2} K^{-1})
h_g	gas convection heat transfer coefficient, W (m^{-2} K^{-1})
h_r	radiation heat transfer coefficient, W (m^{-2} K^{-1})
j	regression coefficient, –
k	thermal conductivity, W (m K)$^{-1}$
KR	solid recirculation rate, –
L_c	cluster characteristic travel length, m
m_{down}	circulating mass flow, kg s^{-1}
m_{fuel}	fuel mass flow, kg s^{-1}
$m_{sorbent}$	sorbent mass flow, kg s^{-1}
n	empirical constant in Eq. (29), –
p	pressure, kPa
Pr	Prandtl number, –
Re	Reynolds number, –
RH	reheater, –
SA/PA	secondary to primary air ratio, –
SH	superheater, –
t_c	cluster residence time, s
T	temperature, K
W	thermal capacity of boiler, MW_{th}
U_c	cluster descent velocity, m s^{-1}
U_{mf}	minimum fluidization velocity, m s^{-1}
U_o	superficial gas velocity, m s^{-1}
U_t	terminal velocity of bed solid particles, m s^{-1}
x	horizontal distance, m
Y	fraction of particles in the dispersed phase, –
z	height above the air distributor, m

Greek symbols

ε	voidage, –
ε_{avg}	cross-sectional average voidage at the considered location, –
ε_{mf}	voidage at minimum fluidization, –
Δ	non-dimensional gas layer thickness between the wall and cluster, –
ΔH	distance between the pressure tappings, m
Δp	pressure drop, kPa
ΔT	furnace temperature difference, K
λ	excess air ratio, –
μ_g	dynamic viscosity of the gas, Pa s
ρ	density, kg m^{-3}
ρ_b	suspension density, kg m^{-3}
σ	Stefan–Boltzmann's constant, W (m^{-2} K^{-4})

Superscriptsad

	air dried basis
ar	as received

Subscripts

avg	average value
b	bed
c	cluster
cal	calculated value
con	convection component of heat transfer coefficient
d	dispersed
exp	experimental value
g	gas
i	bottom level above grid in Eq. (33)
$i+1$	upper level above grid in Eq. (33)
max	maximum value
p	particle
rad	radiation component of heat transfer coefficient
ref	reference value
sat	saturation
w	wall

freezing and drying, treatment on metallic and polymeric surfaces. Thus, the heat transfer study is essentially used to properly/economic design and scale-up of heat transfer surfaces like water membrane walls. With regard to CFB unit in a large-scale, in order to understand the heat transfer process occurring inside CFB reactors, good knowledge of heat transfer mechanism and also the bed hydrodynamics is required. These aspects are of prime importance to optimize and control the furnace temperature with fast changing of load and taking into account different fuels. A proper size of bed particles inside the combustion chamber makes it possible to obtain the vertical distribution of suspension density necessary to maintain the optimum operating temperature and improve its performance.

It is generally known that the heat transfer process inside CFB furnace can be considered to be made-up of three different components: particle convection, gas convection and radiation heat transfer component. Particle convection takes place at areas of the wall which are covered by a dense phase in the form of clusters or strands. When bed particles hardly ever touch the heat transfer surface, the remainder of the wall area is uncovered by clusters or strands and finally heat is transferred to the wall by a fluidizing medium (i.e. air or flue gases) or a disperse phase in the form of a dilute particle-gas mixture. The gas motion at the wall is tied to turbulent fluctuations in the overall gas flow and may be augmented by the motion of the neighboring particle clusters. At elevated bed temperatures the rate of the heat transfer to the wall increases due to an increase in gas conductivity and the contribution of radiation heat transfer. Radiation serves to augment the heat transfer both to the uncovered surface as well as the surface covered by clusters [32].

The aim of this paper is to analyze the effect of bed particle size on heat transfer which is characteristic for the inside of supercritical circulating fluidized bed combustor. In this work, a method to estimate the overall bed-to-wall heat transfer coefficient in CFB furnace, above the secondary air injection level, where membrane wall surfaces are located. The proposed semi-empirical method describes the effective heat transfer rate and provides a correlation between the heat transfer coefficient and the bed particle size. For these reasons, the heat transfer model was tested on the experimental data from CFB boiler in a large-scale. Performance tests