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Effect of bed particle size on heat transfer between fluidized bed of group b particles and vertical rifled tubes

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ABSTRACT

The effect of bed particle size on the local heat transfer coefficient between a fluidized bed and vertical rifled tubes (38 mm-O.D.) has been determined in a large-scale circulating fluidized bed (CFB) reactor. Bed particles with different Sauter mean particle diameter within the range of 0.219–0.411 mm and particle density in the range of 2650–2750 kg/m^3 were used as bed material in this heat transfer study. A gas fluidized bed furnace with 27.6 × 10.6 m cross-section above refractory line and 48 m in height was used. Air coal firing conditions at the membrane wall in the form of water tubes welded with lateral fins corresponded to a suspension density covering the range of 1.36–6.22 kg/m^3, furnace temperatures in the range of 1080–1164 K, a superficial gas velocity varied from 2.99 to 5.11 m/s and solids circulation flux covered a range of 23.3–26.2 kg/(m^2 s). For these operating conditions, the heat transfer analysis of CFB reactor with detailed analysis of bed-to-wall heat transfer coefficient along furnace height was investigated. In this work, the overall heat transfer coefficient was estimated using a mechanistic heat transfer model based on cluster renewal approach. The experimental results show that: (i) higher heat transfer coefficients along furnace height were found under finer bed particles size $d_p < 0.241$ mm, (ii) heat transfer data confirms strong dependency of the overall heat transfer coefficient on suspension density and also hydrodynamic conditions within CFB furnace, (iii) for small bed particles, $d_p < 0.233$ mm, the particle convection component plays dominant role in heat transfer mechanism, (iv) for large bed particles, $d_p > 0.366$ mm, the effect of particle size on relative contribution of radiation from dispersed phase become essential with particle diameter increasing, and (v) for all bed particles with diameters in the range of 0.240–0.411 mm, the gas convection heat transfer coefficient between the fluidized bed (Geldart B particles) and the rifled tubes increased as the bed particles size increased.

1. Introduction

In the design and scale-up of active heat transfer surface for circulating fluidized bed (CFB) reactors is necessary knowledge about energy transport from the core region towards the heat exchangers (i.e. membrane walls, wing walls, omega panels, curtain walls) inside combustion chamber. Water membrane walls are commonly used in combustion or exothermic applications. In large-scale CFB boiler two kinds of membrane wall structures are utilized as active heat transfer surface: *Walther type* in the form of the fin as an integral part of the tube and *American type* in the form of the fin welded to the tube [1]. Wing walls in the form of vertical steam tube panels are located parallel or perpendicular to the furnace walls in the upper part of freeboard zone (i.e. exit region with dilute lean phase). Usually these heat exchangers cover up to about 50% of the furnace height from the furnace ceiling. Meanwhile, omega panels are formed as a few vertical and horizontal tube bundles which are located in the core of the near exit zone. Curtain walls have similar location to the omega panels in furnace chamber of CFB system. In CFB combustors, curtain walls are formed as discrete continuous vertical panels over almost the entire height of combustion chamber. To improve heat extraction from fluidized bed external heat exchangers (EHE) in CFB systems are used. According to Foster Wheeler's idea, the external heat exchangers (INTREX^{tm}) are integrated with sidewalls of combustion chamber. The INTREX^{tm} for second generation circulating fluidized bed boilers are located between the downcomer (after compact separators) and openings at the lower section of furnace with dense phase. This design ensures inside a combustion chamber controlling and maintaining the optimum operating furnace temperature. The thermal behavior of these surfaces depends on structure, geometry configuration [2], location inside furnace [1,3,4] and also gas-solid flow structure [5,6]. Moreover, the knowledge of the heat transfer processes and the contribution of heat transfer mechanisms are vital for proper operation and load turndown of commercial CFB combustors. The

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understanding of the heat transfer mechanisms has been therefore of major importance because of the need for reliable equations which can be applied to a variety of gas-solid CFB systems and operating conditions.

The heat transfer process inside combustion chamber depends upon several factors, for instance: suspension density [7], bed temperature [8], CFB unit load [9], air staging [10], and also characteristic parameters of flue gas [11]. To achieve reasonable predictions on bed-to-wall heat transfer coefficient detailed furnace data (bed temperature, suspension density, etc.) are required to characterize the heat transfer process between the surface and the fluidized bed (i.e. particle-gas suspension flow). Experimental heat transfer data can be transformed into design equations through comparison with available mechanistic models e.g. single particle model, cluster renewal approach and continuous film models.

In single particle models, heat transfer process is considered at the particle level. The primary concern of the single-particle models is to treat the first layer of particles adjacent to the active heat transfer surface. The single-particle model proposed by Di Natale et al. [12] considers the average surface void fraction as the only regression parameter for description of the effect of pressure, temperature, particle diameter and also solid/gas physical properties in a wide range of experimental conditions. An alternative model in order to explain the heat transfer behavior of circulating fluidized bed is the cluster renewal approach. Major feature of the cluster renewal model is the assumption that clusters formed from bed particles downward travel a certain distance and then dissolve or detach themselves from the heat transfer surface. Various researchers [13–19] developed a heat transfer model based on cluster renewal approach for the prediction of the heat transfer coefficient in circulating fluidized bed combustors. They conducted experiments in which heat transfer coefficient was considered to consist of three major components: particle and gas convective heat transfer and radiative heat transfer.

In other heat transfer investigations in CFB facilities, authors [20] developed the concept of temperature penetration depth to evaluation of heat transfer behavior near the wall of gas-solid fluidized beds, according to the cluster renewal approach. They derived two different expressions for heat transfer coefficient for partial and total heat penetration steps. Zarghami et al. [21,22] developed a comprehensive model to predict particle residence time on an active heat transfer surface based on particle behavior near the surface. In the above-mentioned study [21], the radioactive particle tracing technique has been employed to evaluate the radial distribution of bubbles and clusters and the variation of particle residence time. Moreover, the proposed theoretical stochastic model [22] takes into account the wall effect on bubbles and clusters in the bubbling fluidized bed. Nevertheless, the model proposed by the authors [21, 22] can be applicable to turbulent fluidization.

Unlike the cluster renewal approach, the continuous film model assumes that the walls of CFB furnace are always covered by a homogeneous film of gas and solids. Downward movement of solids takes place through an annulus region. Any part of the wall does not come in contact with the up-flowing gas jointly with dispersed phase. Chen et al. [23], Leckner [18] and Mahalingam et al. [24] have used the continuous film model to calculate the heat transfer coefficient.

Limited numbers of researchers have been focused on effect of bed particle size on heat transfer behavior in the laboratory scale units [25–27] or numerical simulations [28], but as far as the authors know, there are no studies about how bed particle size influences on heat absorption from particle-gas suspension to the membrane wall in commercial CFB boilers with high bed diameter and high thermal capacity (>900 MW$_{\text{th}}$). Nonetheless, Andersson [29] considered the effect of bed particle size on heat transfer process between bed and membrane wall in circulating fluidized bed boiler. However, all experimental results were obtained in a 12 MW$_{\text{th}}$ CFB furnace with small cross-sectional area (1.5 × 1.7 m). Thus, this work addresses an existing gap in the CFB literature data. Consequently, carrying out comprehensive studies would make it possible to establish the optimal heat transfer conditions in correlation with the bed particle size. It is expected that the results of present heat transfer study would stimulate discussion and development of cluster renewal approach for heat transfer in large-scale circulating fluidized beds. This would eventually enable detailed characteristic of heat transfer mechanisms in circulating fluidized bed combustors. The knowledge of heat transfer mechanisms is essential for optimum thermal design and scale-up of heat exchangers for CFB boilers.

The current work deals with the assessment of the impact of bed particle size on heat transfer process from the core region to the water membrane walls with rifled tubes. A mechanistic heat transfer model based on cluster renewal approach was used to predict the bed-to-wall heat transfer coefficient in the 966 MW$_{\text{th}}$ CFB boiler. Moreover, the relative contribution of heat transfer mechanisms in a large-scale furnace chamber is discussed in detail. All heat transfer data were correlated with bed particle size.

In summary, this heat transfer study makes a useful contribution to the existing literature on the heat transfer mechanisms in circulating fluidized bed and also facilitates safer combustor design and operation of CFB boilers.

2. Heat transfer model

In the present work, the mechanistic heat transfer model based on cluster renewal approach was used to predict bed-to-wall heat transfer characteristics for better understanding heat transfer mechanism to enhance combustion efficiency at lower operating costs. The principal mechanisms of energy transport from the core region towards the active heat transfer surface are four heat transfer modes: (i) particle convection, (ii) gas convection, (iii) radiation from dispersed phase, and also (iv) radiation from clusters. Contribution of individual heat transfer mechanisms is considered separately by reason of the intricate character of the bed hydrodynamics. The bed hydrodynamic conditions are influencing on the contributions of heat transfer components generated within the furnace chamber of a circulating fluidized bed reactor. Thus, it is difficult to predict overall heat transfer coefficient with confidence. The mechanistic model used in this heat transfer study assumes the core-annulus flow structure above the secondary air injection level inside furnace. Besides, the fast fluidized bed consists of a continuous up-flowing gas phase with dispersed solids (i.e. relatively dilute suspension) and clusters (or strands) traveling downwards. These clusters are formed in the vicinity of wall for certain distance and then disintegrate and again reforming periodically, as shown Fig. 1.

Thus, there is a characteristic length over which clusters maintain their identity. According to the particle renewal theory given by Mickley and Fairbanks [30], at any point of time a membrane wall is partially occupied by clusters and the rest is exposed to the dispersed phase or the gas phase. This fact is due to a major feature of gas-solid flow structure within combustion chamber of CFB reactors.

So, the overall heat transfer coefficient can be written as the sum of four heat transfer mechanisms contributions as follows:

$$h = fh_p + (1-f)h_g + fh_{rc} + (1-f)h_{rd}, \tag{1}$$

where f is the fractional wall coverage by clusters, h_p and h_g represent the convective heat transfer coefficient due to the particle and the gas phase, h_{rc} and h_{rd} are the radiative heat transfer contribution of the cluster and the dispersed phase, respectively. The fraction of wall area covered by clusters can be determined from:

$$f = 1 - \exp\left[-4300(1-\varepsilon)^{1.39}(D_h/H)^{0.22}\right], \tag{2}$$

where ε denotes the cross-sectional bed average voidage, D_h means the hydraulic diameter and H represents the furnace height. The correlation

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