Recent Studies of Heat Transfer Mechanisms in a Fluidized Bed

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Abstract: ***A fluidized bed is mostly used in the thermochemical energy conversion of biomass and coal due to its high combustion and thermal efficiency, as well as its fuel flexibility, low emissions, and simple design. Heat transfer phenomena are vital in the operation of a fluidized bed reactor, therefore, it is imperative to understand the heat transfer modes in the bed for optimum design and operational performance output. This treatise presents an overview of the heat transfer status and predictions in fluidized bed combustion (FBC) for clean energy, with regards to power and heat generation. It accentuates the operational performance factors that affect the heat transfer in a fluidized bed combustion as well as the performance output. The study concludes with a summary of recent emerging trends and progress in a fluidized bed heat transfer knowledge and makes an outlook on the future regarding the challenges and opportunities for the technology. The paper also identifies areas related to fluidization, which is critical for the technology and, hence, will merit further research.***

Additional keywords: *Fluidized Bed, Heat Transfer, Computational Fluid Dynamics, Discrete Element Method, Thermal Conductivity*

Nomenclature

CFD	Computational Fluid Dynamics
DEM	Discrete Element Method
FBC	Fluidized Bed Combustion
DOM	Discrete Ordinates Method
LES	Large Eddy Simulation
FB	Fluidized bed

Greek

μ	viscosity
ρ	Density
β	Drag
τ	Stress

Subscripts

g	Gas
s	solid
cl	cluster
p	particle

1 Introduction

Combustion is the attractive and established technique of generating combined heat and power from biomass or biofuel and coal. The study of heat transfer complexities in relation to the combustion conversions in industrial or laboratory scaled combustion chambers are indispensable to engineers and researchers. Thorough knowledge and understanding of the combustion processes and heat transfer modes facilitate the attainment of high thermal efficiency and low pollution or emissions. Therefore, heat transfer plays a key role in the physical, mechanical, and chemical processes of biomass and coal combustion. Heat transfer significantly contributes to the combustion performance as it determines the energy balance of the reaction process and system as well as influencing the progress of the reaction paths.

Fluidized bed (FB) reactors are extensively used in biomass and coal combustion, energy conversion and other industrial applications due to their capability to handle different types of fuel and low emissions [1–3]. Additionally, they have high thermal and combustion efficiency, simple in design, and are flexible to load change [4]. They have a wide application range in the combustion of biofuels. Fluidized bed reactors are categorized into bubbling fluidized bed, circulating and the conical fluidized bed. The circulating and conical fluidized beds are an upgraded version of the bubbling fluidized bed, thus a second generation fluidized bed [5]. Many fluidized bed applications require the addition or extraction of heat in order to maintain and regulate the desired operating temperature [6,7]. The bed heat transfer and combustion sub-conversion processes are influenced by several parameters such as the bed particle size, suspension density, superficial gas velocity, bed geometry, bulk temperature and gas gap thickness [5,6]. Hence, developing a better understanding of the heat and mass transfer processes as well as the hydrodynamics or physics of a fluidized bed process is of much importance for the design and optimization of the reactor. The heat transfers in a fluidized bed comprise of particle-fluid (convection), particle-particle (conduction) and the radiative heat transfer [5]. Convection (particle-fluid) and radiative heat transfers are dominant in a fluidized bed [8].

In recent times, extensive investigations (theoretical, experimental, and numerical) have been performed on fluidized bed heat transfer mechanisms. Computational fluid dynamics (CFD) could reliably be an effective and efficient tool to predict the bed operating characteristics, heat transfers and the combustion sub-conversions. The modelling of heat and mass transfer in a fluidized bed involves the macroscopic continuum method (CFD) and the microscopic discrete (discrete element method, DEM) technique. The continuity, momentum and the energy equations are used to model the continuum approach. The combined CFD-DEM approach has been widely used to evaluate thermal and heat transfer phenomena in a fluidized bed performance. Besides the computational studies, several experimental investigations have also been presented on a fluidized bed in literature.

Kalita *et al*. [9] studied the effects of biomass particle size on heat transfer modes in a fluidized bed combustion and found that convection heat transfer coefficient increases with

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increasing superficial velocity and system pressure. According to the authors, the bed suspension density increased with heat transfer whereas the radial heat transfer coefficient decreased from the wall to the bed for all operating conditions. In the study by [4], the effect of particle size on heat transfer in a circulating fluidized bed was examined. A semi-empirical method was used to determine the heat transfer coefficient as a function of suspension density and particle size. They contend that the numerical analysis correlated well with the experimental data. The finer or smaller particles showed a high heat transfer coefficient. Saldarriaga *et al.* [10] studied the influence of bed composition and superficial gas velocity on fluidized bed-surface heat transfer. The heat transfer increased from the wall to the spout of the bed as well as for larger bed height and high superficial velocity.

Blaszczuk and Nowak [11] sought to study the particle convection, gas convection, and radiation effects in relation to the overall heat transfer influence on a fluidized bed reactor performance. Their experimental test disclosed a fluctuating internal bed temperature. However, the suspension density was sensitive to the bed height and the gas superficial velocity. The particle convection heat transfer coefficient predominated in the bed to wall whereas the radiative heat transfer coefficient decreased with increasing suspension density. The writers concluded that the experimental investigations correlated well with available reactor data from a large-scale circulating fluidized bed. Hou *et al*. [12] have investigated the heat transfers in a fluidized bed with a CFD-DEM model combined with convection, conduction, and radiation heat transfer models. They investigated the variation of different heat transfers in the fluidized bed in different flow regimes. The authors deduced that the numerical study of the fluidized bed agreed well with the experimental data. However, they reported that their model needs improvement in order to predict the particle heat transfer analysis of CFD-DEM simulation, so as to be able to quantify the macroscopic motion or the energy conservations, constitutive relations, and the boundary conditions used in the continuum based thermochemical behaviour evaluations. Im *et al*. [13] have reviewed experimental and numerical heat transfer methods modelling and behaviour in a fluidized bed. They elaborated on the various numerical simulation modelling schemes as well as experimental investigations employed in a fluidized bed reactor heat transfer and performance prediction.

In 2016, Gan *et al*. [14] investigated the effects of particle size on heat transfer in a fluidized bed. They aimed to assess the influence of ellipsoidal and spherical particles on conductive heat transfer as well as radiative and convective heat transfer in the bed. Convective heat transfer was higher in prolate particles when compared with the sphere and oblate particles. Luo *et al*. [15] reported on heat transfer of the particle-scale modelling of gas-solid motion in a bubbling fluidized bed making use of the LES-DEM approach. They concurred that the higher the superficial velocities the higher the convective heat transfer coefficient, therefore, the overall heat transfer was dominated by convective heat transfer. Moreno *et al*. [16] have investigated the heat transfer coefficient of biomass gas and solid particles surface. The investigations predicted surface heat transfer with a percentage deviation of 15 % when the numerical analysis was compared with the experimental data. Abdelmotalib *et al*. [17] have evaluated the hydrodynamic and heat transfer effects in a fluidized bed combustion using the Eulerian-Eulerian two-fluid model coupled with the kinetic theory of granular flow. The gas velocity and granular temperature effects on the wall-to-wall heat transfer coefficient were determined. The numerical and the experimental studies showed an increasing heat transfer coefficient with increasing gas velocity and pressure drop.

Krzywanski *et al*. [18] aimed to study the bed to wall heat transfer coefficient of a circulating fluidized bed using the fuzzy logic surrogate model. They confirmed that the computational results agreed well with the experimental data showing a percentage difference of between 1 % and 3 %. The effects of biomass particle size on radiative heat transfer have been evaluated in a fluidized bed by [19] using an in-house Method of Lines radiation code combined with the Discrete Ordinates Method (DOM). Changing the biomass or fuel particle sizes resulted in significant variations in radiative heat fluxes on the bed wall. In order to understand the particle temperature distribution in a fluidized bed reactor, Li *et al*. [20] applied experimental and numerical techniques to study the hydrodynamic and thermal behaviour of the reactor. The thermogravimetric and simultaneous thermal analysis were used to examine the kinetics, heat, and equilibrium effects. The temperature field and the particle position were captured using infrared thermography (IT) and a visual camera. They confirmed that the experimental method presented a detailed thermal behaviour of the bed and was accordant with the numerical investigations.

Irrespective of the progress made in the evaluation of convective and radiative heat transfer phenomena in FBs adopting both experimental and numerical investigations, hitherto comprehensive facts on the particle convective heat transfer, thermal radiation and temperature distribution is inconsistent. In addition to this, few of the previous studies highlights the significance of conductive heat transfer in FB combustors. This work aims to review the heat transfer mechanisms and modes in a fluidized bed and the substantive factors that influence the heat transfer and the fluidized bed performance. This involves discussion of several treatises of heat transfer studies in the literature. The respective mechanistic models, as well as experimental and computational modelling of FB heat transfer occurrences, have also been presented. The study concludes with a summary of observations as well as remarks on fluidized bed heat transfer investigations that needs further research.

2 Heat transfers in a fluidized bed

The heat transfers in a fluidized bed combustion or gasification are radiation (particle-wall, particle-particle, and fluid-particle), convective (particle- fluid), and conduction (particle-particle or particle-wall). Alternatively, the heat transfer methods can be further classed as surface-bed, gas–bed, and particle-bed heat transfer [5]. In addition, the heat transfer in a fluidized bed occurs by particle convection or conduction, gas convection, and radiation. The contribution of heat transfer coefficient of these heat transfer phenomena is very important at elevated temperatures. The overall heat transfer coefficient is estimated from the individual heat transfer coefficients.

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$$h_{overall} = h_{c,p} + h_{c,g} + h_{rad} \quad (1)$$

where, $h_{c,p}$ is the particle convective or conductive heat transfer coefficient., $h_{c,g}$ is the gas convective heat transfer coefficient, and h_{rad} is the radiative heat transfer coefficient.

The particle convection and the interphase gas convection are the heat transfer coefficients that predominantly influence convective heat transfer in a fluidized bed. The particle convection component depends on the heat transfer by particle circulation between the bulk of the bed and the regions directly adjacent to the heat transfer surface. The gas interface convection component ensures convective mixing, therefore, enhancing the heat transfer in the gas gaps between the particles and the heat transfer surface and between neighbouring particles.

2.1 Convective heat transfer

Convective heat transfer characterizes the propagation of heat energy in a fluid medium in the static or dynamic state and occurs when there is a temperature difference or gradient between gas and solid. It can occur naturally or using mechanical means. Alternatively, the flow can be internal or external as well as laminar or turbulent for both the natural and forced convective heat transfers. Convective heat transfer is predominant in a fluidized bed reactor [2,21] at temperatures (< 700 °C). The surface geometry and temperature, the fluid temperature and velocity, and the fluid thermophysical properties characterise the magnitude of the convective heat transfer coefficient [22].

2.2 Conduction heat transfer

Conduction heat transfer occurs in a solid medium due to a temperature jump in that medium or direct contact between the particles. It takes place as the transfer of kinetic energy in fluids which are either by particle-particle path or particle-fluid-particle path. The heat transfer by conduction is very dominant in static granular fluidized bed and contributes much to the overall heat transfer in fluidized bed performance. It is very substantial in bed particles with large thermal conductivity [14]. Nevertheless, experimental investigations have shown that the heat transfer by conduction from a cluster of the solid particle to a heating surface is much larger than heat transfer by convection [5] in a fluidized bed reactor.

2.3 Radiative heat transfer

Radiative heat transfer occurs when two solid surfaces having different temperatures are separated by a transparent fluid phase. Heat transfer by radiation is prevalent in fluidized combustors at high temperatures and contributes or accounts for 70 % [23] of the heat transfer in the bed. At high temperatures of between 700 °C and 1000 °C, radiation heat transfer becomes more and more significant in the bed thermochemical and combustion processes [19, 24–26]. However, at low temperatures, radiation heat transfer can be neglected [22]. A fluidized bed with thicker wall and higher particle concentration increases the bed radiation resistance and hence decreases heat transfer by radiation in the furnace. Contrariwise, radiation heat transfer decreases with the bed particle size or diameter and increases with increasing bed superficial gas velocity.

3 Heat transfer mechanistic models

Fundamentally the principles applied in predicting heat transfer modes in a fluidized bed are analogous to the basic heat transfer theories in thermodynamic science studies. However, several mechanistic heat transfer models have been postulated to describe the heat transfer modes and mechanisms in FB. These include mechanistic heat transfer coefficient models for the particle-convection (the single phase models, cluster renewal models, continuous film models), thermal radiation (surface interchange models, and continuous medium models) and last but not least the gas-convection models. Some of these models are briefly discussed in this treatise.

3.1 Particle-convective heat transfer

3.1.1 Single particle, cluster renewal and continuous film models

These models are fundamentally adopted to model the particle-convective heat transfer component. In the single particle model particles are presumably considered to have the same initial temperature as the bed bulk temperature and close to the bed wall. However, there is heat exchange between the wall, particles and the surrounding gas. The heat transfer coefficient owing to single particle convection is expressed as [27].

$$h_s = \frac{1.574(1-c)k_g}{d_p c^{0.5}} \quad (2)$$

Regarding the cluster renewal model, the heat transfer coefficient is given as [27,28].

$$h_s = \frac{1}{\frac{d_p}{nk_g} + \left(\frac{t\pi}{4k_{cl}C_{pcl}\rho_{cl}}\right)^{0.5}} \quad (3)$$

Considering the continuous film model the FB walls are assumed to be covered with a homogeneous film of gas and particles, nonetheless, the gas in the core does not have contact with the wall [27]. The heat transfer coefficient is computed with the relation.

$$h_s = \frac{1}{\frac{d_p}{10k_g} + \frac{1}{h_z}} \quad (4)$$

where C_{pcl} and ρ_{cl} refers to the cluster heat capacity and the density. d_p is the dimensionless particle diameter.

The local heat transfer coefficient of the moving emulsion layer is defined using the relation.

$$h_s = \frac{k_e}{\delta_z} + 2\frac{k_e}{\delta_z}\sum_{i=1}^{\infty} exp\left\{\frac{-i^2\pi^2 k_e t}{\rho_e C_{pe}\delta_z^2}\right\} \quad (5)$$

k_e and k_g are the effective suspension and gas conductivities.

3.2 Thermal radiation heat transfer

3.2.1 Surface interchange models

The radiation between the wall and the bed is modeled as the surface interchange between two or more plates [27]. In this paper, Brewster [29] deduced a formulation for the thermal radiation with respect to the heat flux to the wall as:

$$q_r = \frac{\frac{e_{eff}}{a_{eff}}\sigma T_b^4 - \frac{e_w}{a_w}\sigma T_w^4}{\frac{1}{a_{eff}} + \frac{1}{a_w} - 1} \quad (6)$$

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Basu [30] considered the transfer of radiation from clusters close to the wall and disperse phase to the wall and defined a relationship for the radiation heat exchange coefficient for the surface interchange as [31,32]:

$$h_r = f_w h_{r,cl} + (1 - f_w) h_{r,d} \quad (7)$$

Where

$$h_{r,cl} = \frac{\sigma(T_b^4 - T_w^4)}{\left(\frac{1}{e_{cl}} + \frac{1}{e_w} - 1\right)(T_b - T_w)} \quad (8)$$

and

$$h_{r,d} = \frac{\sigma(T_b^4 - T_w^4)}{\left(\frac{1}{e_d} + \frac{1}{e_w} - 1\right)(T_b - T_w)} \quad (9)$$

where $h_{r,cl}$ and $h_{r,d}$ denotes heat exchange coefficient due to cluster radiation and disperse phase radiation. T_b and T_w are the bulk and wall temperature. e_d and e_w defines the disperse phase and wall emissivity.

3.3 Gas-convective heat transfer

The gas convective heat transfer coefficient in a fluidized bed can be evaluated with this relation [27,28,32].

$$h_g = \frac{k_g C_p}{d_p C_g} \left(\frac{\rho_{dis}}{\rho_p}\right)^{0.3} \left(\frac{u_t^2}{g d_p}\right)^{0.21} Pr \quad (10)$$

C_p and C_g defines the particle and gas heat capacity.

4 Numerical modelling of FB heat transfer

The heat transfer mechanisms in a fluidized bed have been modelled using different mechanistic and empirical approaches. Moreover, investigators have proposed other methods such as the macroscopic and the particle scale which involves the tracing of particle motion and temperature in the fluidized bed reactor. However, it is difficult to quantify the heat transfer phenomena with this technique. Hou *et al.* [33] highlighted that the particle scale method is limited in defining the basic details or structural information of heat transfer mechanisms. In view of this, numerical and computational investigations have been performed recently in order to establish a comprehensive understanding of the heat transfer mechanisms in fluidized beds. The method includes coupling of the computational fluid dynamics (CFD) study and discrete element modelling (DEM) analysis of a fluidized bed [34]. In the DEM model, the explicit time integration method is used to determine the translational and rotational motions of the discrete particles. This approach provides discrete coordinates, velocity, and reactions of the contact particles at each time step. Therefore, the solid particles are modelled at individual levels.

The computational fluid dynamics method deals with continuum analysis of macroscopic particles. In the CFD or the continuum approach, the macroscopic behaviour of the particles is examined using the continuity, momentum, and the energy equations together with constitutive relations. Thus, the CFD approach uses the continuity and Navier-Stokes equations to examine the phase parameters. The effectiveness and reliability of the approach depend on the constitutive relations of the reactor solid and fluid phases as well as the momentum exchange between the phases [35]. Above all, the CFD-DEM approach has had intense developments and has proven to be effective and efficient in assessing most of the macroscopic and microscopic scale characteristics for complex units involving multiphase flow analysis [36,37].

4.1 CFD-DEM investigations

The CFD-DEM computational technique has been extensively implemented to study the heat transfer phenomena in FB in recent years in order to understand the heat transfer and hydrodynamic behaviour in the reactor so as to be able to predict their performance. Some of the current updates and developments on this method are reviewed and discussed in this section. Lu *et al*. [38] have studied the effect of bed-wall heat transfer in a supercritical water and gas-solid fluidized bed using the Eulerian two-fluid scheme based on kinetic theory of granular flow. They sought to examine the influence of particle distribution, temperature distribution, and transient heat transfer characteristics in the bed. The supercritical water FB, bed-wall heat transfer coefficient was susceptible to the supercritical velocity with low volume fraction. However, the gas-solid fluidized reactor bed-wall heat transfer and volume fraction effect was vice versa. The bed-wall heat transfer is mainly due to convection heat transfer. In the analysis by [3], the DNS-IB numerical approach was implemented to study heat transfer of spheres in a fluidized bed. The maximum heat transfer occurred near the entrance of the bed due to a high particle-fluid temperature gradient. However, as the fluid moves up, it warms and decreases the heat transfer rate. The average Nusselt number increased with increasing fluidization velocity. The work by [39] combined a semi-empirical three-dimensional model and the radiative zone method to investigate FB radiative heat transfer. A uniform temperature was obtained with a higher heat flux on the bed wall. Nevertheless, radiation effect was predominant in the upper part of the furnace where the gas is dominant. Cannetto *et al*. [40] simulated a fluidized bed in order to determine the reactor behaviour at different gas velocities applying the Eulerian scheme together with the kinetic theory of granular approach. According to the authors, the investigation showed that their proposed numerical model is capable to analyse the gas-solid phase performance of the bed. The mass balance behaviour on heat transfer in a large-scale circulating fluidized bed has been presented by [41].

In 2016, [6] investigated the heat transfer in a fluidized bed aiming at the effects of surface geometry on the heat transfer phenomena. Compared to the cylindrical geometry, the spheres showed the highest heat transfer. Nikku *et al*. [42] have also studied the momentum exchange effect in biomass FB with regards to the particle size and shape. Im *et al*. [43] studied the heat transfer and hydrodynamic features of a conical fluidized bed using the Eulerian-Eulerian technique. The effect of specularity coefficient on a fluidized bed heat transfer has been examined by [44]. The wall-bed heat transfer coefficient decreased with increasing specularity coefficient. Dihn *et al*. [45] analysed the performance of a bubbling fluidized bed adopting the Eulerian multi-fluid model incorporated with the kinetic theory of granular flow. They intend to evaluate the heat transfer and hydrodynamics effects on the bed performance. Heat transfer phenomena in the furnace were examined using solid temperature distribution, the variation of heat flux, and the heat transfer

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coefficient. The heat transfer was sensitive to solid concentrations and prevalent in the dense bed regions.

Bellan *et al*. [36] have evaluated the hydrodynamics and heat transfer effects in FB. The maximum bed temperature is highly dependent on the top layer position and focal point of the concentrated radiation. Simulation of municipal solid waste incineration has been presented by [46] using the CFD-DEM approach. The DEM method was performed using an in-house code and coupled to the ANSYS FLUENT CFD software. They evaluated the impacts of conduction, convective and radiation heat transfer between the particles in the bed. Increasing the radiative heat flux accelerates the release of volatiles and the drying process. Raghavan *et al*. [47] investigated the effects of temperature on FB performance. The air velocity, temperature, and particle size were varied to evaluate their effect on the bed heat transfer. Fluidization velocity decreased with increasing temperature for smaller particles and vice versa for larger particles.

4.2 Computational fluid dynamic scheme

The Eulerian method or the two-fluids (Eulerian-Eulerian method) combined with the granular kinetic theory are the CFD models most widely used in fluidized bed numerical modelling. The Eulerian approach is capable of providing profound understanding and information about the local values of phase hold-ups and their spatial distribution, which is vital for comprehensive knowledge and understanding of the heat transfer processes in a fluidized bed [48]. Alternatively, the Eulerian-Eulerian method (two-fluid method (TFM)) is the extensively used CFD scheme or model due to its less computational time and high accuracy [47]. As pointed out earlier the conservation and constitutive equations are beneficial for characterizing the particles and flow behaviour in FB. The mass conservation for the gas and solid phase are determined with these equations [50–52].

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\right) = 0 \quad (11)$$

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\right) + \nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\right) = 0 \quad (12)$$

On the other hand, the momentum equation for the gas and solid phase are expressed as [53,54]:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{v}_g\right) + \nabla\cdot\left(\alpha_g\rho_g\vec{v}_g\vec{v}_g\right) = -\alpha_g\nabla p_g + \nabla\cdot\tau_g + \alpha_g\rho_g g + K_{gs}\left(\vec{v}_s - \vec{v}_g\right) \quad (13)$$

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s\vec{v}_s\right) + \nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right) = -\alpha_s\nabla p_s + \nabla\cdot\tau_s + \alpha_s\rho_s g + K_{gs}\left(\vec{v}_g - \vec{v}_s\right) \quad (14)$$

K_{fs} refers to the interphase momentum coefficient, p_s and p_f are the phases pressures. g denotes the acceleration due to gravity. τ_s and τ_f are the phase stress tensors. v_g and v_s are the phase velocities. ρ_s and ρ_f are the densities at the solid and gas phase. α_s and α_f express the fluid and solid phase volume fractions.

The stress tensors at the gas and solid phase are defined as [43].

$$\tau_g = \mu_s\alpha_g\left[\nabla\vec{v}_g + \nabla\vec{v}^T{}_g\right] + \alpha_g\left[\lambda_g - \frac{2}{3}\mu_g\right]\nabla.\vec{v}_g I \quad (15)$$

$$\tau_s = \mu_s\alpha_s\left[\nabla\vec{v}_s + \nabla\vec{v}^T{}_g\right] + \alpha_s\left[\lambda_s - \frac{2}{3}\mu_s\right]\nabla.\vec{v}_s I \quad (16)$$

Moreover, the energy conserved at the phases are determined using the relation in equations (17) and (18) [54].

$$\frac{\partial}{\partial t}\left(\varepsilon_g\rho_g H_g\right) + \nabla\cdot\left(\varepsilon_g\rho_g\vec{v}_g H_g\right) = \nabla\cdot\varepsilon_g k_g.\nabla T_g - h_{gs}\left(T_s - T_g\right) \quad (17)$$

$$\frac{\partial}{\partial t}\left(\varepsilon_g\rho_s H_s\right) + \nabla\cdot\left(\varepsilon_s\rho_s\vec{v}_s H_s\right) = \nabla\cdot\varepsilon_s k_s.\nabla T_s - h_{sg}\left(T_s - T_g\right) \quad (18)$$

Some of the constitutive equations essential to close fluidized bed governing equations are delineated in equations 19-35. Granular motion is prevalent by particle-to-particle interactions in FB due to collisions. The granular motion is mostly analyzed with the kinetic theory models. Akin to the gas temperature, the granular temperature is used to define the fluctuations in solid velocity [50]. The kinetic fluctuation energy considered in the numerical modelling is defined in equation 19 for the solid phase [55].

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\left(\alpha_s\rho_s\Theta_s\right) + \nabla.\left(\alpha_s\rho_s\vec{v}_s\Theta_s\right)\right] = \left(-p_s I + \tau_s\right):\nabla.\vec{v}_s + \nabla.\left(k_\Theta\nabla\Theta_s\right) - \gamma_s + \Phi_{gs} \quad (19)$$

where the diffusion coefficient and granular temperature are determined as

$$k_\Theta = \frac{150\rho_s d_s\sqrt{\Theta_s\pi}}{384(1+e)g_0}\left[1 + \frac{6}{5}(1+e)\alpha_s g_{0,ss}\right]^2 + 2\rho_s d_s\alpha_s^2(1+e)g_{0,ss}\sqrt{\frac{\Theta_s}{\pi}} \quad (20)$$

$$\Theta_s = \frac{1}{3}v^2 \quad (21)$$

Gidaspow and Syamlal-O'Brien drag is typically adopted to model FB interphase momentum coefficient and are presented in equations 22, 23 and 26. The Gidaspow drag model is given as [50]:

$$\beta_{gs} = 150\frac{\alpha_s{}^2\mu_g}{\alpha_g d_s{}^2} + 1.75\frac{\alpha_s\rho_g\left|\vec{v}_g - \vec{v}_s\right|}{d_s} \quad for\ \alpha_g \le 0.8 \quad (22)$$

$$\beta_{gs} = \frac{3}{4}C_D\frac{\alpha_s\alpha_g\rho_g\left|\vec{v}_s - \vec{v}_g\right|}{d_s}\alpha_g{}^{-2.65} \quad for\ \alpha_g > 0.8 \quad (23)$$

The drag coefficient C_D is calculated as:

$$\frac{24}{\alpha_g R_{es}}\left[1 + 0.15\left(\alpha_g R_{es}\right)^{0.687}\right] \quad for\ R_{es} < 1000 \quad (24)$$

Or

$$C_D = 0.44\ for\ R_{es} \ge 1000 \quad (25)$$

Syamlal-O'Brien drag model is expressed below in equation 26 [54].

$$\beta_{gs} = \frac{3}{4}\frac{\varepsilon_s\varepsilon_g\rho_g}{v_{r,s}^2 d_s}C_D\left(\frac{Re_s}{v_{r,s}}\right)\left|\vec{v}_s - \vec{v}_g\right| \quad (26)$$

where the drag coefficient is computed from equation 27.

$$C_D = \left(0.63 + \frac{4.8}{\sqrt{Re_s/v_{r,s}}}\right)^2 \quad (27)$$

The Reynolds number for the solid phase is calculated from equation 28:

$$R_{es} = \frac{\rho_g d_s\left|v_s - v_g\right|}{\mu_g} \quad (28)$$

The solid phase shear viscosity μ_s is computed as:

$$\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr} \quad (29)$$

The solid collision viscosity is determined:

$$\mu_{s,col} = \frac{4}{5}\alpha_s\rho_s d_s g_{0,ss}\left(1 + e_{ss}\right)\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (30)$$

For Gidaspow formulation the kinetic viscosity $\mu_{s,kin}$ is estimated from the equation 31:

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$$\mu_{s,kin} = \frac{10 d_s \rho_s \sqrt{\theta_s.\pi}}{96\alpha_s(1+e_{ss})g_{0,ss}} \times \left[1 + \frac{4}{5} g_{0,ss}\alpha_s(1+e_{ss})(3e_{ss} - 1)\right]^2 \quad (31)$$

However, for Syamlal-O'Brien the kinetic viscosity is determined using

$$\mu_{s,kin} = \frac{\alpha_s d_s \rho_s \sqrt{\theta_s.\pi}}{6(3-e_{ss})g_{0,ss}} \times \left[1 + \frac{2}{5} g_{0,ss}\alpha_s(1+e_{ss})(3e_{ss} - 1)\right] \quad (32)$$

Solid frictional viscosity is given as:

$$\mu_{s,kin} = \frac{p_s sin\phi}{2\sqrt{I_{2D}}} \quad (33)$$

Solid bulk viscosity λ_s is estimated using:

$$\lambda_s = \frac{4}{3}\alpha_s \rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (34)$$

The radial distribution function $g_{0,ss}$ is defined as:

$$g_{0,ss} = \left(1 - \left[\frac{\alpha_s}{\alpha_{s,max}}\right]^{1/3}\right)^{-1} \quad (35)$$

4.3 Discrete element method theory

In this method, the discrete particles' motion is determined using Newton's second law of motion. However, the particles in motion are considered as moving mass points, hence, the fluid flow details around the particles are neglected. The particle undergoes three classes of heat transfer: the conductive heat exchange through the contact area between the colliding particle-to-particle and particle-to-wall pair, convective heat exchange between particle and fluid, and lastly radiative heat exchange between the particle and its surroundings. The translational, rotational and the mass and moment of inertia of particle i are shown in equations 36 and 37 [12,57].

$$m_i \frac{d\vec{v}_i}{dt} = m_i \vec{g} + \sum_{j=1}^{n} \vec{F}_{c,jj} + \vec{F}_{D,i} + \vec{F}_{B,i} \quad (36)$$

$$I_i \frac{d\vec{\omega}_i}{dt} = \vec{T}_i \text{ , } I_i = \frac{2}{5} m_i r_i^2 \quad (37)$$

where I denote the moment of inertia, m is the mass of the particle. $\vec{v}_i$ and $\vec{\omega}_i$ are translational and rotational velocities of the particles. $\vec{T}_i$ denotes the torque applied on the particle. It is worth to note that the CFD and DEM schemes or modules are coupled together to model the heat transfer and FB performance.

5 Experimental studies of a fluidized bed heat transfers

Relevant experimental investigations have been conducted to determine the performance of a fluidized bed reactor with respect to the heat transfer and hydrodynamics occurrences in the bed. The experimental test ensures the examination of controllable factors such as heat transfer coefficient, particle size, bulk temperature, system pressure, suspension density, and superficial velocity in order to establish reliable design parameters for fluidized combustors.

Tsuji *et al*. [57] have quantified the heat transfer and temperature as well as particle motion in a fluidized bed using particle tracking velocimetry (PTV) and infra-red thermography (IT). The convective motion and temperature of the bed individual particles were investigated. Sun *et al*. [58] have evaluated heat transfer characteristics in a biomass fluidized bed combustion. Higher biomass quantity ensures uniform temperature profiles and higher bed-wall heat transfer in the bed. However, the fine particles yielded from the combustion phenomena reduced the thickness of the heat-conduction gas layer between clusters and water wall, hence improving the heat transfer coefficient by 10%. In the recent analysis by [59], transient gas-particle heat transfer in a fluidized bed was predicted using emitted infrared radiation. They applied the non-intrusive, high spatial resolution, and time-varying experimental approach. The high rates of energy stored in the particles were found along the particulate downward entrainment zones surrounding the inlet gas channel. The analysis witnessed new gas-particle heat transfer coefficient in the spouting fountain with increased spatial resolution. Consequently, the highest convective heat transfer coefficients were noticed at the core of the fountain due to high turbulent mixing nature, relative velocity differences, and unsteady periodic spout swaying.

Yang *et al*. [60] examined the heat transfer between freely moving spheres and small particles. The surface resistance parameters were determined using the test results. The wall-bed convection heat transfer coefficient in a fluidized bed riser has been measured by [61]. Garić-Grulović *et al*. [62] discussed the analogy between momentum exchange and heat transfer in a fluidized bed reactor. They investigated the influence of particle size, voidage, and velocity on heat transfer in the bed. The heat transfer coefficients and fluid-particle interphase drag coefficient were also studied. The heat transfer coefficient decreases with increasing voidage. Peters *et al*. [63], using infra-red thermography, digital image analysis, and particle tracking velocimetry determined the heat transfer in a fluidized bed. The investigators suggested that their experimental method provides details in establishing the heat transfer in a fluidized bed for different particle size, aspect ratio, and gas velocity. Abdel-Aziz *et al*. [64] studied the heat and mass transfer in a three-phase fluidized bed having high-density particles at high gas velocities. They deduced that the solid particles decreased the gas hold-up and the interfacial contact area between the gas and liquid. Mandal *et al*. [65] have also experimentally determined the heat transfer impact in a gas-solid packed fluidized bed. Somjun and Chinsuwan [66] investigated the heat transfers in a fluidized bed and indicated that wedge membrane fins are capable of improving the heat transfer on the bed wall.

6 Factors influencing fluidized bed heat transfer and performance

Several parameters influence fluidized bed performance and heat transfer phenomena which includes, the suspension density, the bed geometry, velocity of gas flow, the bed temperature, heat transfer coefficient, and particle size. Of late, both experimental and numerical investigations have been performed to determine the performance of FB reactor regarding the heat transfer and hydrodynamics phenomena in the bed. The experimental investigation is used to validate the numerical studies of the aforementioned performance indicators and determinants for a reliable design and predictions of FB performance.

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6.1 Particle size

The heat transfer coefficient in a fluidized bed invariably depends on FB unit particle size. Notably, the gas-solid phase fluidization behaviour depends on the particle diameter. The contact resistance is directly proportional to the particle diameter. Hence, the influence of particle size on heat transfer is typically relevant at smaller particle size and the heat flux inside the bed will substantially increase with smaller particles [67]. However, at higher temperatures, the situation is very critical since the particle diameter influence conduction, convection and radiation heat transfer between the wall and the particles [13]. Relatively, smaller bed particles have higher heat transfer than larger particles due to the larger specific interfacial area which favourably promotes heat transfer. Ngoh [49] found that the rate of heat transfer from air to particles depends on the amount of interfacial surface area, which increases with high voidage within the bed. However, the voidage increased with smaller particles and the overall temperature difference between the gas and solid phases decreased with smaller particles. According to [8,71], the shape of particle size distribution is a relevant parameter with regards to the heat transfer in FB reactors. Pagliuso *et al.* studied the effects of radiation heat transfer in FB furnace for five narrowed sized diameter quartz sand particles (179, 230, 385, 460, and 545 μm) [71]. They correlated an empirical formula for the heat transfer coefficient as a function of the particle size and suspension density as:

$$h = h_R \left(\frac{d_R}{d}\right)^n \tag{37}$$

Nonetheless, the effect of particle diameter on the heat exchange has an exponential shape. In other investigative studies by Blaszczuk *et al.* [68], smaller and finer bed particles generated higher bed-to-wall heat transfer coefficient than larger ones. They used bed particles with Sauter mean diameter ranging from 0.219-0.411 mm. The heat transfer coefficient increases rapidly and becomes maximum in the FB for finer particles. The impact of fluid-particle and radiation from the dispersed phase in bed-to-wall heat transfer coefficient is exacerbated by the increase in bed particle size, particularly for coarse bed particles. However, the cluster radiation component in the heat transfer mechanism gradually decreases along the furnace height with an increase in bed particle diameter. On the other hand, smaller particle size can considerably promote conduction and convection in the bed. This is possible as a result of the large temperature drop across the particles. It has been reported elsewhere [69] that large particle size could contribute to high rate of particle-particle heat transfer coefficients and heat transfer in the fluidized bed. Andersson [70] have studied the effects of particle size on heat transfer in circulating fluidized bed boilers implementing experimental evaluations. The study was performed using silica sand with average diameters of 0.22, 0.34, and 0.44 mm. The bed-to-wall heat transfer exchange was independent of particle size for all the tested particle diameters. Meanwhile, the distribution of heat flow around the tube and fin geometry was susceptible to particle size for different bulk densities. Xie *et al.* [75, 76] have modelled the heat transfer in a circulating fluidized bed. The writers demonstrated that particle size influences heat transfer via its effect on the gas gap thickness, its impact on heat convection between the gas and particles and finally its influence on the suspension radiation absorption and scattering. Xie *et al.* confirmed that the total heat flux increases with the particle size at low temperatures. However, at high suspension temperatures, the circumstance is more difficult owing to the particle diameter effects on the convection and radiation heat transfer. Therefore, the heat flux could increase or decrease with decreasing particle size.

6.2 Bed temperature

A fluidized bed temperature is a function of the heat transfer which influences the gas phase physical properties and the bed fluid dynamics [2]. Increasing temperature can affect the particles and fluids reaction kinetics. The higher the bed bulk temperature the higher radiative and convective heat transfer coefficients. Accordingly, as the bed temperature increases the thermal conductivity and specific heat of the fluidized gas increases [55] so as the fluid-particle heat transfer coefficient but the gas density decreases. Likewise, FB volume fraction, as well as the gas superficial velocity and particle configuration and size, will considerably impact the thermal conductivity. In this regard, the bed radiation heat transfer can be amplified as well as the influence of other heat transfer occurrences. At lower bed temperatures below 500 ℃, radiative heat transfer is insignificant but as the bed temperature starts to rise above 500 ℃ and at higher temperatures, thermal radiative heat transfer becomes a vital component in the bed. In addition, at higher temperatures, the radiative heat transfer element escalates at a faster rate due to the rapid growing T^4-factor [41]. Basu *et al.* [28] studied the bed-to-wall heat transfer in a pressurized fluidized bed and showed that the rise in heat transfer coefficient with high temperatures is attributed to the increase in thermal conductivity of the fluidizing gas as well as the rise in radiation from the bed at high temperatures. He *et al.* [73] have studied the heat transfer mechanism in a high temperature circulating fluidized bed using numerical evaluations. They investigated the influence of bed temperature on particle-convective heat transfer, gas-convective heat transfer, and radiative heat transfer and their overall contribution to the total heat transfer. The study disclosed that as the height of the FB furnace increases the bed temperature at the upper part of the furnace increases. However, the radiative and gas-convective heat transfer increases. The radiative heat transfer accounted for about 30-60 % of the total heat transfer whereas gas-convective heat transfer contributed 8-18 % of the total heat transfer. Patil *et al.* [74] have investigated the effects of temperature on heat transfer in circulating fluidized bed using bed particles of size 460 μm. Three different bed units were implemented in the study and it was indicated that the temperature decreased with increasing riser cross-section and decrease the heat transfer. In [71], the authors postulated that heat flux increases with increasing temperature due to an increase in radiation, a higher driving force for conduction and increased in the thermal conductivity of the FB gas.

6.3 Suspension density

The suspension density is one of the key parameters which predominantly influences a fluidized bed heat transfers [7,68]. The heat transfer is a function of the bed suspension

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density, however, as the bed height increases the suspension density decreases so as the heat transfer. For FB units the gas thermal capacity is lower than the solids, therefore, the heat transfer across the solids will be significantly higher. In a pertinent analysis by [76], they highlighted that suspension density monotonically increases with increasing bed operating pressure and likewise the axial heat transfer coefficient with regards to the weight composition ratios for biomass and sand blends. The workers noticed that the suspension density was higher at 90 gm and 60 gm weight compositions in their investigations. The particle concentration in the bed annulus wall positively impacts the suspension density of FB. Meanwhile, FB with higher suspension density will have a thicker wall layer and possibly amass more particles in it. Thence, a thicker FB wall layer and higher particle concentration reinforce the radiation resistance, however, attenuating the radiative heat transfer [6,22] across the bed. All the same, the propensity of particle-particle conduction heat transfer component will be enhanced.

On the contrary, in denser FB's the wall is significantly exposed to the cooled layers of the wall cluster than the bed inner hot part. As a consequence, a change in the bed load owing to a decrease in the suspension density, the convective heat transfer decreases whereas the radiative heat transfer increases [77]. Eriksson [75] have investigated the radiation heat transfer in circulating fluidized bed (CFB) combustor using the two flux method. The radiation heat transfer coefficient decreased significantly with suspension densities less than 20 kg/m^3. It was found that increment in particle concentration of the clusters, the fraction of wall covered by clusters as well as the wall layer thickness could intensify the tendency of radiation heat transfer. However, as the suspension density decreases the total heat transfer coefficient decreases and this is more and more significant in industrial CFB. Golriz [32] have developed and formulated empirical correlations to predict the heat transfer in circulating fluidized bed. The radiative heat transfer at the bed membrane walls was about twice the convective heat transfer at low suspension densities. However, at higher suspension densities the contribution of both heat transfer modes were of the same magnitude.

6.4 Superficial gas velocity

Increasing fluidized bed gas superficial velocity can lead to a pressure drop at the bed riser and increased suspension density. However, higher gas velocity can perhaps enhance the bed radiation heat transfer as a result of thin wall layer owing to the increased particle distribution [75]. On the other hand, improved gas velocity ensures homogeneous mixture in the bed, therefore, enhancing the heat transfer from the walls to the particles and amongst the particles [45]. The influence of gas velocity on heat transfer coefficients depends on its effects on the solid motion near the wall [75]. Banaei [52] have investigated the influence of gas velocity on FB heat transfer using numerical evaluations. The fluidized bed is highly isothermal at increasing gas velocities owing to improved solids circulation and enhanced gas-solid contacts. Thus, the bed solids temperature was noticed to be uniform at higher superficial gas velocity and average Nusselt number. However, the bed overall Nussellt number, average gas velocity, average solid temperature and maximum temperature decreased with the gas velocity. Recently, Kumar and Agarwal [50] showed that FB is uniformly fluidized at a superficial gas velocity of 0.25-0.35 m/s. According to [77] apart from a dilute bed, the superficial gas velocity does not greatly impact heat transfer. Nevertheless, in large-scale reactors, a change in the primary air increases the heat transfer coefficient and the reverse is true for a change in the secondary air in the upper part of the reactor.

7 Conclusions

A brief overview of the current heat transfer mechanisms and modes studies in a fluidized bed has been discussed. The various techniques for evaluating heat transfer mechanism in fluidized bed has been presented as well as the respective performance parameters that influence heat transfer in the bed and FB performance. The following conclusions are made from the study:

1. The study of heat transfer modes in a fluidized bed is of much importance as it influences the overall performance of the bed. Though the heat transfer in a fluidized bed is very complicated and rigorous the combined computational fluid dynamics and discrete element (CFD-DEM) method has shown to be very effective in modelling and predicting a fluidized bed heat transfers and characteristic behaviour. The CFD-DEM methods such as the Eulerian-Eulerian technique, the two-fluid model (TFM), and the Eulerian-Lagrangian were found to be computationally stable and have a better accuracy in determining the heat transfer phenomenon in the bed. It can be used to identify and quantify the underlying or significant variables that influence the heat transfer modes. In conclusion, the computational models or schemes are still state-of-the-art models and needs more improvement in order to quantify particle scale and mesoscale heat transfer information in the numerical investigations. The computational modelling is limited to the multiphase flow [42] of the furnace. Hence, it requires more effort to involve a wider range of different heat transfer phenomena and components.
2. Fluidized bed reactor heat transfer is either through convection, conduction, or radiation. These heat transfers are susceptible and sensitive to controlling parameters such as the superficial gas velocity, particle size, bed geometry, bed peak temperature, suspension density, and heat transfer coefficient. Albeit these factors influence the bed heat transfer phenomena and the overall performance. It cannot be conclusively confirmed that their effects on the heat transfer and the overall reactor performance output are constant as their impact on the bed performance varies from bed to bed or phase to phase. Accordingly, the bed heat transfers and hydrodynamic behaviour may vary for different bed geometry and designs.
3. Amongst the heat transfer mechanisms radiative and convective heat transfer have indicated to be predominant. Under very high temperatures radiative heat transfer dominates in the fluidized bed contributing to about 70% of the heat transfer in the bed. However, it is significant to elucidate the underlying effects of heat transfer by radiation on the bed performance. In spite of the considerable investigations that have been performed

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on the bed convective and radiative heat transfer phenomenon yet detail information on the particle convective motion and temperature distribution is inadequate. With regard to this, new techniques such as the infrared thermography, particle tracking velocimetry, and digital image analysis have been employed to further study these fields. Lastly, conductive heat transfer investigations in a fluidized bed are limited, therefore, much effort and study has to be directed in that area.

4. To sum up, experimental investigations together with numerical evaluations have recognized to present a better picture or reflection of the heat transfer mechanisms as well as the hydrodynamic processes in a fluidized bed reactor.

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