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Heat transfer in fluidized beds with immersed surface: Effect of geometric parameters of surface

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ABSTRACT

In this work CFD simulations of a fluidized bed with an inserted heated surface were carried out in order to study heat transfer, focusing on the effect of the surface geometry in this phenomenon. The Eulerian-Eulerian model along with the kinetic theory of granular flows were used to describe the gas-solid behavior. The experimental set-up consisted of a bed with 1.8 m height and 0.1 m diameter with glass bead particles. Gas was introduced at a constant velocity. To define the best setup for this case, different drag models, specularity coefficients, and a turbulence model were tested. It was verified that the best results were obtained with the Gidaspow drag model, a specularity coefficient equal to 0.1, and the $\kappa-\varepsilon$ RNG dispersed turbulence model. Inside the bed, ten different immersed heated surface geometries were described, including cylinders, spheres and cones. The spheres resulted in the highest heat transfer coefficient, and the cylinders, the lowest. An increase in the diameter of the immersed cylinder led to drastic changes in the bed hydrodynamics and a consequent decrease in the heat transfer coefficient.

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1. Introduction

Fluidized beds are versatile equipment characterized by high rates of heat and mass transfer, which allow numerous uses in the chemical industry. The applications of fluidized beds encompass a vast range of physical and chemical processes, including fluid catalytic cracking [1,2], coating [3], drying [4], synthesis reactions [5], combustion [6], and gasification [7,8]. Despite the several uses of fluidized beds, engineers and researchers still encounter challenges in their modeling and scale up. These difficulties prove that the complex phenomena occurring inside fluidized beds are still not completely understood.

Often, the addition or removal of heat in a fluidized bed is required, especially when the process includes chemical reactions. Therefore, it is extremely important to understand how this phenomenon is affected by several of its parameters. Over the years, researchers have been conducting experiments to clarify this question. They identified the solids suspension density as the factor that most influences the heat transfer coefficient [9–13]. One of the main advantages of the fluidized bed is the high rates of heat transfer between the bed and the immersed surface. Thus, the study of this phenomenon is an important field of research that needs to be further elucidated. Stefanova et al. [14] measured the heat transfer coefficient between the bed and a heated tube and found that this parameter was larger in the turbulent regime. Abid et al. [15] studied the influence of the angle of a heated tube inside a fluidized bed in the heat transfer, verifying changes caused by the hydrodynamic behavior close to the tube. Sundaresan and Kolar [9] analyzed the effects of the size and axial position of the heat transfer surface. Di Natale et al. [16] empirically tested different heated surface geometries and verified that the heat transfer coefficient can vary up to 40% depending on the geometry.

In recent years, computational advances have given rise to computational fluid dynamics (CFD), an important tool that has been widely used by researchers to gain an understanding of the hydrodynamics and heat transfer in fluidized beds. Two different approaches are regularly employed in studies of fluidized beds. The Lagrangean approach is a discrete method based on molecular dynamics. The Eulerian approach considers both gas and particulate phases as an interpenetrating continuum [17]. The first approach requires a large computational effort and is not viable for industrial cases. Thus, the Eulerian approach is most commonly used for the simulation of fluidized beds, and even though it does not provide the same level of detail as the Lagrangean approach, it has been producing satisfactory results. When using the Eulerian approach, it is a common practice to use the kinetic theory of granular flows to describe the rheology of the particulate phase.

The kinetic theory of granular flows (KTGF) assumes that the behavior of the particulate phase is similar to that of gases, by drawing analogy with the kinetic theory of gases [18,19]. The KTGF was used along with the Eulerian approach in various heat transfer studies in a fluidized bed. Schmidt and Renz [20] used the KTGF to predict the heat transfer coefficients of a fluidized bed with an immersed tube. Behjat et al. [21]

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Table 1
Governing equations.

Conservation of mass		Equation
Gas:	$\frac{\partial(\varepsilon_g\rho_g)}{\partial t}+\nabla\cdot(\varepsilon_g\rho_g\vec{v}_g)=0$	(5)
Solids:	$\frac{\partial(\varepsilon_s\rho_s)}{\partial t}+\nabla\cdot(\varepsilon_s\rho_s\vec{v}_s)=0$	(6)
Conservation of momentum		
Gas:	$\frac{\partial(\varepsilon_g\rho_g\vec{v}_g)}{\partial t}+\nabla\cdot(\varepsilon_g\rho_g\vec{v}_g\vec{v}_g)=\nabla\cdot(\tau_g)-\varepsilon_g\nabla P-\beta(\vec{v}_g-\vec{v}_s)+\varepsilon_g\rho_g g$	(7)
Solids:	$\frac{\partial(\varepsilon_s\rho_s\vec{v}_s)}{\partial t}+\nabla\cdot(\varepsilon_s\rho_s\vec{v}_s\vec{v}_s)=\nabla\cdot(\tau_s)-\varepsilon_s\nabla P-\nabla P_s+\beta(\vec{v}_g-\vec{v}_s)+\varepsilon_s\rho_s g$	(8)
Phase stress–strain tensor		
Gas:	$\tau_g=\mu_s\varepsilon_g(\nabla\vec{v}_g+\nabla\vec{v}_g^{T})+\frac{2}{3}\varepsilon_s\mu_s(\nabla\cdot\vec{v}_g)\mathbf{I}$	(9)
Solids:	$\tau_s=\mu_s\varepsilon_s(\nabla\vec{v}_s+\nabla\vec{v}_s^{T})+\varepsilon_s(\xi_s-\frac{2}{3}\mu_s)\nabla\cdot\vec{v}_s\mathbf{I}$	(10)
Conservation of energy		
Gas:	$\frac{\partial}{\partial t}(\varepsilon_g\rho_g H_g)+\nabla\cdot(\varepsilon_g\rho_g\vec{v}_g H_g)=\nabla\cdot\varepsilon_g\kappa_{g,eff}\nabla T_g-h_{gs}(T_s-T_g)$	(11)
Solids:	$\frac{\partial}{\partial t}(\varepsilon_s\rho_s H_s)+\nabla\cdot(\varepsilon_s\rho_s\vec{v}_s H_s)=\nabla\cdot\varepsilon_s\kappa_{s,eff}\nabla T_s+h_{sg}(T_s-T_g)$	(12)
Drag models		
Wen & Yu [30]		
	$\beta=\frac{3}{4}C_D\frac{\varepsilon_s\varepsilon_g\rho_g\lvert\vec{v}_s-\vec{v}_g\rvert}{D_p}\varepsilon_g{}^{-2.65}$	(13)
	$C_D=\frac{24}{\varepsilon_g Re_s}[1+0.15(\varepsilon_g Re_s)^{0.687}]$	(14)
Gidaspow [18]		
$\varepsilon_g>0.8$	$\beta=\frac{3}{4}C_D\frac{\varepsilon_s\varepsilon_g\rho_g\lvert\vec{v}_s-\vec{v}_g\rvert}{D_p}\varepsilon_g^{-2.65}$	(15)
$\varepsilon_g\le 0.8$	$\beta=150\frac{\varepsilon_s(1-\varepsilon_g)\mu_g}{\varepsilon_g D_p^2}+1.75\frac{\rho_g\varepsilon_s\lvert\vec{v}_s-\vec{v}_g\rvert}{D_p}$	(16)
	$C_D=\frac{24}{\varepsilon_g Re_s}[1+0.15(\varepsilon_g Re_p)^{0.687}]$	(17)
Syamlal & O'Brien [31]		
	$f=\frac{C_D Re_s\varepsilon_g}{24v_{r,s}^2}$	(18)
	$C_D=\left(0.63+\frac{4.8}{\sqrt{\frac{Re_s}{v_{r,s}}}}\right)^2$	(19)
	$\beta=\frac{3\varepsilon_s\varepsilon_g\rho_g}{4D_p v_{r,s}^2}C_D\frac{Re_s}{v_{r,s}}\lvert\vec{v}_s-\vec{v}_g\rvert$	(20)
	$v_{r,s}=0.5(A-0.06Re_s+\left(\sqrt{(0.06Re_s)^2+0.12Re_s(2B-A)+A^2}\right)$	(21)
	$A=\varepsilon_g^{4.14}$	(22)
	$B=\begin{cases}0.8\varepsilon_g^{1.28} & for\ \varepsilon_g\le 0.85\\ \varepsilon_g^{2.65} & for\ \varepsilon_g>0.85\end{cases}$	(23)
Beetstra [28]		
	$\beta=180\frac{\mu_g}{D_p^2}\frac{(1-\varepsilon_g)^2}{\varepsilon_g}+18\frac{\mu_g}{D_p^2}(\varepsilon_g^3)(1-\varepsilon_g)(1+1.5\sqrt{1-\varepsilon_g})+0.31\frac{\left(\frac{1}{\varepsilon_g}+3\varepsilon_g(1-\varepsilon_g)+8.4\mathrm{Re}_s^{-0.343}\right)}{\left(1+10^{3(1-\varepsilon_g)}\mathrm{Re}_s^{-\frac{1}{2}(1+4(1-\varepsilon_g))}\right)}$	(24)

Table 2
Constitutive equations.

Constitutive equations		Equation
Solids pressure [34]	$p_s=\varepsilon_s\rho_s[1+2(1+e)\varepsilon_s g_0]\Theta_s$	(25)
Solids bulk viscosity [34]	$\xi_s=\frac{4}{3}\varepsilon_s\rho_s D_p g_0(1+e)\sqrt{\frac{\Theta_s}{\pi}}$	(26)
Solids shear viscosity	$\mu_s=\mu_{s,KTGF}+\mu_{s,f}$	(27)
	$\mu_{s,KTGF}=\mu_{s,col}+\mu_{s,kin}$	(28)
Collisional viscosity	$\mu_{s,col}=\frac{4}{5}\varepsilon_s\rho_s D_p g_0(1+e)\sqrt{\frac{\Theta_s}{\pi}}$	(29)
Kinetic viscosity	$\mu_{s,kin}=\frac{10\rho_s D_p\sqrt{\pi\Theta_s}}{96(1+e)g_0}[1+\frac{4}{5}(1+e)g_0\varepsilon_s]^2$	(30)
Frictional viscosity [35]	$\mu_{s,f}=\frac{p_s\ ,\sin\theta}{2\sqrt{I_{2D}}}$	(31)
Radial distribution function [34]	$g_0=\left[1-\left(\frac{\varepsilon_s}{\varepsilon_{s,\ ,max}}\right)^{\frac{1}{3}}\right]^{-1}$	(32)
Granular energy dissipation	$\gamma_s=\frac{12(1-e^2)g_0}{D_p\sqrt{\pi}}\rho_s\varepsilon_s^2\Theta_s^{\frac{3}{2}}$	(33)

Table 3
Dimension of the different surfaces used.

Geometry	Diameter (mm)	Height (mm)	Heat transfer area (mm^2)
Cylinder 1	20	30	2435
Cylinder 2	20	40	3063
Cylinder 3	20	60	4320
Cylinder 4	20	80	5576
Cylinder 5	40	30	6205
Cylinder 6	60	30	11,231
Sphere 1	28	–	2384
Sphere 2	40	–	4948
Cone 1	30	31	2251
Cone 2	40	40	4066

simulated a polymerization reactor and verified an increase in the temperature at the top of the bed due to the exothermic reaction. Armstrong et al. [22] conducted a parametric study for various restitution coefficients, particle diameter sizes and inlet velocities in a fluidized bed. Chang et al. [23] investigated the heat transfer between particles of different classes in a bubbling bed. They concluded that this heat transfer mechanism is much smaller than the heat transfer between gas and particles. Armstrong et al. [24] showed that the addition of immersed tubes in a fluidized bed leads to changes in the hydrodynamics of the bed and consequently in the heat transfer phenomenon. Although a large number of parameters have already been studied, the role of the immersed surface geometry in the heat transfer phenomenon is still not complete elucidated.

This study aims to show how the heat transfer coefficient is influenced by the geometric shape of the immersed heat transfer surface. For this, the Eulerian approach was used along with the KTGF. The influence of different drag models, specularity coefficients and turbulence modeling in the heat transfer coefficient is shown. Results for the heat transfer coefficient for ten distinct surface geometries are presented.

2. Mathematical modeling

The Eulerian multiphase model for granular flows was used in FLUENT 14.0 to describe the behavior and interactions of the granular and gas phases in a fluidized bed. This model solves the two phases individually using the conservation equations shown in Table 1. Both phases are present in all control volumes of the grid so that the sum of the volume fraction of both phases is equal to unity. The conservation of momentum for different phases is coupled through the drag force term $\beta\cdot(\vec{v}_g-\vec{v}_s)$. Most drag models were created using empirical data; however new methods, such as lattice-Boltzmann simulations, have been showing good results [25–29]. Four different drag models were tested in this study: Wen & Yu [30], Gidaspow [18], Syamlal & O'Brien [31] and Beetstra [28]. The selection of Wen & Yu, Gidaspow and Syamlal & O'Brien models was based in an extensive literature review where it was found that these are the most widely used drag models in fluidized beds simulations [6,17,32,33]. Beestsra model was included because it was recently developed using the results of Lattice-Boltzmann simulations, therefore providing a good source of comparison with other models, that have empirical bases. The mathematical descriptions of four drag models are presented in

Table 4
Mean heat transfer coefficient calculated with different drag models.

Drag model	Mean heat transfer coefficient ($W\cdot m^{-2}\cdot K^{-1}$)
Experimental [16]	230.00 ± 6.00
Gidaspow [18]	171.10
Syamlal & O'Brien [31]	158.58
Wen & Yu [30]	142.77
Beetstra [28]	142.65

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