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CFD simulation and experimental validation for wall effects on heat transfer of finite cylindrical catalyst ☆

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ABSTRACT

In this paper, heat transfer of single cylindrical particle affected by wall has been investigated numerically and experimentally for Reynolds number range 2000 to 6000. The heat transfer in two different orientations, axial and cross flow over the particle has been considered in simulation with MultiPhysics Software FEMLAB version 2.3. The heat and mass transfer analogy technique has been applied for validation of the simulation results. The coated particle with naphthalene was sublimated to obtain the corresponding Sherwood numbers. The results show that the CFD model can predict the particle-to-fluid heat transfer for two situations due to trivial error (an average error of 6%) compared to experimental values. Influence of wall on heat transfer of particle in seven different bed-to-cylinder diameter ratio (N = 1.66, 2.65, 2.75, 5, 6.66, 12, and 18) have been discussed in different velocities. According to obtaining results, with increasing the bed-to-cylinder diameter ratio over the 12 wall have no significant consequence on Nusselt number. Due to this fact, a CFD based correlation has been proposed to consider the wall effects on particle-to-fluid Nusselt number with an average error of 2.19%.

1. Introduction

Packed-beds are widely used in petrochemical, fine chemical and pharmaceutical industries. Detailed knowledge of flow in the void space of such packed beds is essential for understanding different characteristics of these beds. Heat transfer plays an important role in consideration of packed bed performance, and in view of this fact it had been very essential in previous studies. Consideration of single cylindrical particle heat transfer in cross flow is one of these aspects. There exist hundreds of experimental studies in terms of local and mean heat transfer in this case. The majority of these studies mainly focus on dependency of Nusselt on Reynolds and Prandtl numbers and their effects on heat transfer.

Zukauskas and Morgan have completely considered the heat transfer of cylinder [1,2]. Although the effects of free turbulence flow on heat transfer effects have been taken into account in these studies; moreover, wall effect and length to cylinder diameter ratio have been ignored. Churchill et al. [3] have proposed a correlation for calculating mean heat transfer that has been used in many other works in this field as verification case. They claimed that turbulence flow, wall effects, and channel to cylinder diameter ratio have minor effects on the heat transfer. Quarmby and Al-Fakhri [4] have scrutinized the effect of length to cylinder diameter ratio on heat transfer. They experimentally considered a range of length to cylinder diameter ratio between 1 and 12. In so doing, they found for short cylinders (aspect ratio is smaller than 4), the effect of aspect ratio on mean heat transfer is considerable and when this ratio is bigger than 4 it can be ignored. This fact was considered by Chang and Mills [5] that led to derive a correlation in terms of Nusselt number with respect to length to cylinder diameter ratio. Because of extreme difficulty in measuring fluid flow and heat transfer inside the bed by conventional means without disturbing the packing arrangement, efforts towards improvement in modeling using computational fluid dynamics (CFD) have been recently developed. In general, 2D and 3D CFD models have been used in various fields to simulate flow profiles and heat transfer. The earliest CFD fixed bed simulations used two-dimensional models. Dalman et al. [6] investigated an axisymmetric radial plane. This work gave a first insight in flow structure in fixed beds. McKenna et al. [7] obtained valuable insight into the effect of particle size on particle–fluid heat transfer from 2D CFD study of small spherical particles. They have validated their basic models with Ranz-Marshal (RM) correlation and have shown the weakness of that correlation in predicting heat transfer from small clusters of spherical particles. Lloyd and Boehm [8] determined the sphere spacing effect on the drag coefficient and the particle to fluid heat transfer by studying on linear array of eight spheres in 2D. It was found that the heat transfer from the spheres decreased with reduction of particle spacing. The 3D models have been applied for packed beds more recently. Derx and Dixon [9] used a simple model to obtain the wall heat transfer coefficient. An eight-sphere model, in which eight spheres are located into two layers with four ones without solid-solid contact points, has been studied by Logtenberg and Dixon [10,11]. This model shows that

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Nomenclature

A	Area
C_p	Specific heat capacity
D	Diameter
j_H	Colbourn j factor (heat transfer coefficient)
j_D	Colbourn j factor (mass transfer coefficient)
k	Thermal conductivity
L	Length of cylindrical particle
Nu	Overall Nusselt number, hD/k
$\overline{Nu}_D$	Circumferentially averaged Nusselt number
P	Pressure
Pr	Prandtl number
Re	Reynolds number
Q	Sink or source term in energy equation
V	Velocity vector
t_o	Thickness of distributor
T	Temperature
y^+	Dimensionless distance from the wall
x	Cartesian x-coordinate

Greek symbols

$C\mu$, $C\varepsilon1$, $C\varepsilon2$	Empirical constant
ρ	Density
μ	Dynamic viscosity
ν	Kinematic viscosity
σ_k, σ	Empirical constant
ε	Turbulence energy dissipation
κ	Turbulence kinetic energy

Subscripts

dis	Distributor
b	Bulk
o	Orifice
p	Particle
t	Turbulent
W	Wall

Superscripts

†	Transpose

conventional fixed bed models could not describe flow and heat transfer behaviors. Nijemeisland et al. [12,13] modeled the heat transfer of low channel to particle ratio by using CFD. They presented an extensive overview of prior work on modeling and measurement of the characteristics of these packed beds. Furthermore, they showed that CFD method is reliable for modeling flow and heat transfer phenomena inside the packed bed. In similar studies, Guardo et al. [14] drew a comparison between the performance in flow and heat transfer estimation of five different RANS (Reynolds-Averaged Navier–Stokes) turbulence models in a fixed bed composed of 44 homogenous stacked spheres. In one of the few heat transfer studies of cylindrical particles, Nijemeisland et al. [15] simulated heat transfer and fluid flow in a near wall segment of a steam reformer tube-filled with cylindrical particles in which inert packing was heated up, they illustrated that particles with no internal voids appear better than particles with internal voids, in the bed interior. In another investigation, AhmadiMotlagh and Hashemabadi [16] have studied two and three dimensional CFD modeling of heat transfer from discrete cylindrical particles in different situations of flow. They reported a good qualitative as well as reasonable quantitative agreement between CFD results and empirical correlations. Romkes et al. [17] investigated the mass and heat transfer characteristics of a composite structured reactor packing containing spherical particles. They showed that the CFD simulations could be used to adequately predict the rate of mass and heat transfer from the catalyst particles to the fluid. In another study, AhmadiMotlagh and Hashemabadi [18] investigated the hydrodynamics and heat transfer characteristics of a randomly packed bed of cylindrical particles with a channel-to-particle diameter ratio of 2. Their results were validated by naphthalene sublimation mass transfer experiments and the particle heat transfer Nusselt number were obtained by the use of analogy between mass and heat transfer.

As it mentioned in above studies, the cylindrical catalysts have been the subject of fewer studies rather than spherical catalysts. In spite of the simplicity of modeling the spherical particles, the growing applications of cylindrical catalysts in reaction engineering requires a vital need for further exploration of heat transfer behavior from these particles. Despite the Reynolds and Prandtl number impacts on heat transfer of packed beds, some secondary parameters such as free stream eddies, particle length to diameter ratio, and fraction of channel to cylinder diameter have some influences on heat transfer phenomenon. Correlations that have been presented for heat transfer coefficient in previous works have been mainly ignored the effect of these secondary factors. On the grounds of this fact, in this paper, effects of some parameters such as tube-to-particle diameter ratio and flow direction on cylinderical particles have been illustrated.

2. Theory

2.1. Governing equations

In this work compressible turbulence steady state flow heat transfer has been taken into account. The conservation equations of continuity, momentum, and energy can be simplified respectively:

$$\nabla\cdot(\rho V) = 0 \tag{1}$$

$$\nabla\cdot(\rho VV) = -\nabla P + \nabla\cdot\left[(\mu+\mu_t)\left(\nabla V + \nabla V^{\dagger}\right)\right] \tag{2}$$

$$\nabla\cdot\left(-(k+k_t)\nabla T + \rho C_p T V\right) = Q \tag{3}$$

where Q is a heat sink or heat source term which is set to zero in this study, μ_t and k_t are the turbulent viscosity and thermal conductivity respectively that μ_t can be defined as:

$$\mu_t = \rho C_\mu \frac{\kappa^2}{\varepsilon} \tag{4}$$

and C_μ is a model constant which is equal to 0.09. The standard **κ-ε** is used in order to take into account of turbulence flow [17]. Where the transport equations for the turbulent kinetic energy **κ** and the turbulence dissipation rate ε are defined respectively [21]:

$$\frac{\partial\kappa}{\partial t} + V\cdot\nabla\kappa = \nabla\cdot\left[\left(\nu + \frac{C_\mu}{\sigma_k}\frac{\kappa^2}{\varepsilon}\right)\nabla\kappa\right] + C_\mu\frac{\kappa^2}{\varepsilon}\left(\nabla V + \nabla V^{\dagger}\right)^2 - \varepsilon \tag{5}$$

$$\frac{\partial\varepsilon}{\partial t} + V\cdot\nabla\varepsilon = \nabla\cdot\left[\left(\nu + \frac{C_\mu}{\sigma_\varepsilon}\frac{\kappa^2}{\varepsilon}\right)\nabla\varepsilon\right] + C_{\varepsilon1}C_\mu\kappa\left(\nabla V + \nabla V^{\dagger}\right)^2 - C_{\varepsilon2}\frac{\varepsilon^2}{\kappa} \tag{6}$$

where the model constants in the above equations are determined, experimentally [16]:

$$C_{\varepsilon1} = 1.44,\ C_{\varepsilon2} = 1.92,\ \sigma_\kappa = 1,\ \sigma_\varepsilon = 1.3$$

Turbulent thermal diffusivity ($k_t/\rho C_p$) is usually related to eddy viscosity via a turbulent Prandtl number ($Pr_t \approx 0.85$–0.9).