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Experimental investigation on effect of random packing with uniform sized spheres inside concentric tube heat exchangers on heat transfer coefficient and using water as working medium

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ABSTRACT

Concentric tube heat exchangers are used extensively by the energy industry. In the present study, the behavior of overall heat transfer coefficient with randomized packing of uniformly sized spheres inside the concentric tube heat exchangers is investigated at the laboratory scale. In this work, the heat transfer coefficient on the tube side is calculated using the experimental measured hot and cold fluid temperature differences, mass flow rates of hot and cold fluid. The correlations of are used to calculate the convective heat transfer coefficient (h_o) on the annular side and tube side of the concentric tubes packed with uniform sized spheres. However, the logarithmic mean temperature difference is the assumption made for the temperature difference across the packed bed. The calculated overall heat transfer coefficient using correlation and experimental measured one are in very good agreement for a given heat load. The reduction in length in comparison to heat exchangers without packing is found to be ∼95%. A packed bed heat exchanger design methodology is presented.

Nomenclature

Symbol	Definition	Unit
A_i	Area on inner side (tube side)	mm^2
A_o	Area on outer side (annular side)	mm^2
C_{pc}	Specific heat capacity of cold fluid	$J\ kg^{-1}\ K^{-1}$
C_{ph}	Specific heat capacity of hot fluid	$J\ kg^{-1}\ K^{-1}$
D_i	Inner diameter of annular side pipe	mm
D_a	Annulus diameter	mm
d_e	Equivalent diameter for annular side packed bed	mm
d_i	Inner diameter of Tube side pipe	mm
d_o	Outer diameter of Tube side pipe	mm
d_p	Particle diameter	mm
f	Friction factor	dimensionless
h_o	Outer side wall heat transfer coefficient (Annular side)	$W\ m^{-2}K^{-1}$
h_i	Inner side wall heat transfer coefficient (Tube side)	$W\ m^{-2}K^{-1}$
h_w	Wall heat transfer coefficient	$W\ m^{-2}K^{-1}$
k_{pipe}	Thermal conductivity of tube wall	$W\ m^{-1}K^{-1}$
k_{sp}	Thermal conductivity of solid balls	$W\ m^{-1}K^{-1}$
k_f	Thermal conductivity of fluid	$W\ m^{-1}K^{-1}$
L	Length of packed bed	mm
$\dot{m}_h$	Mass flow rate of hot fluid	$kg\ s^{-1}$
$\dot{m}_c$	Mass flow rate of cold fluid	$kg\ s^{-1}$
Qc	Heat transfer on cold line	W
Qh	Heat transfer on hot line	W
S_B	Particle surface area per unit volume of packed bed	m^{-1}
T_{hi}	Inlet fluid temperature in hot line	°C
T_{ho}	Exit fluid temperature in hot line	°C
T_{ci}	Inlet fluid temperature in cold line	°C
T_{co}	Exit fluid temperature in cold line	°C
ΔT_{lm}	Logarithmic mean temperature difference	°C
U	Superficial velocity (based on bed cross-sectional area)	$m\ s^{-1}$
U_{pbhe}	Overall heat transfer coefficient for packed bed heat exchanger	$W\ m^{-2}K^{-1}$
V_h	Hot fluid velocity	$m\ s^{-1}$
V_c	Cold fluid velocity	$m\ s^{-1}$
Dimensionless numbers		
Nui	Nusselt number on inner side, $\frac{h_i d_p}{k_f}$	dimensionless
Nuo	Nusselt number on outer side, $\frac{h_o d_p}{k_f}$	dimensionless

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Nuw	Nusselt number near wall region, $\frac{h_w d_p}{k_f}$	dimensionless
Pr	Prandtl number	dimensionless
Re_p	Reynolds number based on particle diameter, $\frac{\rho U d_p}{\mu}$	dimensionless
Re_a	Reynolds number based on annulus diameter, $\frac{\rho V D_a}{\mu}$ where, V = fluid velocity based on bed cross sectional area	dimensionless
Re_e	Reynolds number based on equivalent diameter, $\frac{\rho V_c d_e}{\mu}$	dimensionless
Re	Reynolds number based on pipe or bed diameter, $\frac{\rho U D}{\mu}$	dimensionless
Greek symbols		
ε_t	Void fraction (mean) or Porosity tube side	dimensionless
ε_a	Void fraction (mean) or Porosity annular side	dimensionless
ε_l	Local void fraction (porosity) varying in radial direction	dimensionless
ρ	Density	kg m^{-3}
μ	Dynamic Viscosity	Pa. s
Abbreviations		
PBHE	Packed Bed Heat Exchanger	
NAPB	Narrow Annular Packed Bed	
Subscripts		
a	Annular	
c, h	Cold, Hot	
e	Equivalent	
l	Local	
i, o	Inner, Outer	
p	Particle	

1. Introduction

Energy needs are on rising demand as development is on the fast track mode. In the present times, we are witnessing a huge rise in the energy usage pattern (living standards) of the population with the rapid change in technology. Heat exchange forms significant entity in the energy (power generation) industry. Also, there is enormous demand for heat transfer equipment which are compact and effective. Concentric tube heat exchangers are used extensively by the energy industry. In the present study, the behavior of overall heat transfer coefficient with randomized packing of mono-dispersed spheres packed inside the concentric tube heat exchangers is investigated at the laboratory scale.

Initial work on the wall heat transfer coefficient measurements in packed columns were done by Colburn [1], Leva [2] and Leva and Milton et al. [3]. They have given correlations in which Nusselt number is dependent upon particle Reynolds number (Re_p) and particle to bed diameter ratio (D/d_p = 2.5 to 3.5) with constant wall temperature maintained. The general correlation for Nusselt number in terms of pipe based Reynolds number was given by Schumacher [4] using data of the above mentioned authors. This correlation is valid only for pipe based Reynolds number range greater than 9500 and smaller bed to particle diameter ratios which is shown in Eq. (1).

$$Nu = \frac{h_w D_i}{k_f} = 7.5\ \ (0.023)\,(Re)^{0.75} \tag{1}$$

Chennakesavan [5] conducted experiments for wall heat transfer coefficients measurements in packed beds based on bulk mean temperature of fluids flowing through packings. The constant wall temperature is maintained on the packed bed walls by steam condensation on the outer wall. The outer wall temperature of packed bed was monitored by mounting copper-constantan thermocouples on the wall, the fluid inlet and outlet temperature were measured using thermometers. Uniform sized glass spheres of diameter 3.97 mm and 19 mm were randomly packed in tube of 57.15 mm inner diameter with heating length of 102 mm and liquids used were water, toluene, 45% aqueous glycerin, and nitro benzene.

The correlation given by him is shown in Eqn. (2) which is valid only for pipe based Reynolds number range 900 < Re < 40,000and tried to align with open pipe correlations.

$$Nu = \frac{h_w D_i}{k_f} = \left(0.4 - 0.5\frac{d_p}{D_i}\right)\,(Re)^{0.8}\ \ (Pr)^{0.33}\left(\frac{\mu_f}{\mu_w}\right)^{0.14} \tag{2}$$

Kunii et al. [6] conducted experiments by placing thermocouples in the near wall region of packed bed with air as flowing fluid and constant wall temperature boundary condition maintained by using steam jacket. Celite spheres of diameter 28 mm and 42 mm were packed. They measured heat transfer coefficients in the near wall region and termed it as apparent heat transfer coefficient due to presence of wall region and core region. For the set of experiments conducted, it was also being assumed that the wall region has thickness of half particle diameter from the pipe walls.

Dekhthyar et al. [7] conducted experiments to determine the wall heat transfer coefficients (h_w) in packed bed. Glass spheres of diameter 0.9, 3.2 and 8.9 mm were packed in 52 mm inner diameter copper pipe of length 531 mm with water and 47% aqueous glycerin solution being used as the working fluids. Constant heat flux is maintained on the outer wall of packed bed. The outer wall temperatures of packed bed test section were measured using the 15 copper-constantan thermocouples and the radial temperature profiles were measured near the exit region (x/D_i = 9.03) using thermocouples. The surrounding air, fluid inlet and exit temperatures were also measured using the thermocouples. The governing equation for heat transfer in packed beds was solved analytically and expression for temperature profile is obtained by neglecting the axial conductivity component in packed beds as the flow regime is turbulent in nature.

Wen and Ding [8] conducted experiments using 5 mm diameter glass spheres packed randomly inside the 41 mm inner diameter and 1100 mm long stainless steel pipe with airflow through this test section. They measured the temperature profile along the central axis at eight locations and radial temperature profiles at two axial planes 576 mm and 764 mm from bed entry.

Constant wall temperature (~100 °C) is maintained using ceramic band heaters and suitable control apparatus. They determined the wall heat transfer coefficient and effective thermal conductivity parameters based on the model using the Two-Dimensional Axial Dispersed Plug Flow (2DADPF) model of packed beds. The error minimization method is used to determine the heat transfer parameters. They have found a large temperature drop near the wall region of packed beds and there is good agreement between the determined wall heat transfer coefficients and Li-Finlayson [9] correlation as given by Eq. (3).

$$Nu_w = \frac{h_w d_p}{k_f} = 0.17\ \ Re_p^{0.79} \tag{3}$$

Researchers such as Bogdan and Mohammad [10], Huang et al. [11] have conducted experiments by inserting wire meshes cut in circular form and placed inside pipes while maintained constant heat flux boundary condition on pipe walls with air as working fluid. They have found heat transfer enhancement due to porous structure due to wire meshes. They conclude that given a constant diameter of the porous medium, further improvement can be attained by using a porous insert with a smaller porosity and higher thermal conductivity.

Dekhthyar et al. [7] have studied the wall heat transfer coefficient in annular packed bed using the spherical ball packing inside the annular tube and passing water and 47% aqueous glycerin solution being used as the working fluids. Glass spheres of diameter 0.9, 3.2 and