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M. Al-Hasan , M. Q. Al-Odat & M. Al-Busoul

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AN EXPERIMENTAL INVESTIGATION OF FORCED CONVECTION HEAT TRANSFER FROM A COILED HEAT EXCHANGER EMBEDDED IN A PACKED BED

M. Al-Hasan,[1] M. Q. Al-Odat,[2] and M. Al-Busoul[1]
[1]*Department of Mechanical Engineering Faculty of Engineering Technology, Al-Balqa' Applied University, Amman, Jordan*
[2]*Department of Mechanical Engineering, Al-Huson University, College, Al-Balqa' Applied University, Irbid, Jordan*

Forced convection heat transfer from a helically coiled heat exchanger embedded in a packed bed of spherical glass particles was investigated experimentally. With dry air at ambient pressure and temperature as a flowing fluid, the effect of particle size, helically coiled heat exchanger diameter, and position was studied for a wide range of Reynolds numbers. It was found that the particle diameter, the helically coiled heat exchanger diameter and position, and the air velocity are of great influence on the convective heat transfer between the helically coiled heat exchanger and air. Results indicated that the heat transfer coefficient increased with increasing the air velocity, increasing helically coiled heat exchanger diameter, and decreasing the particle size. The highest heat transfer coefficients were obtained with the packed-bed particle size of 16 mm and heat exchanger coil diameter of 9.525 mm (1/4 inch) at a Reynolds number range of 1,536 to 4,134 for all used coil positions in the conducted tests. A dimensionless correlation was proposed for Nusselt number as a function of Reynolds number, particle size, coil size, and coil position.

Keywords packed bed, helical heat exchanger, heat transfer, Nusselt number, Reynolds number

INTRODUCTION

Packed beds have wide range of applications as heat transfer and energy-storage devices. One of the significant characteristics of packed beds is the high ratio of solid surface area to volume. This property is useful in applications, such as catalytic reactors, heat recovery processes, heat exchangers, heat-storage systems, and the breeder blanket about fusion reactors [1]. In these applications the heat transfer mechanism includes several sub-processes: convective heat transfer between the solid particles and the fluid flowing through the bed, conduction heat transfer between the bed and the surfaces (walls or immersed surfaces) and between the individual particles in the bed, and radiant heat transfer [2].

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Address correspondence to Dr. Mohammed Q. Al-Odat, Department of Construction Engineering, College of Engineering at AlGunfdh, Umm Al-Qura University, P.O. Box 5555, Makkah, Saudi Arabia. E-mail: m_alodat@yahoo.com.)

NOMENCLATURE

A	cross-sectional area (m^2)
C_P	specific heat of water (J/kg K)
D	coil outside diameter (m)
d_c	coil pipe diameter (m)
d_p	particle diameter (m)
h	convective heat transfer coefficient ($W/m^2.K$)
k_m	effective heat transfer coefficient (W/m.K)
L	packed bed length (m)
m	mass flow rate (kg/s)
Nu	averaged Nusselt number
Pr	Prandtl number
Q	heat transfer rate (W)
Re	Reynolds number
S_p	surface area of particle (m^2)
T	temperature (K)
V_p	volume of particle (m^3)
V_s	superficial velocity (m/s)

Greek Symbols

Δp	pressure drop through the packed bed (N/m^2)
ε	void fraction or porosity of the packed bed
λ	ratio between k_f/k_s
μ	dynamic viscosity of the fluid ($N.s/m^2$)
ρ	density of the fluid (kg/m^3)

Subscripts

b	bed
c	coil
f	fluid
i	in
o	out
p	particle
s	solid
w	water

To use a packed bed for heat exchangers, the selection of particles and the heat transfer between the bed and the heat exchangers is critical. This process is very complicated because of the many packed-bed variables (such as particle size, particle shape, particles and gas thermal properties) and the variation in heat transfer of the heat exchanger design, such as size, shape, spacing pitch, and material. Various investigations have been made with packed beds on heat transfer. Chandra and Willits [3] studied the influence of rock size and the airflow rate on pressure drop and heat transfer characteristics of rock beds in air–rock bed thermal storage systems. The authors found that both the pressure drop and the coefficient of volumetric heat transfer between the air and the rock beds were dependent upon the rock size and the airflow rate. Levec and Carbonell [4] performed steady-state experiments to measure the lateral effective thermal conductivities in the packed bed. In this study, a temperature gradient was imposed at the top of the bed perpendicular to the flow direction, and its spread was measured at different axial locations in the Peclet number range from 10 to 103. Buonanno et al. [5] conducted an experimental study to measure the effective thermal conductivity of uniformly sized rough stainless-steel spheres packed beds. Nasr et al. [6] investigated the effect of particle diameter and bed temperature on the rate of heat transfer due to both conduction and radiation in packed beds of spherical particles. They tested three different packing materials—alurnina, aluminum, and glass—with various particle diameters (2.5 to 13 mm). Dixon and Dongeren [7] studied the influence of changing the tube and particle diameters simultaneously at fixed tube-to-particle diameter ratio N on the pseudo-homogeneous heat-transport parameters in wall-heated packed beds. The packing used in their work was porous ceramic, nylon, and steel spheres. They found that the effective radial thermal conductivity and the apparent wall heat transfer coefficient depend only on the ratio N and not on the tube and particle diameters. Wen et al. [8] reported an experimental study on both transient and steady-state heat transfer behavior of a gas–solid two-phase mixture flowing through a packed bed under constant wall temperature conditions. They found that the presence of suspended particles greatly enhances heat transfer in the packed bed. Furthermore, the steady-state and transient response of packed beds under various effective parameters, including effective axial and radial thermal conductivities, wall-to-fluid heat transfer coefficient, and overall heat transfer coefficient, were extensively investigated [9–14]. Recently, Adeyanju and Manohar [15] carried out a brief review of heat transfer in packed beds with emphasis on both experimental and theoretical techniques.

It terms of embedded heat transfer surfaces in a packed bed, the reported literature is limited. Laguerre and Flick [16] studied the heat transfer between wall and a packed bed of spheres. Christopher et al. [17] experimentally examined the convective heat transfer to a small steel cylinders (wires) immersed in packed beds. Nasr et al. [18] conducted an experimental investigation on forced-convection heat transfer from a cylinder embedded in a packed bed with air as working fluid. They found that the higher heat transfer coefficients were obtained with smaller particles. Nsofor and Adebiyi [19] experimentally studied the gas-to-wall forced-convection heat transfer coefficient in a packed-bed, high-temperature, thermal energy-storage system. Seto et al. [20] considered heat transfer enhancement in sphere-packed pipes under high Reynolds number conditions.

An extensive literature review shows that the heat transfer characteristics of a helically coiled heat exchanger (HCHE) immersed in a packed bed has not been investigated yet. Therefore, the aim of this article is to study experimentally the heat transfer to an HCHE embedded in a packed bed of spherical glass particles. A parametric study is conducted to investigate the effects of particle size, coil size, and position on the coil heat exchanger to the bed heat transfer process at different air velocities. The obtained results were correlated in terms of Nusselt number, Prandtl number, and Reynolds number. The obtained correlation equation agrees well with the experimental data.

EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental test rig used in this work was designed and built to measure the heat transfer coefficient to the HCHE embedded in a packed bed with different spherical glass sizes. The experimental apparatus, shown in Figure 1, consists of the following parts.

(1) An insulated hot water tank with internal cylinder of 300-mm diameter, 350-mm height, and 1.5-mm wall thickness made of galvanized steel, equipped with two electrical heaters of 2-kW power with a thermostat controller.
(2) A cylindrical storage column with 126-mm diameter, 320-mm height, and 1-mm wall thickness made of plastic. The packed column (placed in a storage column) has a height of 220 mm, 122 mm diameter, and 1-mm wall thickness made of a stainless-steel perforated plate held the spheres in place. To avoid any possible blockage for the air passage, a fine mesh stainless-steel screen is placed on the top of the perforated plate. The bed materials used were glass spheres of three nominal sizes (11, 16, and 22 mm).
(3) Three HCHEs made of brass pipe with 6.350-, 7.937-, and 9.525-mm (3/8-, 5/16-, and 1/4-inch) pipe diameters with constant inside coil diameter of 60 mm and having 8 turns. The coils were placed each time inside the packed column

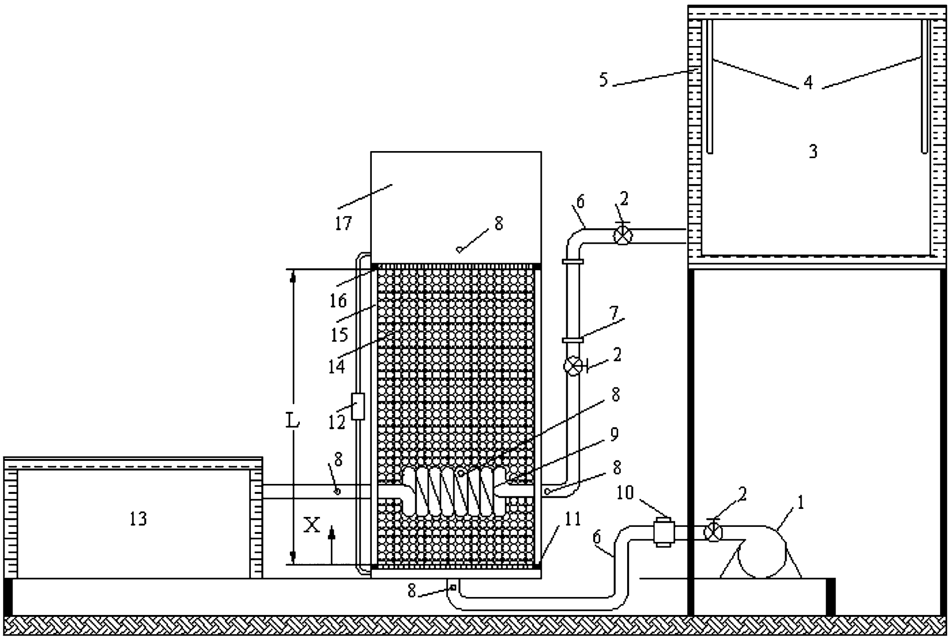

Figure 1. Schematic diagram of the test bed (1— air blower, 2—copper valves, 3—hot water tank, 4—electrical heaters, 5—insulation, 6—water and air pipes, 7—graduated glass vessel, 8—K-type thermocouples, 9—helical coil heat exchangers, 10—digital rotameter, 11—air distributor plate, 12—digital manometer, 13—return water tank, 14—glass spheres, 15—packed, 16—screen, 17—storage column, L—packed bed length).

at 0.25, 0.50, and 0.8 distance ratio of X (measured from the column bottom) and a column height L of 220 mm.

(4) Copper valves with 4.8 mm and 76.2 mm were used to control the water flow from the hot water tank and the airflow through the packed bed column, respectively.
(5) An air blower of 370-W power was used to supply the air from the surrounding to the packed bed column.
(6) A return water tank with the same design as a hot water tank to store the water drained from the HCHEs.
(7) K-type thermocouples connected to a multi-channel digital temperature gauge were used to measure the temperature of water inlet to and outlet from HCHEs, the temperature of air inlet to and outlet from the packed bed column, and the bulk temperature. The thermocouples having a diameter of 1.6 mm were installed inside a stainless-steel 152-mm-long sheath, each. To measure the coil external surface temperature, a T-type (fast response) with a bead of 0.13-mm-outer diameter thermocouple was soldered to surface. The thermocouples were calibrated against a thermometer using a thermostatic water path method.
(8) A digital manometer was used to measure the pressure drop through the packed bed column, and a graduated glass vessel and a stop watch were used to measure the water mass flow rate.

The experimental procedures were as follows. The HCHE was placed in the desired position, and the spherical glass required for the test was charged in the packed column. Air was introduced at the bottom of the packed bed column via a rotameter to the air distributor at different rates to obtain at each time a pressure difference across the packed bed column of 10, 30, 50, and 70 mm H_2O.

Five type-K thermocouples were installed axially to measure the bed temperature at different positions and the average bulk temperature was computed.

The accuracy of the flow rate measurement was $\pm$ 0.5%. The experimental accuracy of the temperature was $\pm$ 0.2°C. Uncertainties of the Nusselt number were estimated to be $\pm$ 4.1%.

The airflow rates were controlled by a copper valve. Hot water was supplied by gravity to the HCHE and was metered by using a graduated glass vessel and a stop watch. Because hot water is supplied by gravity, a uniform wall temperature (UWT) boundary condition can be assumed. The water flow rates were controlled by means of a copper valve. Air and water were fed to the packed-bed column and to the HCHE at the desired flow rates, then after a steady state was attained, which was conformed from the constant values of flow rates and temperatures, the air and water flow rates, air inlet and outlet temperatures, inlet and outlet temperatures of the hot water, bed bulk temperature, and external coil surface temperature were measured four times with a time interval of 1 min for each test. Then the average values were recorded.

THEORETICAL ANALYSIS

Superficial Velocity (V_s)

The superficial velocity is defined from Ergun's equation, knowing the pressure drop from the experimental data, as follows [21]:

$$\Delta p = \frac{150\mu V_s L(1-\varepsilon)^2}{d_p^2 \varepsilon^3} + \frac{1.75 V_s^2 L\rho(1-\varepsilon)}{d_p \varepsilon^3}, \tag{1}$$

where Δp is the pressure drop through the packed bed, L is the bed length, ρ is the density of the fluid, μ is the dynamic viscosity of the fluid, d_p is the equivalent spherical diameter of the particle defined by $d_p = 6 \times \frac{\text{Volume of the particle}}{\text{Surface area of the particle}} = \frac{6\mathrm{V}_p}{S_p}$, ε is the void fraction of the bed (ε is the ratio of the void volume to the total volume of the bed), and V_s is the superficial velocity.

The obtained values of the void fraction are 0.44, 0.46, and 0.49 for particles diameter of 11, 16, and 22 mm, respectively.

The Reynolds number for the particle is defined as

$$\mathrm{Re} = \frac{\rho V_s d_P}{\mu(1-\varepsilon)}. \tag{2}$$

Heat Transfer in a Packed Bed

From the literature review provided herein, two parameters are commonly used to define the heat transfer in packed beds, i.e., the total heat transfer coefficient and the effective heat transfer coefficient. The total heat transfer coefficient is calculated at a steady-state condition between the rate of heat transferred to the coil heat exchanger by the flowing water and the rate of heat transferred to the packed bed using the following equations:

$$Q_w = \dot{m}_w C_p (T_{out} - T_{in}), \tag{3}$$

$$Q_b = h\pi D_c L_c (T_s - T_b). \tag{4}$$

From the equilibrium of these equations, the bed heat transfer coefficient is determined as follows:

$$h = \dot{m}_w C_p (T_{out} - T_{in}) / \pi D_c L_c (T_s - T_b), \tag{5}$$

where m_w, C_p, T_{out}, T_{in}, T_s, T_b, D, and L_c and are the water mass flow rate, specific heat of water, outlet and inlet water temperature, solid temperature, bulk temperature, coil outside diameter, and coil length, respectively.

The effective thermal conductivity k_m can be divided into three components (heat transfer mechanisms), the effective conductivity through the fluid and point contact, the effective conductivity through contact area, and the effective conductivity due to radiation. Several correlations to define the effective thermal conductivity through the solid and fluid phases with stagnant flow and point contact conduction were suggested by Zehner and Schlünder [22], Aichlmayr and Kulacki [23], and Hsu et al. [24]. These correlations neglect the radiation effect and are based on the point contact conduction and void fraction of the bed. Among these correlations, the correlation proposed by Zehner and Schlünder [22] was considered in this study as follows:

$$k_m = k_f \left\{ 1 - \sqrt{1-\varepsilon} + \frac{2\sqrt{1-\varepsilon}}{1-\lambda B} \times \left[\frac{(1-\lambda)B}{(1-\lambda B)^2} \ln\left(\frac{1}{\lambda B}\right) - \frac{B+1}{2} - \frac{B-1}{1-\lambda B} \right] \right\}, \tag{6}$$

with k_s and k_f as the thermal conductivity of solid and liquid phases, respectively; $\lambda = k_f / k_s$ and a shape factor B for a packed bed consisting of uniform sphere is given by $B = 1.25[(1-\varepsilon)/\varepsilon]^{10/9}$.

By using the effective thermal conductivity, Nusselt number can be written as

$$\mathrm{Nu}_D = \frac{h d_P}{k_m}. \tag{7}$$

RESULTS AND DISCUSSION

As described above, experimental test facility was designed, and data have been collected with respect to heat transfer and fluid-flow characteristics of an HCHE embedded in packed bed. The data have been processed to determine the values of heat transfer coefficient as a function of the Reynolds number with various operating parameters. The results of this investigation are discussed in what follows.

Effect of Heat Exchanger Coil Diameter

The coils used have the same turn inner diameter; the difference is only in the pipe diameter that made the coil. The sizes of the coils used in this work were 9.525, 7.937, and 6.350 mm. The effect of Reynolds number on the heat transfer coefficient for different heat exchanger coil diameters and particle sizes A ($d_p = 11$ mm), B ($d_p = 16$ mm), and C ($d_p = 22$ mm) and heat exchanger positions is shown in Figure 2. It can be seen that the heat transfer coefficient increases as Reynolds number increased for all coil diameters and positions. Also, the heat transfer coefficient increases with the increase of the coil diameter, and the maximum values obtained were 26.7, 26.6, and 22.4 for particle diameters of 22, 16, and 11 mm, respectively, for $d_c = 9.525$ mm at a coil position of 0.252, and the minimum values were 10.5, 12.5, and 11.7 for particle diameters of 22, 16, and 11 mm, respectively, for $d_c = 6.350$ mm at a position of 0.816. Furthermore, as shown in Figures 2a and 2c, a small difference of heat transfer coefficient can be observed between the packed bed of 16- and 22-mm particle diameters. Herein, the increase of the Reynolds number compensates the decrease in the heat transfer coefficient due to the increase of the porosity in the case of $d_p = 22$ mm and vice versa in the case of $d_p = 16$ mm, while the heat transfer coefficient, as shown from Figures 2a and 2b, has a higher value in the case of the packed bed of 16-mm particle diameter than that of 11 mm. This can be explained as follows. For a particular packing, particle diameter and the porosity are fixed. If the particle diameter in a bed is decreased, i.e., packing with a small particle diameter, the particles will be tightly pressed against each other, resulting in the decrease of porosity. The flow passage will be more tortuous and constricted due to lesser porosity, but at the same time, the fraction of the effective heat transfer area available for contact with flowing air will be less and vice versa.

Lower porosity will cause higher turbulence in the flow passage, which will increase the heat transfer. But because of the decrease in the fraction of effective heat transfer area, a decrease of particle diameter will be unfavorable to heat transfer. Thus, two counterbalancing heat transfer phenomena occur simultaneously as the particle diameter is changed, a lower porosity resulting in higher-heat transfer and a lower effective heat transfer area yielding lower heat transfer. Therefore, the effect of effective heat transfer area on the heat transfer coefficient is more pronounced than the porosity for the packed bed of 11-mm particle diameter compared with the packed bed of 16-mm particle diameter. The increase of the Reynolds number is another factor for increasing the heat transfer coefficient of the packed bed of 16-mm particle diameter.

Effect of Particle Diameters

Figures 3a, 3b, and 3c show the effect of the particle diameters on the heat transfer coefficient as a function of the Reynolds number for different heat exchanger coil diameters and positions. It can be seen that the heat transfer coefficient increases as the air mass flow rate, in terms of the Reynolds number, increases for all particle diameters and coil positions. For a given HCHE position, the heat transfer coefficient increases with the increase of the coil diameter and reaches its maximum value at a dimensionless position of 0.252 (Figure 3c). This can be attributed to the fact that by increasing the coil diameter, the magnitude of the particles contacts with the coil heat exchanger increases, consequently increasing the heat transfer area. Therefore, the heat transfer coefficient

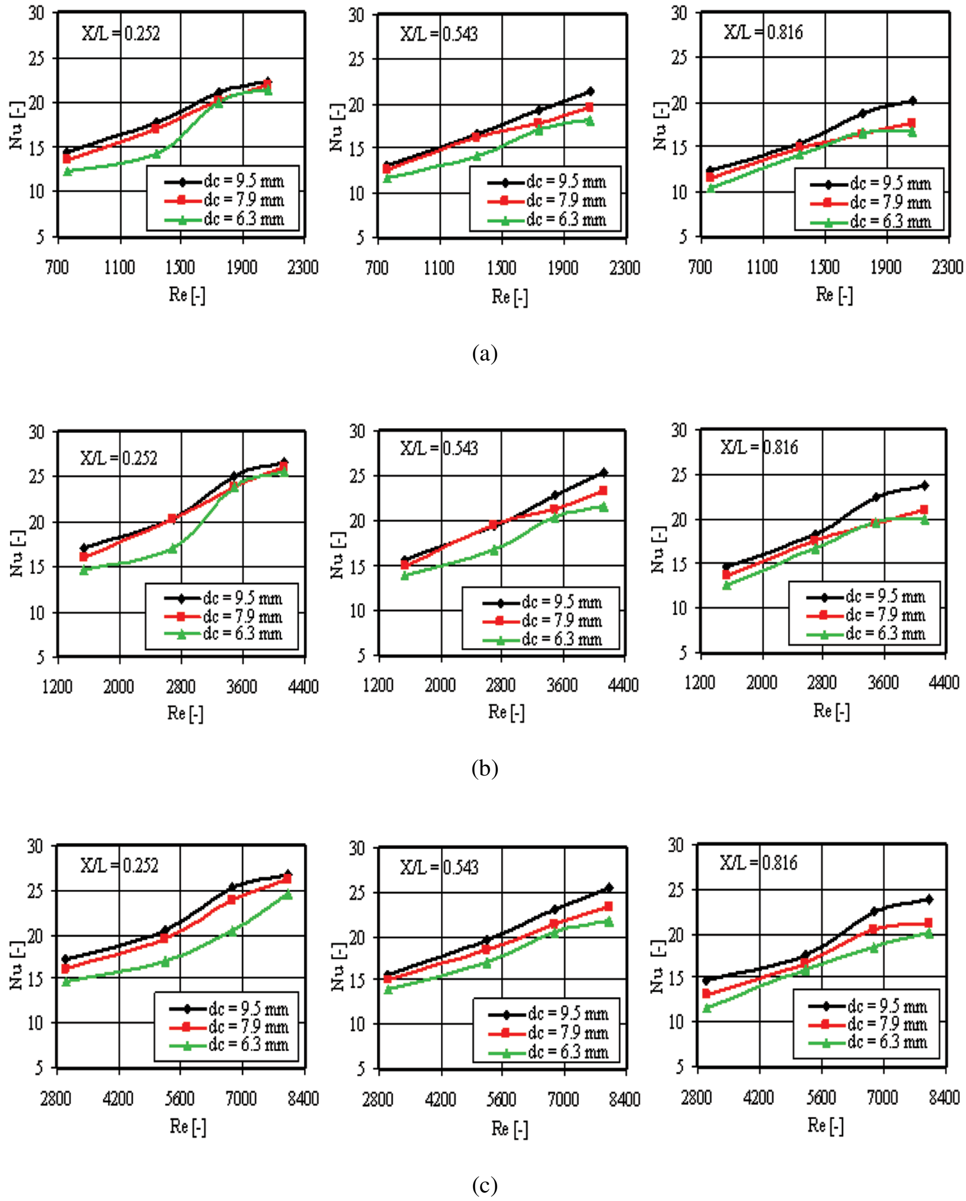

Figure 2. Variation of the heat transfer coefficient as a function of the Reynolds number for different heat exchanger coil and particle diameters and heat exchanger positions: (a) $d_p = 11$ mm, (b) $d_p = 16$ mm, and (c) $d_p = 22$ mm. (color figure available online)

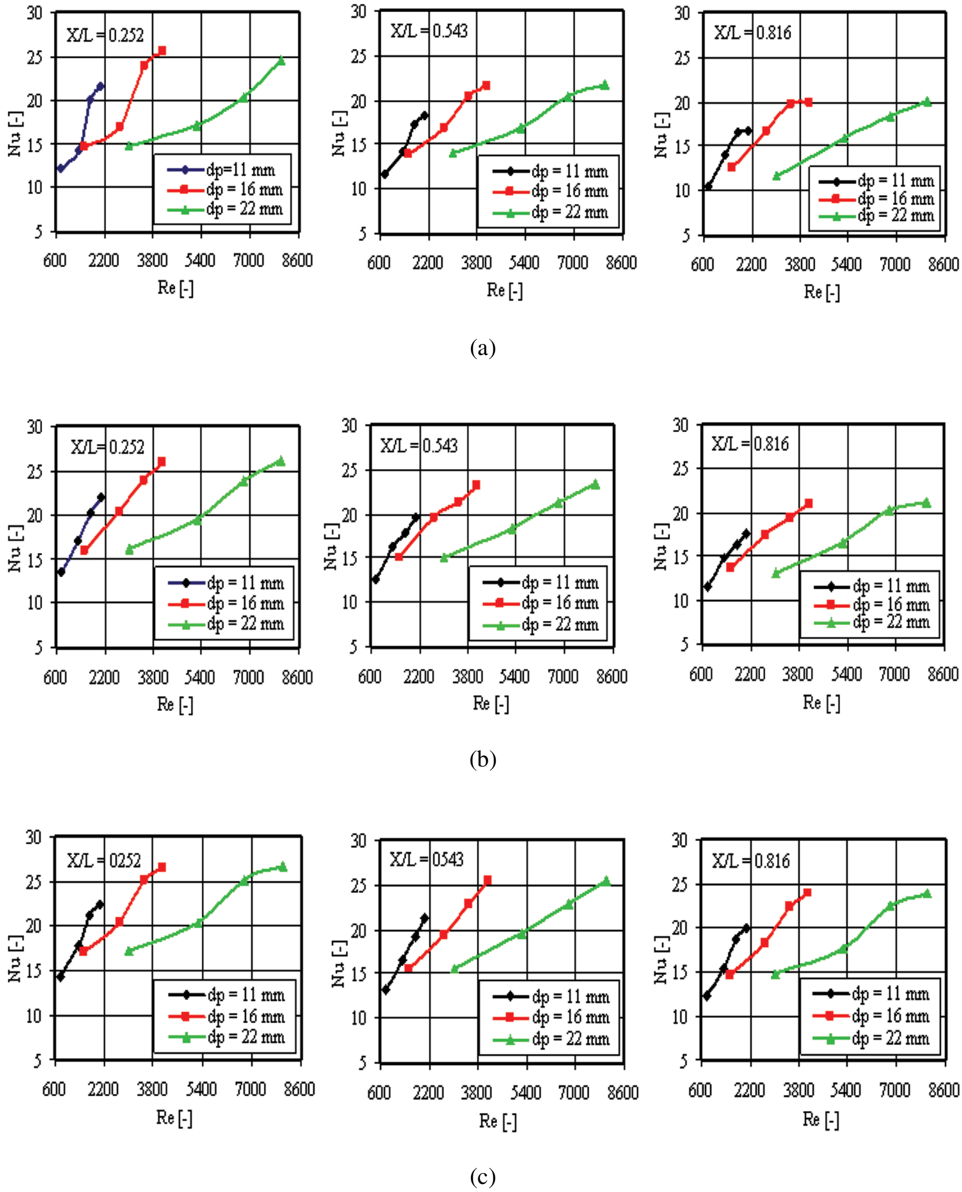

Figure 3. Effect of packed-bed particles diameters on heat transfer coefficient as a function of the Reynolds number for different heat exchanger coil and positions diameters: (a) $d_c = 6.35$, (b) $d_c = 7.937$, and (c) $d_c = 9.525$ mm. (color figure available online)

increases. It can also be observed from the figure that the heat transfer coefficient has highest values with a particle diameter of 16 mm for all heat exchanger positions and coil diameters. These results conformed to the above findings (as shown in Figure 2). In addition, for a given particle diameter, the heat transfer coefficient increases with decreasing the coil position. This can be explained as follows: when the coil positioned in the bottom of the packed column ($X/L = 0.252$), the air stream that passes through a large quantity of particles creates a turbulent flow. Herein, the air motion in the turbulent boundary layer improves the transfer of momentum, and energy hence increases surface friction as well as convection heat transfer coefficient, and this increases the Nusselt number.

Heat Transfer Coefficient Dimensionless Correlations

The effect of interaction among the experimental parameters on heat transfer coefficient is quite complicated, as shown in Figures 2 and 3. To consider the influence of all the experimental parameters on the convective heat transfer coefficient, it is convenient to combine their effects in dimensionless parameters. Generally, these dimensionless parameters are Nu, Re, and Pr, which are used to describe the forced convection heat transfer in the packed bed. Furthermore, an empirical constant depends on different size ratios involved in this investigation. In order to obtain a good correlation, least-square fits were developed for the experimental datasets in this study. The heat transfer coefficient was correlated against Reynolds and Prandtl numbers by equation of the form

$$\mathrm{Nu} = c\,\mathrm{Re}^a\,\mathrm{Pr}^b, \tag{8}$$

where a, b, and c are empirical constants depending on X/L, d_c/D, and d_p/D, respectively. These constant were obtained by using the least-square fitting of the experimental data, shown as

$$c = 1.88\left(\frac{d_p}{D}\right)^{1.65}, \qquad a = 0.52\left(\frac{X}{L}\right)^{0.08}, \qquad b = 2.72 - 20.83\left(\frac{d_c}{D}\right).$$

The obtained correlations were tested for three different cases, shown in Table 1, and the presented correlation equations show good agreement with the experimental data.

The results of the three test cases are shown in Figures 4, 5, and 6. As shown in these figures, the proposed correlations agree with the experimental results.

Table 1. Correlation test cases used for testing

Test case	$\left(\frac{d_p}{D}\right)$	$\left(\frac{d_c}{D}\right)$	$\left(\frac{X}{L}\right)$
1	0.183	0.164	0.252
2	0.267	0.132	0.543
3	0.367	1.06	0.816

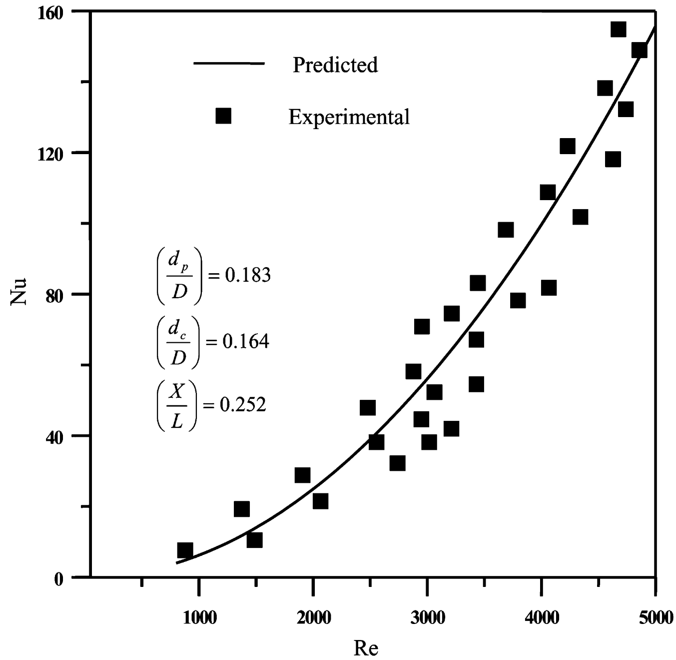

Figure 4. Fit of predicted Nu values and experimental Nu values for test case 1.

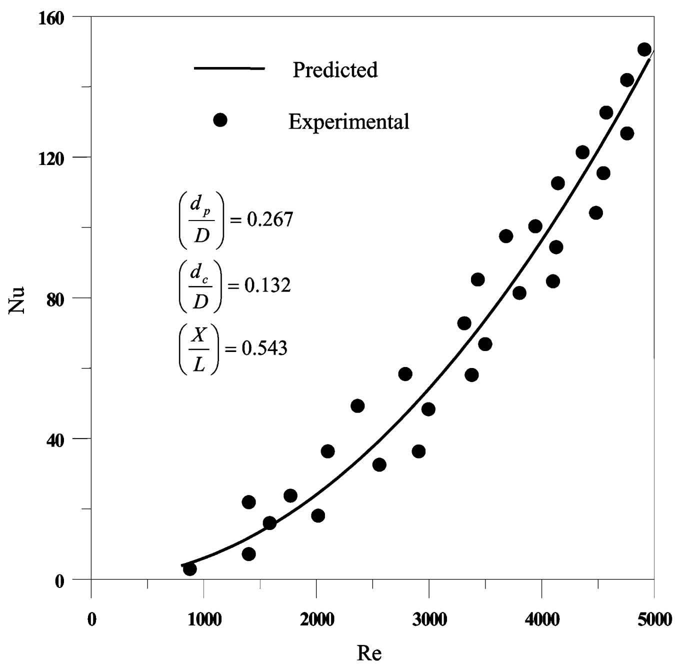

Figure 5. Fit of predicted Nu values and experimental Nu values for test case 2.

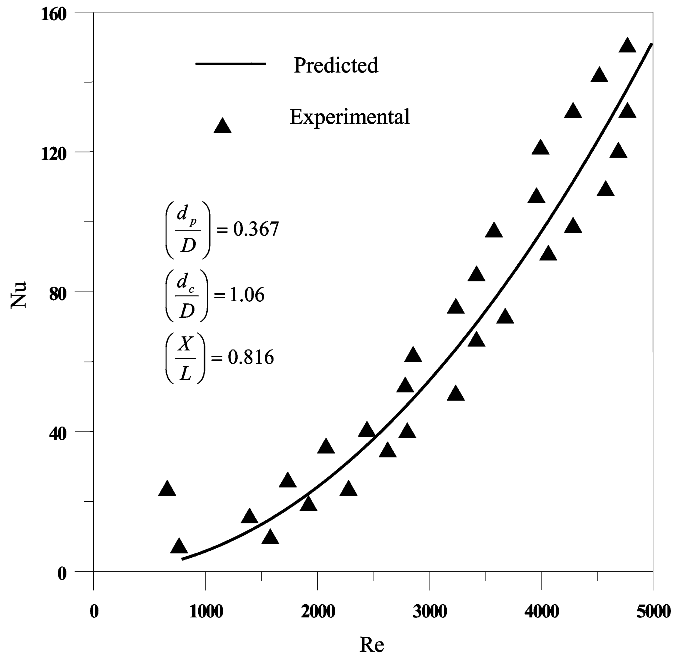

Figure 6. Fit of predicted Nu values and experimental Nu values for test case 3.

CONCLUSION

The HCHE to bed heat transfer was experimentally studied for different bed particle diameters, coil diameters, and positions at various Reynolds numbers. A correlation equation of Nu in terms of Re has been obtained based on more than 200 experimental runs in the range of $1{,}000 < \mathrm{Re} < 5{,}000$. The correlation equation agrees well with the experimental data. On the basis of the obtained results, the following conclusions are drawn.

1. The heat transfer coefficient increases with the increase of the Reynolds number for all tested parameters.
2. Higher heat transfer coefficients were obtained with smaller packed-bed particles due to the decrease in the bed porosity.
3. The increase of the heat exchanger coil diameter increases the heat transfer coefficient due to the increase of the contact heat transfer area between the coil and the particles.
4. The heat transfer coefficient increases with a decrease in axial position due to the turbulent flow of the air, which increases the surface friction as well as the convection heat transfer coefficient.
5. In general, the best heat transfer coefficient values of the system were obtained with the packed-bed particle diameter of 16 mm and the heat exchanger coil diameter of 9.525 mm at a Reynolds number range of 1,536 to 4,134 for all used coil positions in the conducted tests.

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