HEAT TRANSFER FROM CONSTANT HEAT FLUX CYLINDRICAL WALL TO LIQUID FLOW THROUGH PACKED BEDS

انتقال الحرارة من جدار اسطواني ساخن بفيض حراري ثابت الى سائل منساب خلال قنوات محشوه

BY

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يشتمل هذا البحث على دراسة معملية لانتقال الحرارة الموضعي للماء منساب خلال أنبوبة رأسيه دائرية المقطع قطرها الداخلي ١٥ مم وطولها ٣٧٠ مم جدارها ساخن كهربيا بفيض حراري ثابت والانبوبه محشوه بحبيبات كرويه من الصلب ذات أقطار ١٫٠٧ و ٣٫٢ مم . عند اجراء التجارب كانت سرعة الماء (محسوبه على مساحة مقطع الانبوبه) متغيره لتعطي قيم مختلفه لرقم رينولدز (محسوب على القطر الداخلي للانبوبه) من ١٠ الى ١٠٠٠٠ تقريبا وكان رقم براندتل ثابتا تقريبا خلال التجارب . أوضحت النتائج أنه في نطاق السريان الانسيابي (الرقائقي) تكون نسبة طول المدخل الحراري الى قطر الانبوبه الداخلي مساويا ٧ في حين أن هذه النسبه في نطاق السريان الدوامي (الاضطرابي) تكون صغيره جدا لدرجه يمكن معها اعتبار ثبات معامل انتقال الحراره بالحل الجبري على طول الانبوبه . وقد أعطت النتائج توافق حسن عند مقارنتها بنتائج الباحثين السابقين .

ABSTRACT

Results are reported here for an experimental investigation of the local heat transfer of water flowing through vertical circular tube of 15 mm inside diameter and 370 mm length, packed with a spherical steel particles of diameter 3.2 and 1.07 mm. The tube is heated electrically with a constant heat flux on the wall. During this work Reynolds number was varied from 10 to 10000 and Prandtl number was about 7. Results show that, in the laminar flow region the ratio of thermal entrance length to inner tube diameter is equal to 7, while in the turbulent flow region this ratio has a negligibly small value, which means that the mean and local heat transfer coefficients are equal in the turbulent region of packed bed tubes. In comparison with the available literature the present results show a quite good agreement.

INTRODUCTION

Forced convection in packed beds is known to be important in a wi·· variety of engineering applications such as , metallurgical, che·· petroleum industries and energetic. This technique is use·· apparatus designed for thermal processes of dispersed materi·· chemical reactors, catalystic heat generators and others.

The subject of liquid flow in packed bed columns abundantly in the literature, and appears even engineering publications, so no attempt wil·

comprehensive bibliography A more comprehensive list of references cane be found from [1].

Many experimental works concerning the heat transfer through the wall of circular cylinders filled with packed beds have been carried out. In these experiments the bed material had a thermal conductivity (k_s) rangingfrom0.82to350 W/m^2 K, different shaps (such as irrigular shape,spheres,tablet,grains and others),different diameters ranging from 1 mm to 25 mm with the parameter (D/d) ranging from 2 to 100. Apparatus diameter (D) was varied from 12 mm to 300 mm and length (or height) of bed in the range 60 mm to 2000 mm. Many gases were used with (Pr) ranging from 0.4 to 0.8 and many liquids having a Prandtl number ranging from 6 to 1300 and the experiments were carried out under different temperatures from 90 K to 1000 K. Heat transfer results of an experimental investigation at very high temperature processes in disperse systems was given in [2] (average mass temperature extended from 2350 to 3450 K).

The film heat transfer coefficient in packed bed has been studied extensively, and Balakrishnam and Pei [3] have made a critical review of the previous investigations. A method and a procedure to evaluate the film heat transfer coefficient and thermal conductivity in a packed bed are described in [4], where these two transport properties can be determined from the moments of a response curve obtained by introducing a temperature pulse.

Dixon et al [5] predicted theoretically the thermal conductivities and the apparent wall heat transfer coefficient for fluid flow through packed beds is derived from a two-phase continuum model containing the essential underlying and independently measurable heat transfer process.

From the review of literature, one may observe that most studies of forced convection through the wall of a circular cylinder filled with packed bed have been heat transfer measurements under variable heat flux (or under constant temperature).

The method of determining the local heat transfer coefficient from experiments of forced convection through the wall of tube filled with packed bed under constant heat flux on the wall), is many time easier and more accurate than that with constant wall temperature used in the other works. Therefore the main objective of the present work is to cover the absence of the experimental investigation in the available literature about local and average forced convection heat transfer from the wall of a circular cylinder filled with spherical particles where the wall is heated electrically under a constant heat flux.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The experimental works concerned with the determination of heat transfer coefficient in a tube filled with packed bed. One smooth tube is used to standarize the experimental set-up and also to evaluate the increase in the tube side heat transfer coefficient for two spherical particles packed in a copper tube, relative to the smooth one.

A schematic diagram of the experimental test rig is demonstrated in Fig. (1). The test rig was a closed loop in which water from the main tank (6) is circulated to a constant head tank (5) by the aid of a centrifugal pump (4), where the flow rate was regulated by a valve (8). From the constant headtank the liquid flows through a standard rotameter (7), stabilizing section (1) of length 1000 mm, test section (2), mixing section (3) , and then returns to the main tank. The actual test section (2) consists of a 370 mm long copper tube of 15 mm inner diameter and 1.5 mm wall thickness. The test tube (9) is heated using an electric heater made of nickel-chrome wire (10) wounded, with constant pitch, around the outer surface of the tube and insulated electrically from the tube surface with a mica film (11) and thermally from the surrounding with a glass wall insulation (12) of 50 mm thickness.

The water temperature at the test tube inlet and outlet (after the mixing section) was measured by thermocouples (13,14). The temperature of the test tube inner surface was measured by thermocouples (15) at eight points distributed along the length of the section at distances of 0,60,110,160,210,260,310 and 370 mm from the inlet section with four thermocouples distributed around the tube to check the uniformity of porosity and flow velocity adjacent to the inner surface of the tube. To do that a rectangular groves ,1 mm deep, was cut over on the outer surface of the test tube and one circular groove 1 mm deep was cut over on the middle section of the tube,where the thermocouples were impeded inside the groves to their places and kept in contact with the cylinder surface using glue and then thoroughly polished. Owing to the thermal conductivity of the copper, the inside surface temperatures of the test tube were very close to that monitored with the thermocouples.

The voltage drop over the test section was measured by a voltmeter, the current and the electric power were measured by an ammeter and Watt meter respectively, which in tern provided the heat flow rate from the outer surface of the test tube to the liquid flowing through it.

In case of heat transfer between uniform heat flux heated tube and fluid flow inside it one can easily shows that, the mean temperature of the liquid is varied lineary along the length of the tube, therefore the water temperature was measured during the experiments at the inlet of the test tube and the mean temperature at the outlet of the tube after the mixing section.

All thermocouples used were made of 0.15 mm diameter copper-constantan wires and connected to a 12-points self switching temperature recorder (18), having a full scale of 200 °C.

The test tube is packed with a spherical steel particles (16) of diameters 3.2 and 1.07 mm and connected to the test loop by teflon pieces (17) in order to avoid the back conduction effect as shown in Fig. (1).

The flow velocity of water in the test tube was calculated on the basis of the bare tube diameter. The physical properties of water were taken at the mean flow stream temperature, which was calculated as the difference between the average surface temperature of the tube section under consideration and the logarithmic mean temperature difference of this section. The heat gain by the working fluid was calculated from the change of enthalpy of water.

RESULTS AND DISCUSSION

The first group of results concerning the study of heat transfer coefficient between water and tube wall without packed bed. The experimental results in the laminar flow region are plotted in Fig.(2) as a relation between Nusselt number and x/d divided by Peclet number ($Nu = f(1/Pe \cdot x/D)$), for x/D equal to 4.0, 7.34, 10.67, 14.0, 17.34 and 20,67 and Reynolds number ranging from 600 to 2000. It is shown from the figure that, nearly all the experimental data laying in the entrance region, where the heat transfer coefficient was varied with the tube length, and the data are in good agreement with equation (1) given by Petukhov [6].

$$Nu = 1.31\ [(x/D)/Pe]^{-1/3}\ [1+2(x/D))/Pe] \tag{1}$$

In the range of high values of dimensionless length [(x/D)/Pe] the values of Nu differ in about 5-10 % from it's value in the thermal entrance length. In the turbulent region the ratio x/D, as well as x/L , is very small compared with it's value in the laminar flow region which means that the heat transfer coefficient is nearly constant with tube length and varying only with Reynolds number. and the relation between mean Nu and Re is shown in Fig.(3). The experimental data are in a good agreement with equation (2) given by Petukhov [7].

$$Nu = (Re\ Pr\ f/8)\ /\ [1.07+12.7\ f/8\ (\ Pr^{2/3}-1)] \tag{2}$$

where f is the friction factor given by Blasius [8] for turbulent flow as:

$$f = 0.316\ Re^{-1/4} \tag{3}$$

The second group of results concerns heat transfer coefficient in case of water flow through cylindrical packed tube with spherical steel particles of diameters 3.2 and 1.07 mm .

The porosity of the bed was determined experimentally by measuring both the amount of water which fills the pored volume between particles and the whole volume of the tube without packed bed and the following relation were used:

$$\varepsilon = \frac{V_f}{V_t} \qquad (4)$$

The relation between Nusselt number and the dimensionless length (X) in the laminar flow region for bed particle of diameter 3.2 mm are plotted in Fig.(4) at Reynolds number values of 250, 360, 680 and 880. The figure shows that, the thermal entrance length to tube diameter ratio (x/D) in the laminar flow of water through packed tube is small compared with that of water flow in tubes without packed beds and nearly equal to 7.

In the turbulent region the thermal entrance length is very small compared with the laminar flow region, so one can conclude that the local heat transfer coefficient along the packed tube length is constant and equal to the mean heat transfer coefficient.

The relation between the mean Nusselt number and Re for the two bed particle diameters is plotted in Fig. (5). It is shown from the figure that Nu increases with Reynolds number and the decrease of particle diameter. Fig.(6) shows the relation between the effective Nusselt number (Nu_{ef}) and the effective Reynolds number (Re_{ef}). The figure shows that the present experimental data are in a quite good agreement with the work of Irov [9] represented by the following equation.

$$Nu_{ef} = 0.155\, Re_{ef}^{0.75}\, Pr_f^{1/8} \qquad (5)$$

CONCLUSIONS

From the present experimental investigation of packed bed heat transfer of water flowing through vertical circular tube with two spherical steel particles of diameters 1.07 and 3.2 mm the following conclusions are made:

1-the thermal entrance length to tube diameter ratio (x/D) in packed bed heat transfer in the laminar flow region is small, compared with the case of water flow trough the same tube without packing, and equal nearly to 7.

2-In the turbulent region of packed bed in circular tube the thermal entrance length nearly equal zero and the flow is thermally fully developed.

3- the Nusselt number increases with Reynolds number , while it increases with the decrease of particle diameter.

NOMENCLATURE

D inside diameter of the test tube, [m]
d particle diameter, [m]
d_{ef} effective diameter $[4\varepsilon d/6(1-\varepsilon)]$, [m]
h convective heat transfer coefficient, $[W/m^2.{}^oC]$
k thermal conductivity, $[W/m.{}^oC]$
L test tube length, [m]
Nu Nusselt number based on the inside diameter of the test tube, $[hD/k_f]$
Nu_{ef} Nusselt number based on the effective diameter of the bed, $[h\, d_{ef}/k_f]$
Pe Peclet number, [Re.Pr]
Pr Prandtl number, $[\mu\, Cp/k_f]$
Re Reynolds number based on the inside diameter of the test tube, $[\rho v D/\mu]$
Re_{ef} Reynolds number based on the effective diameter of the bed, $[4\rho v d/(6\mu(1-\varepsilon)]$
T temperature, $[{}^oC]$
V volume, $[m^3]$
v fluid velocity based on inner diameter of the test tube, [m/s]
X dimensionless thermal entrance length, [x/D]
x thermal entrance length, [m]

GREEK SYMBOLS

μ absolute viscosity of fluid, [Pa s]
ρ density of fluid, $[Kg/m^3]$
ε porosity, $[m^3/m^3]$

SUBSCRIPTS

f fluid
s particle
t tube
w wall

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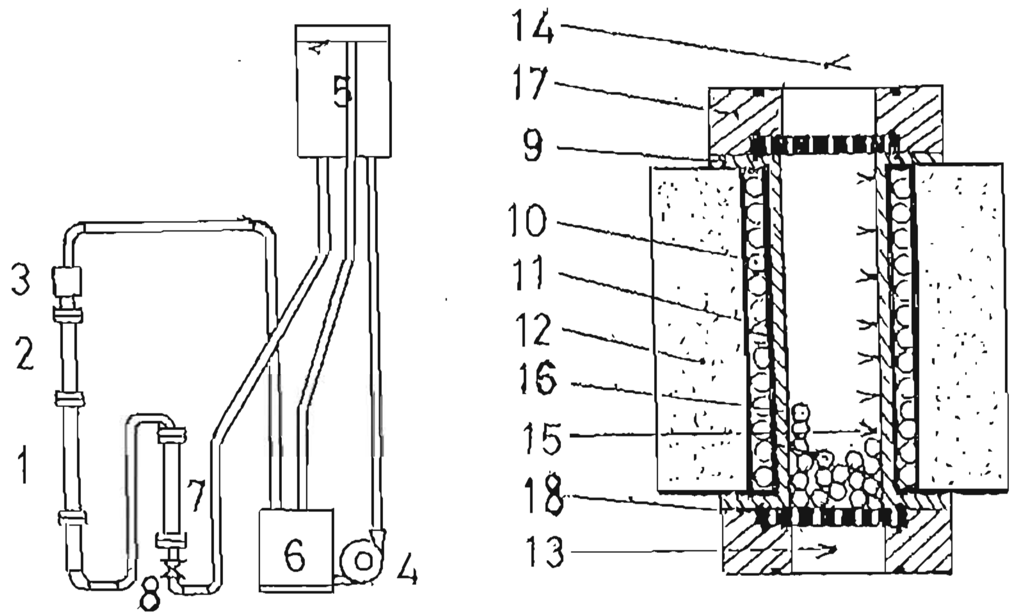

a) Test rig b) Test tube

Fig.(1) Experimental Test Rig.

1- stabilizing section, 2- test section, 3- mixing section, 4- centrifugal pump, 5- constant head tank, 6- main tank, 7- standard rotameter, 8-valve, 9- test tube, 10- electric heater, 11- mica film, 12- glass wool, 13,14 and 15- thermocouples, 16- steal particles, 17- teflon piece and 18- grid

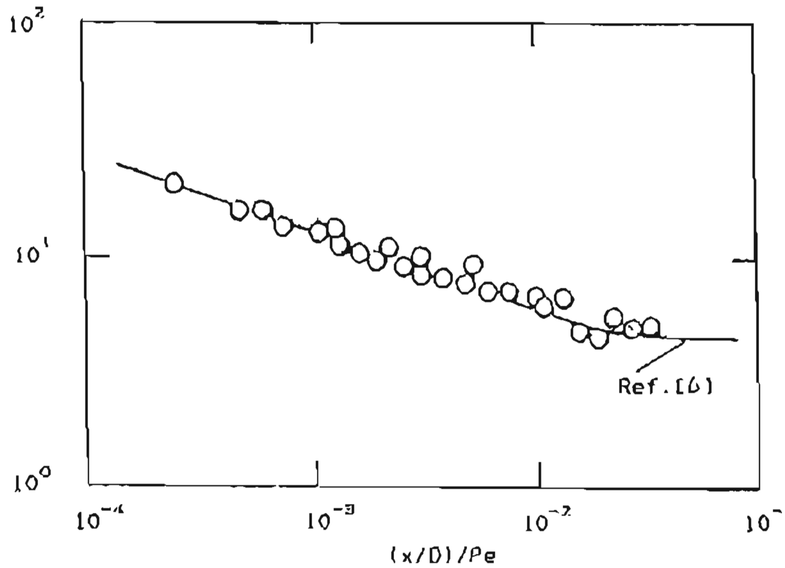

Fig.(2) Nu number variation in the laminar flow of liquid through circular smooth [Gtube.

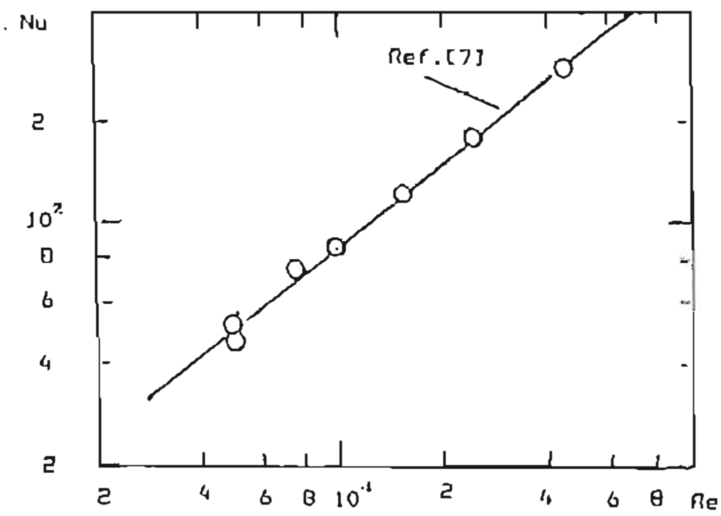

Fig.(3) Nu number variation in the turbulent flow of liquid through circular smooth tube.

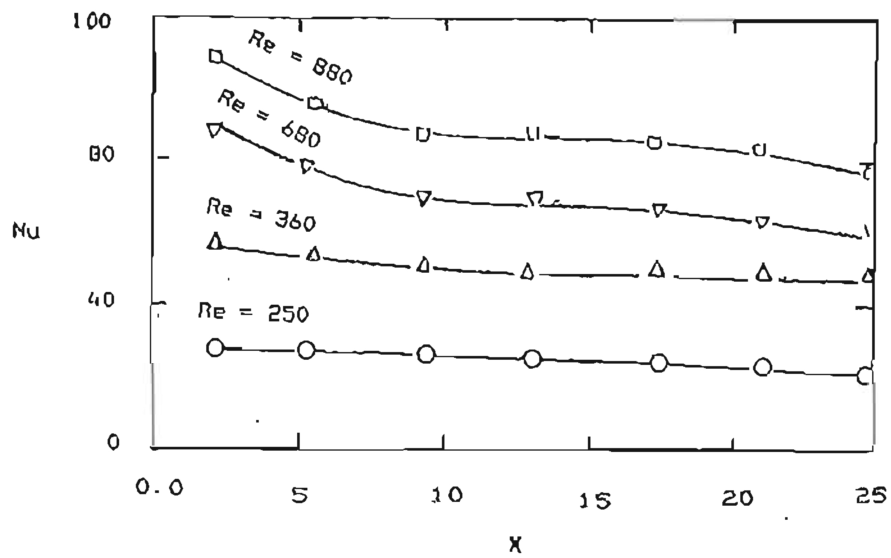

Fig.(4) Variation of Nusselt number with dimensionless thermal entrance length (X) in case of liquid flow through packed bed tubes at different Re number values (d = 3.2 mm).

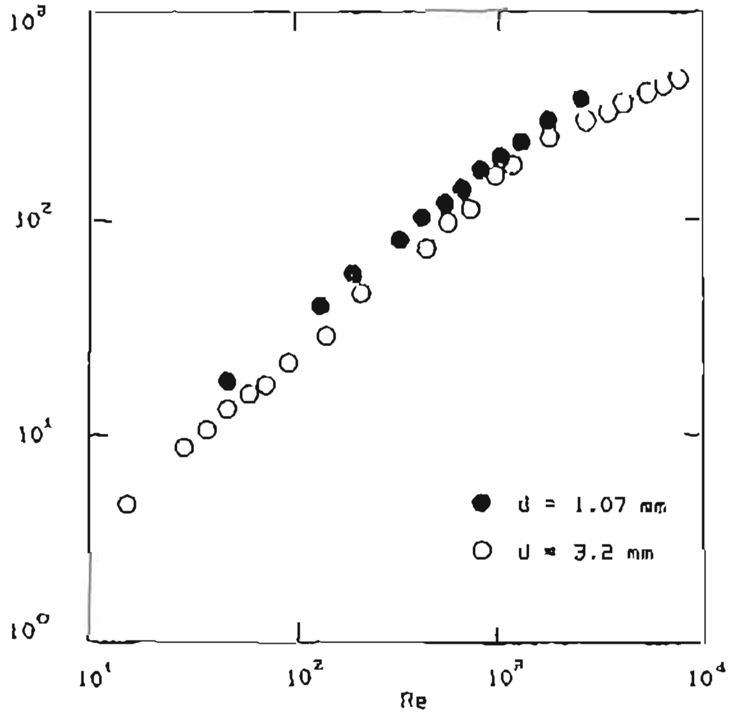

Fig.(5). Nu number variation with Re number at different particle diameter in case of laminar flow of liquid through packed bed tubes.

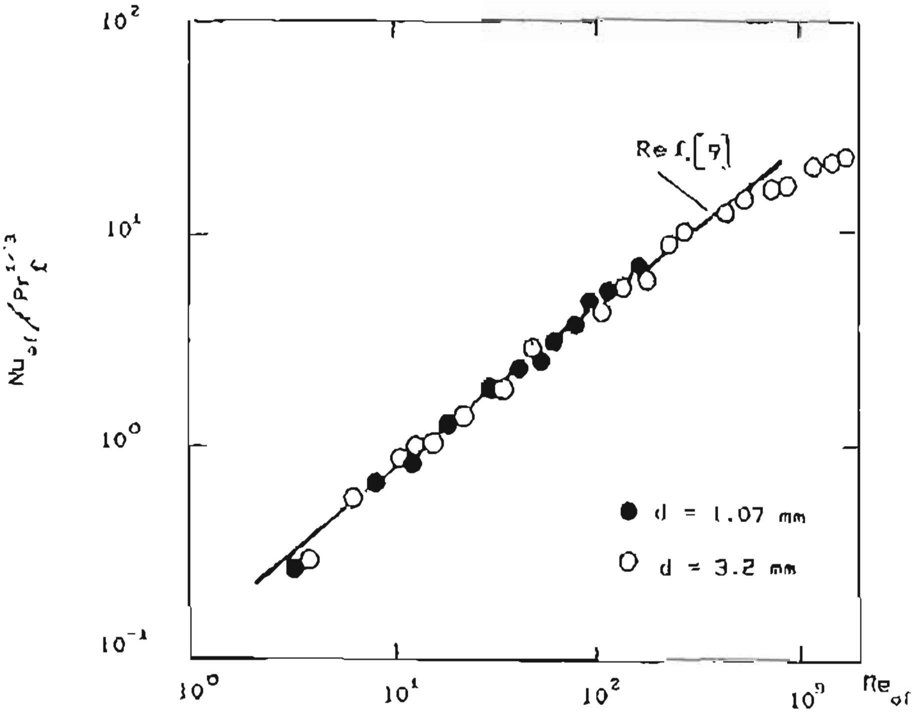

Fig.(6) Relation between Nu_{ef} and Re_{ef} in case of liquid flow through packed bed tubes.