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Wall Effect on Fluid Flow and Heat Transfer of Glass Beads Filled Cylinder

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ABSTRACT

The wall effect on fluid flow and heat transfer for glass bead packed cylinders is studied experimentally. Indeed, the heterogeneous feature due to the confining wall can affect the resistance characteristics and convection heat transfer of packed porous medium channel because the porosity distribution in the channel is uneven. A pipe-in-pipe test section was established, in which the glass bead packed cylinder was heated by the outside annular circulating with temperature controlled hot water. The experimental data of heat transfer were reduced and processed using the Wilson Plot Method, and a correlation of *Nu* with *Re* number and the diameter ratio of the cylinder (*D*) to the packed spheres (*d*) was summarized in a range of $1.84 \le D/d \le 33.2$.

1. INTRODUCTION

The porous medium filled channels are widely used in various fields of scientific research and industrial applications, such as reactor physics research, materials science, development and utilization of geothermal resources, and so on. The phenomenon of fluid flow and heat transfer with porous medium in a channel is paid more attentions. Up to date, many researchers have studied that problem both experimentally and numerically (e.g. Dixon et al. (2005), Eppinger et al. (2011), Yang et al.(2012), Castillo-Araiza et al. (2007)), and some experimental correlations for heat transfer have been put forward.

The wall effect refers to the phenomenon that the porous medium near the wall are arranged forcedly under the influence of the wall, porosity near the wall is generally larger than that in the internal space. i.e. due to the wall effect, the porosity inside the porous medium packed channel is not uniform spanwise. Therefore, the velocity distribution for fluid flow with and without wall effect might be rather different due to the uneven porosity, it will inevitably affect the heat transfer characteristics as well (e.g. Mueller, G.E.(1992), Rupesh K. Reddy, Jyeshtharaj B. Joshi (2010), Raichura, R. C.(1999))..

Regarding the wall effect on the heat transfer characteristic of porous medium packed channel, some previous publications are available. In the earlier experimental researches, the Nusselt number *Nu* for the porous packed channel was generally correlated as a function of Reynolds number Re_d, in which the length scale is given by the filled sphere diameter d, such as the formula proposed by Li, C.H. and Finlayson, B. A. (1977),

$$Nu_d = 0.17\,\mathrm{Re}_d^{\,0.79} \tag{1}$$

Where the diameter ratio *D/d* was in the range of 3.3~20, Re_d is in the range of 20~7600. Dixon and Labua (1985) then took the diameter ratio of $N = D/d$ into account, where *D* is the equivalent channel diameter, and obtained a form of correlation as follows:

$$Nu_d = (1 - \frac{1}{N})\,\mathrm{Pr}^{1/3}\,\mathrm{Re}_d^{\,0.61} \tag{2}$$

Where Re_d is larger than 100. Demirel, Y. and Sharma, R.N., (2000) also obtained an empirical correlation suitable in a relative larger *Re* number range of 200~1450, the diameter ratio *N* was in the range of 4.5~7.5

It seems that a more delicate work should be due to Varahasamy and Fand (1996), who proposed that the forced convective heat transfer with wall effect in porous medium packed channel could be contributed by three components: the "coarse" component f_1 (in cylinder diameter *D* scale), the "fine" component f_2 (in filled sphere diameter *d* scale), and the two interaction f_3. They put forward the basic form of heat transfer correlation in porous medium packed channel as follows:

$$Nu = Cf_1 f_2 f_3 = C\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{f}\left(f'\,\mathrm{Re}_d'\right)^{d}\left[\arctan\left(D/d\right)^{c}\right]^{e} \tag{3}$$

The theoretical model was used for correlating their experimental data, and the constants in the above formula were determined. Eq. (3) is similar with the Dittus-Boelter formula. In this expression, the *Nu* number is not only a function of *Re*, but also Re_d, because ($f'Re'_d$) is also a function of Re_d. In addition, the expression uses 'arctan' function to represent the wall effect on convective heat transfer in porous medium packed channel. When *D/d* is infinite large for the case of open fluid channel, the term $\left[\arctan\left(D/d\right)^{c}\right]^{e}$ approaches a constant value.

Seto et al. (2008) used the form of correlation proposed by Fand (1996) to study the wall effect in porous medium packed channel with Re number as high as 15000. In the experiment, water was used as flowing medium, the tube filled with the spherical particles was used as a porous medium test section, the diameter ratios *D/d* were 3, 2.2, 2 and 1.3. When the diameter ratio *D/d* is equal to 3, 2.2, 2, the maximum error between the calculated Nu and the experimental Nu is 15%, and when the diameter ratio D/d is equal to 1.3, the maximum error is 10%, which proves the rationality of the model.

In the paper, using the experimental method, the wall effect in porous medium packed channel is further studied. Numerous test cases were obtained by varying the circular tube diameter *D* and/or the diameter of spheres *d*. Using the Wilson Plot Method, the heat transfer characteristics with wall effect in porous medium packed channel are presented. Since that there has been no general agreement on the accurate correlation of Nu predicting the heat transfer of particle filled porous channel, the present experimental is valuable to enrich the database of porous medium packed channel flow and heat transfer, especially with the consideration of heterogeneous effect due the channel wall. (e.g. Ergun, S. (1952), Yu et al. (2010)),

2. EXPERIMENTAL METHOD

The experimental system is shown in Figure 1. In the heat transfer experiment, we use three circular test tubes with different inner diameters (9.5mm, 20.5mm and 30.3mm), and six different diameter glass beads in a range of 0.92mm <*d*< 5.2mm as porous medium; the effective heat transfer tube length is 500mm. The experimental fluid is water and the flow is upstream. The constant temperature water is obtained from the thermostatic water bath, and exchange the heat in porous medium packed channel, then flow back to the thermostatic water bath, the cycle of hot water is a closed loop. Cold water is from a tap. In the experiment, the flow rate and the inlet temperature of hot water are kept constant. By changing the flow rate of cold water, we can change the total heat transfer coefficient of porous medium packed channel. We use T-type thermocouples for temperature measurement and the flow rates for both hot and cold water is measured by weighing method.

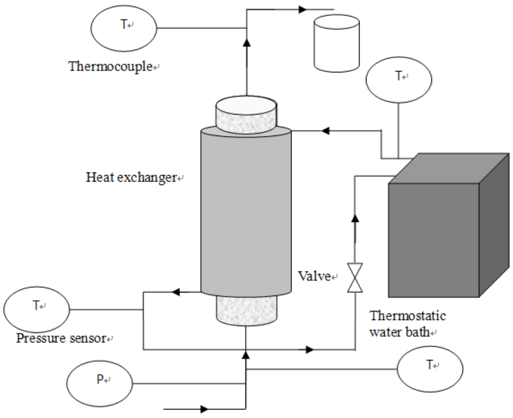


Figure 1: The experimental system.

3. DATA PROCESSING METHOD

In the paper, we use Wilson Plot Method (e.g. Jose Fernandez-Seara, (2007)) to determine the heat transfer coefficient inside the tube. In general, the method is that keeping the heat transfer coefficient outside (or inside) of the tube as a constant, and at the same time changing the flow rate and inlet temperature inside (or outside) of the tube so as to change the total heat transfer coefficient. Then, the total heat transfer coefficient and the fluid velocity inside (or outside) tube should be fit in linear function to obtain the heat transfer coefficient inside (or outside) tube.

The total heat transfer coefficient calculated based the outside tube area is as follows:

$$\frac{1}{KA_o}=\frac{1}{h_iA_i}+\frac{\ln(D_o/D_i)}{2\pi\lambda l}+\frac{1}{h_oA_o} \tag{4}$$

in which D_i, and D_o are the internal and external diameters of the heat exchanger, respectively, $A_o=\pi D_o l$, $A_i=\pi D_i l$, l is the effective length for heat transfer. If Eq. (4) is multiplied by A_o on both sides, then it becomes

$$\frac{1}{K}=\frac{A_o}{h_iA_i}+\frac{\ln(D_o/D_i)A_o}{2\pi\lambda l}+\frac{1}{h_o} \tag{5}$$

The classic form of the averaged Nu number for convective heat transfer in Porous medium filled channel is

$$Nu=C\,\mathrm{Re}^n\,\mathrm{Pr}^{0.4} \tag{6}$$

Where *C* and *n* are the fitting constants determined by the experiments, which vary with different conditions. We also have the definitions below:

$$Nu=\frac{h_iD_i}{\lambda_f}\,,\quad \mathrm{Re}=\frac{UD_i}{\nu_f} \tag{7}$$

Then, put the above definitions into the Eq. (6), we can obtain the convective heat transfer coefficient inside tube h_i:

$$h_i = C\frac{\lambda}{D_i}\left(\frac{UD_i}{\nu}\right)^n \mathrm{Pr}^{0.4} \tag{8}$$

According Eq. (8), we can see that if the thermal physical properties of fluid (λ, ν and Pr) be regarded as constants in all of experimental runs, the expression of convective heat transfer coefficient inside tube h_i can be simplified as:

$$h_i = C'U^n \tag{9}$$

If Eq. (9) is substituted into Eq. (5), we can have

$$\frac{1}{K} = B\left(\frac{1}{U}\right)^n + A \tag{10}$$

Where $A = \dfrac{\ln(D_o/D_i)A_o}{2\pi\lambda l} + \dfrac{1}{h_o}$ and $B = \dfrac{A_o}{C'A_i}$.

During the experiment, we measured a series of fluid flow velocities U and the total heat transfer coefficients K at different conditions. Based on these data, coefficients A and B will then obtained by the least square method of data analysis. Moreover, the internal forced convection heat transfer correlations with wall effect in sphere filled channel could be put forward.

4. DISCUSSION AND ANALYSIS

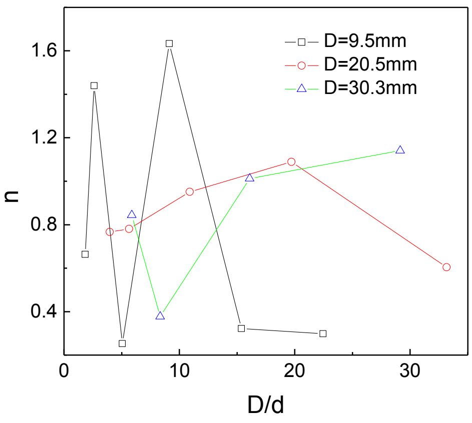


Figure 2: The variations of the power index of *Re* with changing diameter ratios of *D/d*

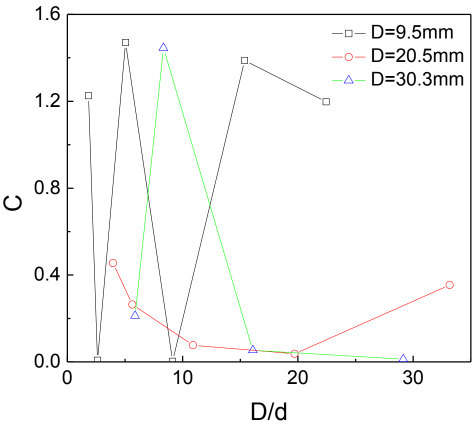


Figure 3: The variations of the empirical *n* coefficient *C* with changing diameter ratios *D/d*

Figures 2 and 3 show the exponent index n and the constant C respectively in Eq. (9) for various D and the combination of D/d. We can see that for the three kinds of filling tubes, as the ratios of the filling pipe diameter and particle diameter D/d increases, the variations of the power index n are not identical. For the case filling tube diameter D = 9.5 mm, the value n fluctuates with increasing the ratio of D/d in the experimental range of D/d. There are two maxima, respectively at about D/d= 4 and D/d = 10. For the case of filling tube diameter D = 20.5 mm, the value n shows firstly increasing then decreasing with the increase of the diameter ratio D/d. For the case of D = 30.3 mm, the value n shows firstly decreasing then increasing, which is opposite to the case of D = 20.5 mm.

We can also see from the figures that when the diameter d = 1 mm or so, the power exponents n of Re have maximum values of the three kinds of filling tubes. For D = 9.5 mm, the maximum value of n is about 1.63, while D = 20.5 mm and D = 30.3 mm, the maximum values of n are about 1.09 and 1.14 respectively. Therefore, using porous medium packed channel to enhance the heat transfer, a small inside diameter of the pipe is more favorable.

According to the experiment data of heat transfer, we can obtain a heat transfer correlation in porous medium packed channel considering the wall effect:

$$\begin{aligned} &Nu = 0.24\,\mathrm{Re}^{0.763}\,\mathrm{Pr}^{0.4}(D/d)^{1.48} \quad 1.840 \le D/d \le 3 \\ &Nu = 0.14\,\mathrm{Re}^{1.03}\,\mathrm{Pr}^{0.4}(D/d)^{-0.5} \quad 3 < D/d \le 33.172 \end{aligned} \tag{11}$$

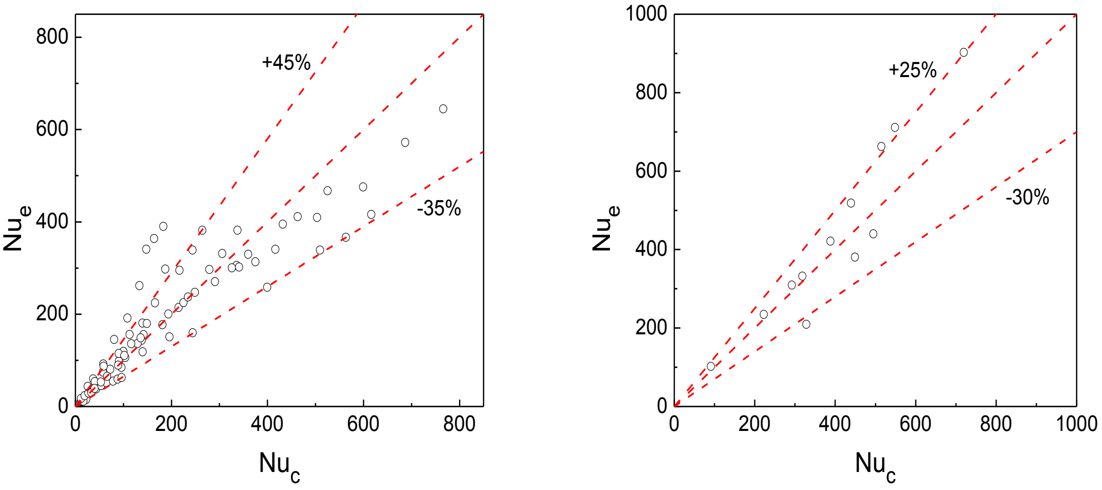
The heat transfer coefficient outside the tube can be calculated as

$$h_{oc} = \frac{1}{A - \dfrac{A_o \ln\left(D_o / D_i\right)}{2\pi\lambda l}} \tag{12}$$

While the heat transfer coefficient inside the tube is

$$h_{ie} = \frac{A_o}{\left(\dfrac{1}{K} - A\right) A_i} \tag{13}$$

According to the heat transfer coefficient inside the tube, h_{ie}, we can calculate the experimental Nu_e as $Nu_e = \dfrac{h_{ie} \cdot D}{\lambda_f}$



(a) *D/d* > 3 **(b) *D/d* < 3**

Figure 4: The contrast for the measured Nu_e and the calculated Nu_c using Eq. (11)

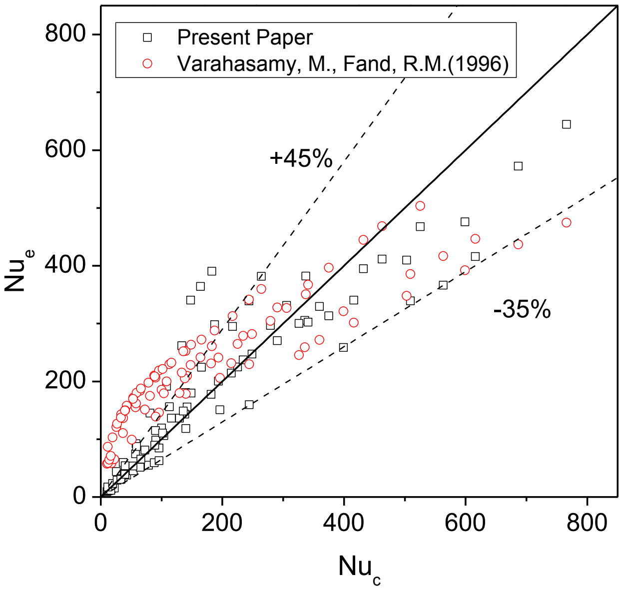


Figure 5: The calculated Nu_c by Eq. (11) and the correlation of Varahasamy and Fand (1996) .

If we define the mean absolute error MAE is:

$$MAE = \frac{1}{N}\sum\frac{\left|Nu_e - Nu_c\right|}{Nu_e}\times 100\% \tag{14}$$

The mean absolute errors for the heat transfer coefficient Nu in the paper are 16.78% while D/d is in a range of 1.84 ≤ *D/d* ≤3, and 21.71% while *D/d* is in a range of 3 ≤ *D/d* ≤33.172, respectively.

Figure 5 shows the experimental data plotting by using the correlation of Eq. (11) and the correlation proposed by Varahasamy and Fand (1996). It is seen that our predicated values are lower than those calculated by using Varahasamy and Fand's formula while Nu number is less than 200, but in good agreement while at large Nu number. One of the reasons is probably due the thermal boundary difference in the heat transfer experiment. Our test section are heated by flowing hot water through the outer annulus, while in Varahasamy and Fand's experiments, the test section was heated by electric coil surrounding the porous medium parked tube. The other is that the length of our test section is about 5D, which is shorter than 8D the low limitation for applying their formula.

5. CONCLUSIONS

The wall effect on the characteristics of fluid flow and heat transfer in porous medium packed channels has been investigated. In this paper, we have used the Wilson Plot Method to process the heat transfer experimental data, and summarized a heat transfer correlation with wall effect in porous medium packed channel in a *D/d* range 1.84 ≤ *D/d* ≤33.172. Comparing the experimental data with the calculated from the formula, we have found that the mean absolute error in is less than 21.71%. It seems that before and after *D/d*, the wall effect due to the change of *D/d* on heat transfer shows totally opposite direction, and more experimental data are needed for small ratio of *D/d,* even the experiment at small *D/d* might be more difficult to perform.

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