EXPERIMENTAL INVESTIGATION ON SINGLE PHASE FLOW CHARACTERISTICS OF UPWARD FLOW IN NARROW ANNULUS OF CONCENTRIC TUBE HEAT EXCHANGER

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Keywords :

Friction factor
Narrow annulus
Reynolds number

Abstract :

This research was carried out to investigate the single phase flow characteristics of upward flow with/without heat exchange in narrow annulus of concentric tube heat exchanger. In this experiment, direction of flow was upward flow. Hydraulic diameter of the narrow annulus was 4.77 mm. Flows in the inner tube and in narrow annulus were in opposite directions. Working fluid used in this research was water. From this research, it was shown that the flow characteristics of water through the narrow annulus were different from those in conventional pipes. For the flow without heat exchange in narrow annulus, the flow transition from laminar to turbulent flow was initiated earlier than that in normal pipes at a Reynolds number range from 1,533 to 1,880. The flow transition with heat exchange occurred for a Reynolds number in the range of 1,545 to 1,846. Flow friction factor of the upward flow with heat exchange was larger than that without heat exchange at the Reynolds number was lower than 600. The flow friction characteristics in narrow annulus had relations to the water temperature difference at the inlet and outlet of the annulus. Their influences on the flow friction were concentrated in the laminar flow area.

INTRODUCTION

Heat exchanger is a device that is used as a medium for heat transfer between hot fluid and cold fluid. Heat exchanger is widely used in engineering, for example: in terms of heating, air conditioning, power plant, waste heat recovery and chemical processes. Heat exchangers with small channels are used in products or equipment that has a high heat flux such as: nuclear reactors, bioreactors and highly efficient electronic devices. Narrow channels are used in a variety of devices incorporating single-phase liquid flow. Narrow channels are widely used in nuclear industry. Pipeline drilling through underprop of heat exchanger, and the plank components of reactor etc. all form narrow channels. The flow and heat transfer characteristics of these narrow channels play an important role in the security and reliability of the nuclear equipment. The investigations on narrow channels became of greater importance recently.

Fluid needs to be pumped through a heat exchanger, thus determining the pumping power of fluid that is needed is a priority as part of system design and analysis of operating costs. Pumping power is proportional to pressure drop of fluid, where it is associated with fluid friction and the contribution of other pressure drop along the path of fluid flow. A pressure drop means that there are energy losses due to friction between the fluids with the channel surface. Fluid pressure drop has a direct relationship with the heat transfer in heat exchanger, operation, size, and other factors, including economic considerations. Determining the pressure drop in a heat exchanger is the main thing for many applications, there are at least two reasons: (1) fluid needs to be pumped through a heat exchanger, this means it is needed the fluid pumping power. Pumping power is proportional to the pressure drop in heat exchanger, (2) heat transfer rate can be significantly affected by changes in saturated temperature for a fluid that has condensation or evaporation if there is a large pressure drop along the flow. This is because the saturated temperature changes associated with changes in saturation pressure and affect the temperature difference for heat transfer.

Concentric tube heat exchanger with a narrow annulus has been used widely in industry because it has several advantages, among others: suitable for heat exchanger with a low temperature difference, has high heat transfer effectiveness, and its compact design without complex machining processes. However, concentric tube heat exchanger with a narrow annulus also has a weakness, namely a high pressure drop and requires a clean working fluid. Pressure drop in concentric tube heat exchanger with a narrow annulus is an important design parameter in engineering applications because it determines the required pumping power. The greater the pressure drop in concentric tube heat exchanger with a narrow annulus, the greater the pumping power required to maintaining the flow, which affects the cost of pumping is the greater.

Changhong (2005) classify the narrow channel with either rectangular or annular geometry is limited by the hydraulic diameter of ≤ 5 mm. Classification of the channel by Mehendale et al. (2000) as follows, where D is diameter :

1. Conventional passages D > 6 mm
2. Compact passages 1 mm < D < 6 mm
3. Meso – channels 100 µm < D < 1mm
4. Microchannels 1 µm < D < 100 µm

Many researchers have examined the flow characteristics in small channels. Mala et al (1999) examined the characteristics of water flow in microtubes with diameters range from 50 to 254 mm. The results showed that the flow characteristics in microtubes with smaller diameters deviate from predictions of conventional theory, while in microtubes with large diameters, the results of research in accordance with conventional theory. In this study, flow transition occurs in the range of Reynolds numbers from 500 to 1,500. Sun et al (2004) conducted a study of water flow resistance characteristics in a narrow annulus with heat exchange carried out in conditions of 1 atm. This study used a test section consists of three concentric tubes with annular gap size 0.9 mm 1.4 mm, and 2.4 mm. The results showed that flow transition from laminar to turbulent flow before the Reynolds number reaches 2,000.

Celata (2004) investigated the single-phase fluid flow in micropipes, where R114 flowing in the capillary pipes with a diameter of 130 mm. Reynolds number was varied from 100 to 8,000. The investigation showed that in the laminar flow area, friction factor according to the theory of Hagen - Poiseuille for Reynolds numbers less than 600-800. For higher Reynolds number, experimental data deviate from the theory of Hagen - Poiseuille. The transition from laminar to turbulent flow occurred at Reynolds number range 1,800-2,500. Lu et al (2008) investigated the flow characteristics with/ without heat exchange in a narrow annulus. This study using a tube-in-tube heat exchanger with annulus gap of 3.08 mm and the pressure measurement length of 1,410 mm. Fluid used in this study is water with a horizontal, upward, and downward flow direction. In this study the range of Reynolds number (Re) based on annulus hydraulic diameter is from 3 to 30,000. In this study the transition flow in a narrow annulus is initiated earlier than conventional pipe at 1,100 < Re <1,500.

EXPERIMENTAL

A schematic diagram of the experimental apparatus is given in Figure 1. Flow in the inner tube and the narrow annulus is the opposite direction. Flow path on a narrow annulus is an opened loop. The cold water tank is mounted at a high altitude to provide a regular driving pressure, which would guarantee the flow being steady. The flow rate of cold water is surveyed by a weight-measuring technique. Having weighed the cold water pumped by centrifugal pump and immediately discarded. The inner tube loop is a closed loop. Hot water is driven by a centrifugal pump, flowing through the test section and then returns to the hot-water tank. Electric water heater serves to heat the water in the hot water tank. Heater used was 10 units with a total power used is 6,000 W. Electric water heater is controlled by thermocontroler to maintain constant temperature in the hot water tank. Tests performed with Reynolds number of cold water flow in a narrow annulus from 110 to 8,500.

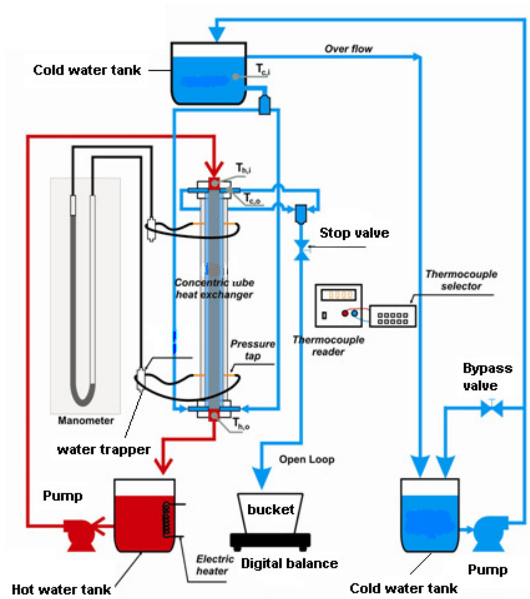

Figure. 1 Schematic diagram of experimental apparatus

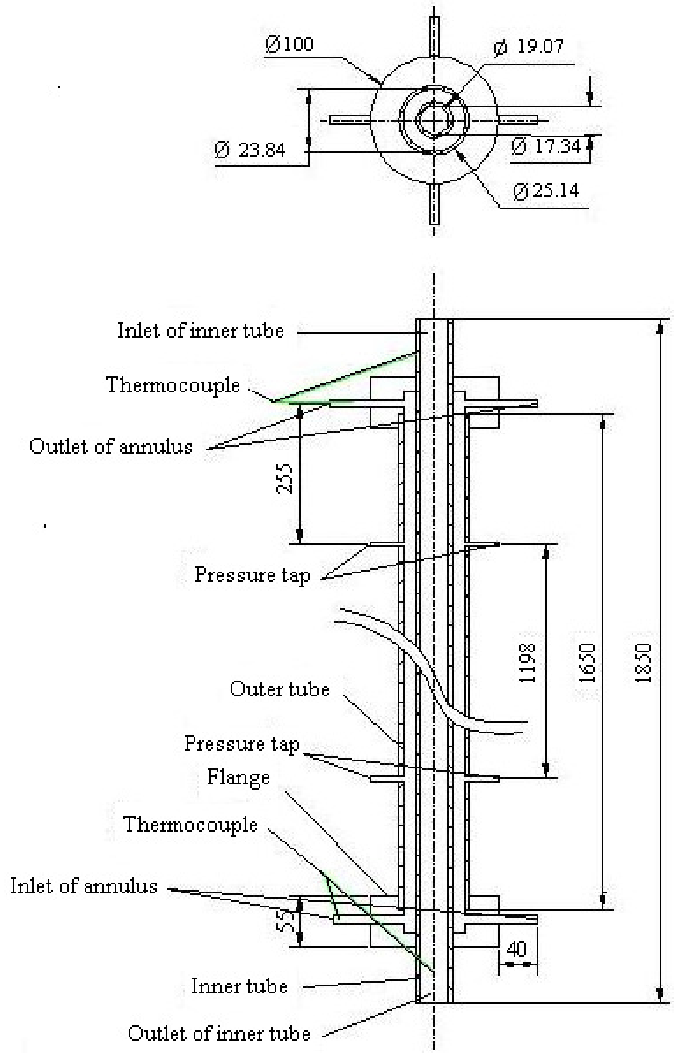

Figure.2 Detail of the test section

Test section is a concentric tube heat exchanger. Detail of the test section can be seen in Figure 2. The inner tube is made of aluminium with a 17.34 mm inside diameter and 19.07 mm outside diameter. Outer tube is made of aluminium with a 23.84 mm inside diameter and 25.14 mm outside diameter. Annulus gap width is 2.38 mm. The pressure measuring length is 1,198 mm. The hydraulic diameter of narrow annulus is 4.77 mm. Test section was isolated by thermoplex insulator to minimize heat transfer to the environment through convection and radiation. In this study, to measure the temperature of the water used T-type thermocouple which has a sensitivity of 43 µV/°C and 0.1 mm in diameter. Thermocouples are mounted on the inner tube to measure the temperature of hot water in and out of the inner tube, on the cold water tank to measure the temperature of cold water enter the narrow annulus, and on the exit narrow annulus to measure the temperature of cold water out of the narrow annulus. U tube manometer with water as the working fluid serves to measure the pressure difference of water flow in the narrow annulus. Installation of pressure taps, at a distance of 25 times the narrow annulus hydraulic diameter of the inlet and the outlet water in a narrow annulus to ensure that the area is already a fully developed region (Olson, et al, 1963).

RESULTS AND DISCUSSION

Friction factor (*f*) of single phase fluid flow in a conventional circular pipe can be calculated by the following equations; Equation (1) for laminar flow and Equation (2) for turbulent flow from Blasius:

$$f = \frac{64}{Re} \quad ; Re < 2{,}300 \qquad (1)$$

$$f = 0.3164.Re^{-0.25} ; 4.10^3 < Re < 3.10^4 \qquad (2)$$

Moody diagram gives the friction factor associated with the Reynolds number (Re) and relative roughness (e/D). To avoid the use of graphical methods in getting *f* for turbulent flow, the

Equation (3) which has been widely used for the friction factor is from Colebrook:

$$\frac{1}{f^{0.5}} = -2.0.\log\left(\frac{e/D}{3.7} + \frac{2.51}{\mathrm{Re}.f^{0.5}}\right) \qquad (3)$$

A difficulty in the use of the Colebrook equation is an implicit form of this equation. Miller (1996) suggests that a single iteration will give results within 1% if the initial estimate is calculated from Equation (4):

$$f_0 = 0.25\left[\log\left(\frac{e/D}{3.7} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^{-2} \qquad (4)$$

Moody diagram and Colebrook equation has the accuracy up to ± 10%.

The flow frictional pressure drop (ΔP) in upward water flow in the narrow annulus can be calculated with the Equation (5):

$$\Delta P = f\,\frac{l.\rho.V^2}{2.D_h} \qquad (5)$$

From equation (5), then friction factor (f) in the narrow annulus can be calculated with Equation (6) :

$$f = 2\,\frac{D_h.\Delta P}{l.\rho.V^2} \qquad (6)$$

Where D_h is hydraulic diameter of narrow annulus, l is pressure measuring length, ρ is density of fluid and V is fluid velocity.

Sun (2004) has the equation of friction factor for laminar flow in the annulus mathematically as shown in Equation (7), where r_i and r_o are inner and outer radius of annulus respectively.

$$f = \frac{\left(1 - {r_i}/{r_o}\right)^2 \ln\left({r_i}/{r_o}\right)}{\left[1 + \left({r_i}/{r_o}\right)^2\right]\ln\left({r_i}/{r_o}\right) + 1 - \left({r_i}/{r_o}\right)^2}\,\frac{64}{\mathrm{Re}} \qquad (7)$$

In this study, the dimensions of the test section are used substituted into Eq. (7) thus obtained Equation (8):

$$f = \frac{95.9}{\mathrm{Re}} \qquad (8)$$

The effect of Reynolds number on the friction characteristics in the flow without heat exchange can be seen in Figure 3. For the flow without heat exchange, water temperatures enter in the narrow annulus and inner tube ranged from 27.9ºC to 29ºC. Through the comparison between the friction characteristic curve of water flow in a narrow annulus and that in the conventional circular pipes as shown in Figure 3, it is shown that in the laminar flow region (Re < 1,500) friction factor in the narrow annulus are 12.07 to 31.08% larger than with conventional circular pipe (compared with Eq.1.). Regression equation for the flow friction factor in laminar flow region is,

$$f = \frac{80}{\mathrm{Re}} \qquad (9)$$

with an application range of Re < 1,500. The results obtained with regression equation, f = 80/Re, is 1.25 times the value calculated by equation f = 64/Re, but smaller by 19.87% from the value determined by Equation (8). In the turbulent flow area (Re > 1,900), the friction factors in the narrow annulus were 3.8% larger than in conventional circular pipe (compared with Eq.2.) Also, in the turbulent flow area (Re > 1,900), the friction factor in the narrow annulus are 0.5 to 7.84% larger than the Colebrook equation (Eq.3.) Areas where there is a change trendline value of friction factor for the laminar flow area to the trendline value of friction factor for the turbulent flow area inferred as the transition flow area. In this study the transition flow area in the narrow annulus is initiated earlier than the conventional circular pipe at 1,533 ≤ Re ≤ 1,880.

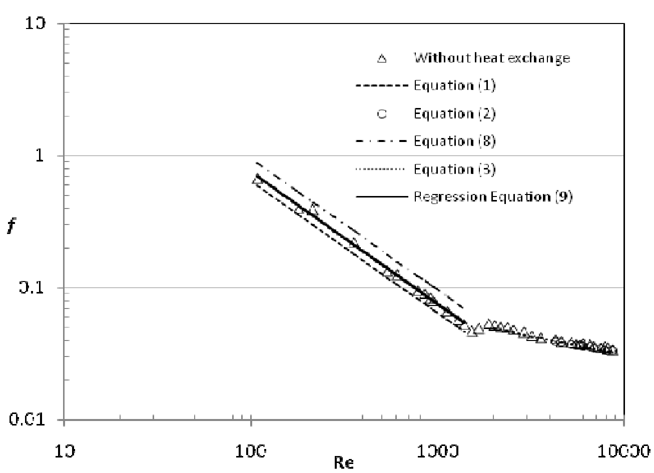

Figure 3 Friction characteristics of upward flow without heat exchange

Figure 4 shows the relationship between Reynolds number on the flow friction characteristics of upward flow with/without heat exchange. For the flow without heat exchange, water temperatures enter in the narrow annulus and inner tube ranged from 27.9ºC to 29ºC. For the flow with heat exchange, temperature of cold water enters in narrow annulus ranged from 27.9ºC to 29ºC, while the temperature of hot water enter in inner tube is kept constant at 60°C. For the flow with heat exchange, the system is run until the water temperatures out of the narrow annulus and inner tube are the temperature in steady state.

In Figure 4 shows that in the laminar flow area, flow friction curve with heat exchange and those without heat exchange are relatively different. Flow friction factor that occurs in upward flow with heat exchange larger than that without heat exchange at Re ≤ 600. It differences diminish as the Reynolds number increases. Heat exchange influences on the flow friction, especially in regions with low Reynolds number. In regions with Re ≤ 600, the friction factors with heat exchange are 1.22 to 2.83 times larger than those without heat exchange. In regions with Re ≤ 600, heat exchange causes the flow in the narrow annulus becomes asymmetric. This is because differences in water temperature on the outer wall of the inner tube with the center of the annulus. While the water flowing symmetrically without heat exchange will decrease the flow friction. Similar results were also obtained by Jiang (1998) and Lu (2008).

When the Reynolds number increased heat exchange also increased, causing the viscosity of water is much smaller. The small value of water viscosity will decrease the flow friction. In this study the transition flow with heat exchange in the narrow annulus in the range 1,545 ≤ Re ≤ 1,846.

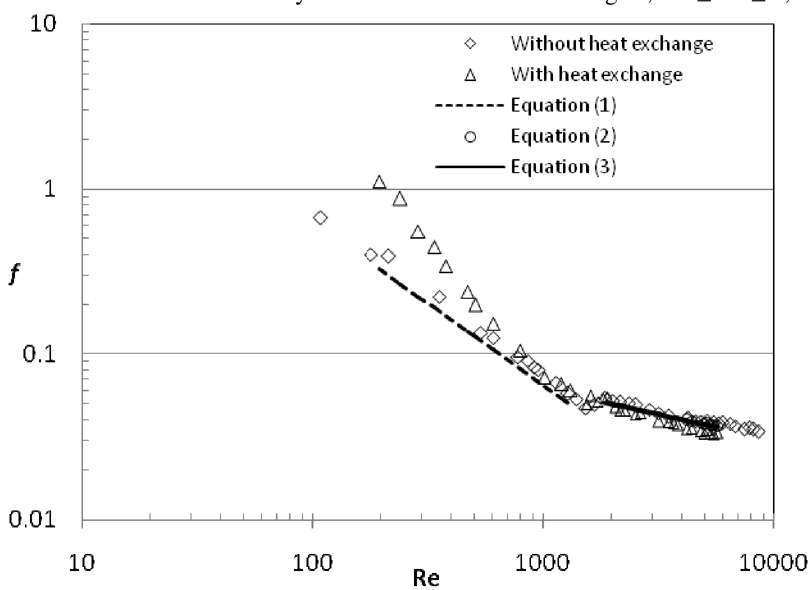

Figure 4 Friction characteristics of upward flow with/without heat exchange

The relationship between the Reynolds number and the water temperature difference at the inlet and outlet of the narrow annulus is shown in Figure 5. Temperatures of water flowing in and out of the narrow annulus are temperature obtained in the steady state. In regions with Re ≤ 600, the temperature difference of water flowing in and out of the annulus narrow ranged from 25.4°C to 28.1°C. In the same Reynolds number area, the flow frictions with and without heat exchange have relatively large differences. As the Reynolds number increases, the water temperature differences diminish, and the difference between the flow frictions with and without heat exchange decreases, too. In the turbulent flow area (Re > 1,900), the water temperature difference becomes smaller with a range of 12.5^{o}C – 14.6^{o}C, and the flow friction characteristics curves with and without heat exchange are relatively similar. It is shown that the influence of heat exchange on the flow friction is concentrated in the laminar flow area. In the turbulent flow area, heat exchange has little influence on the flow friction, which is similar to the results obtained by Sun (2004) and Lu (2008).

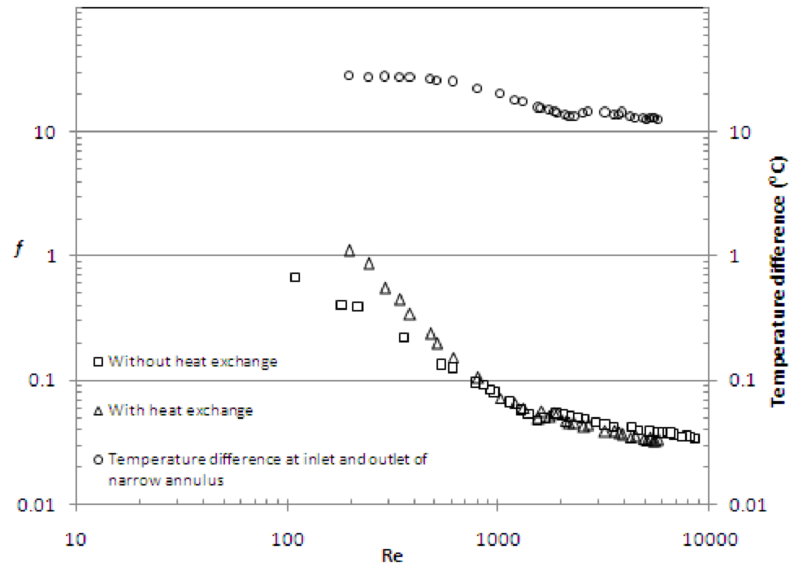

Figure 5. The relationship between friction factors with the temperature difference.

CONCLUSION

From the experimental measurements and analyses, it is shown that the single phase flow characteristics of upward flow through narrow annulus of concentric tube heat exchanger are different from those in conventional-sized tubes. When the water flows through the narrow annulus without heat exchange, the transition from laminar to turbulent flow is initiated earlier than that in normal pipes at a Reynolds number ranged from 1,533 to 1,880, whereas with heat exchange, the transition from laminar flow to turbulent flow is initiated at a Reynolds number ranged from 1,545 to 1,846. The flow friction characteristics of the upward flow with heat exchange is larger than that without heat exchange when the Reynolds number is lower than 600. The flow characteristics in the narrow annulus have relations to the water temperature difference at the inlet and outlet of the annulus. Their influences on the flow characteristics are relatively obvious in the laminar flow area.

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