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Experimental study on heat transfer characteristics of annular flow between vertical concentric pipe

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Abstract. Concentric pipe heat exchangers have been utilized extensively in practical project, such as petroleum, chemical, geothermal energy utilization and other fields. The study of annular flow between vertical concentric pipes is dominated by boiling heat transfer, while the study of forced convection heat transfer for single-phase flow is scarce. In this paper, an experimental investigation is carried out to study of the flow and heat transfer characteristics of the annular flow between vertical concentric pipes. The annular in a vertical concentric pipe heat exchanger with 25mm ring gap is tested with different volume flow rates and different constant heat flow densities. The results show that the Nusselt number of annular flow between vertical concentric pipes increases with Reynolds number. The local convective heat transfer coefficients reduce with the distance from the top to the bottom, which lead to a gradually increased trend in the fluid temperature along the flow direction. Based on the experimental data, an empirical equation of the Nusselt number is obtained to evaluate the overall heat transfer performance of vertically concentric pipe heat exchangers.

1. Introduction

As one of the most popular topics in the world, energy is important material basis for social development and basic condition for human survival. With the continuous development of modern civilization, energy supply has become difficult to meet the increasing social demand. In order to alleviate energy supply and demand, the world has been actively working on developing new energy sources and finding ways to save energy [1]. The study of convective heat transfer and strengthening heat transfer is an effective way to save energy and improve the utilization efficiency with minimal cost [2].

Concentric pipe heat exchanger is an important form of heat exchanger. It possesses the properties of high thermal efficiency as well as flow stability. The structure is compact with less possibility to produce precipitation and pollution, which can satisfy the compactness and efficiency requirements. Therefore, the concentric pipe heat exchanger is widely used in nuclear power plant, solar energy utilization, petrochemical industry, biological refrigeration and geothermal energy application [3-5].

In order to save energy and improve energy efficiency, it is necessary to further study the heat transfer characteristics of concentric pipe heat exchanger. The outcome from this research may provide a theoretical support for the geothermal development, where the vertical concentric pipes are widely used. Most of the existing studies focused on the structure design of the concentric heat



exchangers (Quarmby et al. 1968; Trombetta et al. 1971), and the investigation on the characteristics of annular flow between concentric pipes is rather scarce. To maximize the performance of the concentric pipe heat exchanger in geothermal applications, it is imperative to explore the fluid flow and heat transfer characteristics in vertically placed concentric pipes. This research attempts to explore the characteristics of fluid flow and heat transfer of annular flow in the vertical concentric pipes. It aims to develop a convenient method to approximately evaluate the overall performance of concentric pipe heat exchanger used in the geothermal applications.

2. Experimental details

In this study, water is pumped into the top of the ring gap to absorb heat, and then the heated annular flow flows down to the bottom through the ring gap and discharge from the experiment section. Three heating powers (250, 390 and 560 W) and eight flow rates (0.5, 0.8, 1, 1.3, 1.5, 2, 2.5 and 3 m³·h⁻¹) i.e., totally 24 working conditions, were tested in this experiment. The heat transfer characteristics of the annular flow are analyzed by collecting those data from the different working conditions.

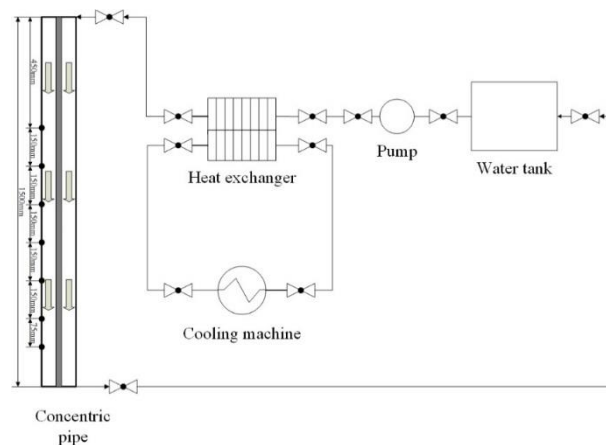


Figure 1. The experiment system.

This experiment includes five sections: heating section, cooling section, power section, water storage section and experimental part. The heating section comprises a DC power supply and a silicon rubber heating belt. The cooling section includes a multilayer plate heat exchanger and an industrial cooling machine. Fluid is pumped by a three-phase asynchronous pump. A square water tank with the volume of 0.125 m³ acts as the storage section of the experiment.

The concentric pipe heat exchanger is the key section of this experiment, which consists of two circular pipes of different materials. The outer pipe with inner diameter of 50 mm and the inner pipe with outer diameter of 25 mm are made of polypropylene and stainless steel respectively. The ring gap between them is 25 mm. The length of the concentric pipe heat exchanger is 1500 mm in order to ensure that the fluid in the experimental section can reach turbulent state. Three centralizers are fixed on the upper, middle and lower parts of the inner pipe and tightly stuck on the inner wall surface of the outer pipe to reduce the violent vibration of the inner pipe during the operation process, so that the inner pipe can always maintain a stable vertical concentricity.

On the outer wall of the outer pipe, eight thermocouples are proportionally arranged along the vertical direction so as to obtain the temperature of the outer wall before calculating the temperature of inner wall. At each point, shallow hole is drilled to bury the head of the thermocouple. The OMEGA thermal adhesive was pasted on the hole to fix it tightly.

In addition, to ensure that the outer pipe receives uniform heat flux, a circular stainless steel pipe of the same length is placed outside the outer pipe. The gap between these two pipes is about 3 mm, which is filled with conductive silicone oil. The heating belt is evenly wound around the outermost circular pipe. Insulation cotton covering the heating belt reduces the heat loss to the surroundings.

3. The formulas

This experiment is the forced convection heat transfer under constant heat flux in the annular flow between outer and inner pipes. The inlet water temperature of the experimental section is t_f' and the outlet water temperature is t_f'' .

The qualitative temperature can be expressed as:

$$T_m = \frac{t_f' + t_f''}{2} \quad (1)$$

The conductive heat transfer amount of water in the experimental section is:

$$Q_c = q_v \rho C_p (t_f'' - t_f') \quad (2)$$

In steady state, the heat conduction rate through the outer pipe is approximately considered to be constant, and the heat flux from the outer wall to the inner wall is:

$$q = \frac{Q_c}{\pi D_i L} \quad (3)$$

Assuming that the water temperature is linearly distributed in the ring gap, the fluid temperature at section i is:

$$t_{fi} = t_f' + \frac{x_i}{L} (t_f'' - t_f') \quad (4)$$

where x_i is the distance from the entrance to the position of section i , and L is the total length of the experimental part.

The inner wall temperature of the outer pipe can be derived from its outer wall temperature of the same section:

$$T_2 = \frac{Q_c \ln\left(\frac{r_2}{r_1}\right)}{2\pi\lambda dL} + T_1 \quad (5)$$

where r_1 and r_2 are the inner radius and outer radius of the outer pipe, λ is the thermal conductivity of stainless steel.

Then the local convective heat transfer coefficient at each section can be calculated as:

$$h_i = \frac{q}{T_{li} - t_{fi}} \quad (6)$$

According to the local convective heat transfer coefficient, the average convective heat transfer coefficient can be obtained:

$$\bar{h} = \frac{1}{L} \int h_x dx \quad (7)$$

The equivalent diameter of the annular flow is:

$$D_e = D_i - d_o \quad (8)$$

The Re and the Nu can be calculated by the average convective heat transfer coefficient, the equivalent diameter of the annular flow and the working fluid bulk temperature related parameters as follows:

$$Re = \frac{uD_e}{\nu} \quad (9)$$

$$Nu = \frac{\bar{h}D_e}{\lambda_f} \quad (10)$$

4. Results and discussion

The distance of eight temperature measuring points to the entrance is shown in table 1.

Table 1. Distance from the entrance to measuring points.

Point	1	2	3	4	5	6	7
x(mm)	450	600	750	900	1050	1200	1275

It is observed from Figure 2 that Nu increases almost as Re increases, which means with the increase of Reynolds number, the convective heat transfer capacity of the annular flow increases. In addition, the convection heat transfer capacity of the annular flow is almost independent of the heat flux.

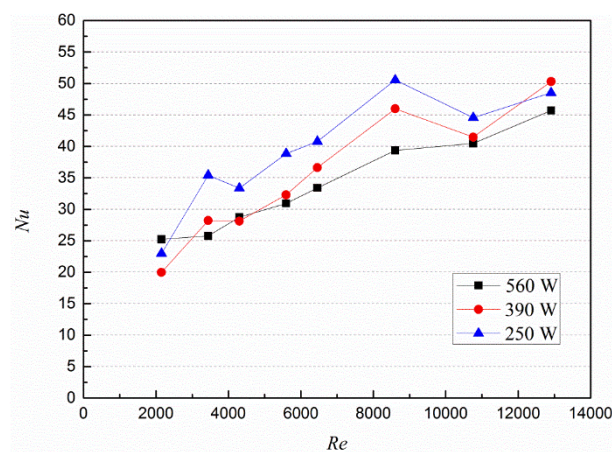


Figure 2. Re and Nu at different heating powers.

It can be seen from Figure 3 that from the top to the bottom of the pipe, the wall temperature gradually increases from around 20 °C to higher values, despite several points where the temperature is lower than the previous point. As the Re becomes larger, the flow rate of the working fluid in the annular flow accelerates and the heat transfer between the water and the inner pipe wall is strengthened. Therefore, under the same heating power, the wall temperature presents a downward trend with the increase of Re .

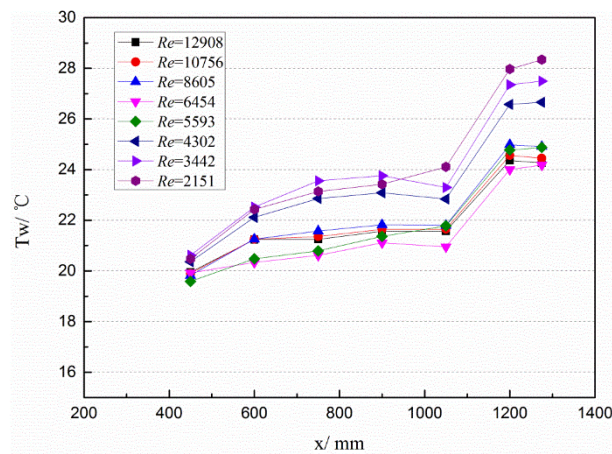


Figure 3. Effect of Re on wall temperature.

It is observed from Figure 4 that with the increase of the distance between the measuring point and the inlet location, the local conductive heat transfer coefficient decreases. At the same measuring point, the coefficient increases with the increase of Re . As the flow rate increases, the ability of annular flow to cool the pipe wall increases. With the development of the fluid, the boundary layer gradually becomes thinner, and the heat transfer coefficient increases and with the fluid mixing increases, the heat transfer coefficient also increases accordingly. Figure 5 is the curve of heat flux on convective heat transfer coefficient when Re is 10756. Under the same Re , the convective heat transfer coefficient remains nearly unchanged with the change of heat fluxes.

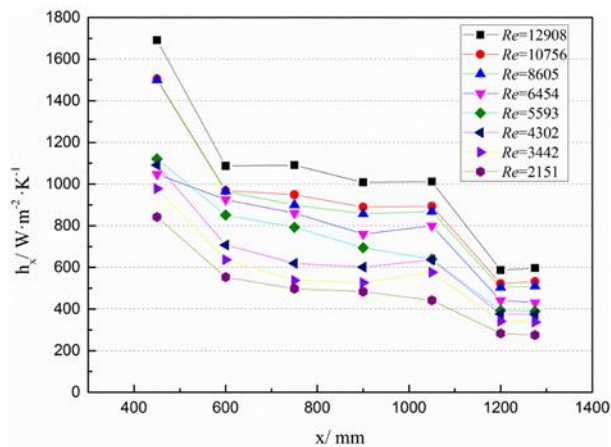


Figure 4. Effect of Re on heat transfer coefficient.

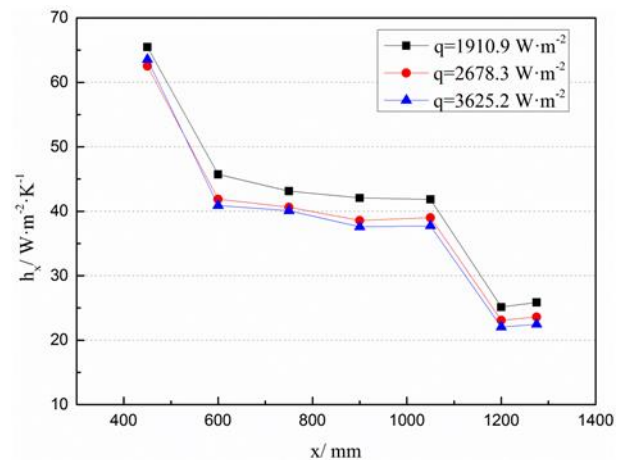


Figure 5. Effect of heat fluxes on the heat transfer coefficient.

In Figure 6 the black blocks represent experimental points, and the solid line represents the fitting results of experimental data. The fitting formula is:

$$Nu = 1.117Re^{0.398} \quad (11)$$

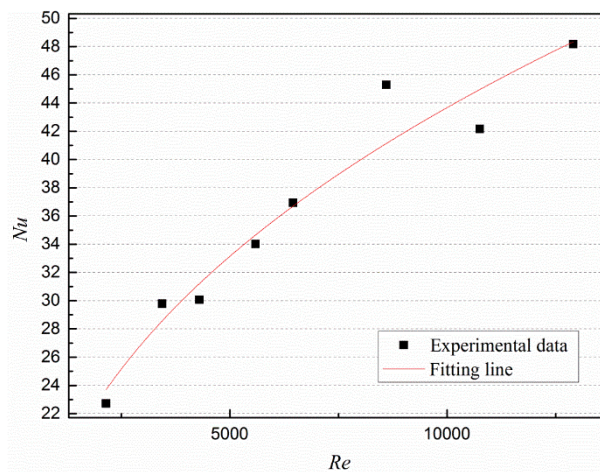


Figure 6. The empirical heat transfer equation.

5. Conclusion

In this paper, the experimental research on the heat transfer characteristics of the annular flow between vertical concentric pipes is carried out. By controlling the volumetric flow rate and heating power and measuring the temperature distribution along the pipe wall, the local convective heat transfer coefficients have been obtained for analysis and formula fitting.

The results show that under all the three heating power conditions, Nu and the heat transfer coefficient increase with the growing Re . The working fluid temperature gradually raises up from the top to the bottom of the pipe, causing lower amount of heat exchange with the pipe wall and relative higher wall temperature. It also can be clearly seen that the local convective heat transfer coefficients reduce with the distance from the top to the measuring point increases. Eventually, the empirical heat transfer equation based on experimental conditions has been conducted. Based on the experimental data, the obtained empirical equation quantitatively expresses the relation between Nusselt number and Reynolds number in the current test conditions. It can be used to evaluate the overall heat transfer performance of the annular flow through vertically placed concentric pipes.

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