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Study on the heat transfer of cross flow in vertical upward tubes*

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Abstract: A special device was designed to measure temperature difference in this study of heat transfer of water and oil cross flow inside vertical upward tubes. A new heat transfer correlation was obtained for cross flow. The experimental results showed that the dependence of heat transfer on Reynolds is much smaller in a narrow space than that in a wide space. It was found that the heat transfer correlation of cross flow in a narrow space is obviously different from that in a wide space, and that the heat transfer correlation obtained in a wide space may not be applicable to the cross-flow heat transfer in a narrow space. Further, the single-phase heat transfer capability of water cross flow was compared with that of oil cross flow. The experimental results showed that the average heat transfer coefficient of water is about 2~3 times that of oil when they have the same superficial velocity.

Key words: Heat transfer, Cross flow, Upward
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INTRODUCTION

Cross flow and heat transfer were widely found in oil production and chemical facilities. A detailed study of the hydrodynamic characteristics and heat transfer of cross flow is necessary for optimal design of the system and the development of new measuring techniques. Studies on the heat transfer in single-phase liquid cross flow were carried out in the past decades. Air or water was often chosen as the working fluid, in these studies commonly focused on fluids flowing across round tubes. Many important results were achieved and most investigators have obtained their heat transfer correlations within their applicable range (Holman, 1997; Giedt, 1949; Knudsen and Katz, 1958). In this study, special equipment was used to measure the temperature difference between the rod and the mainstream flow. The heat transfer in single-phase water and oil flowing through a rod was studied. New correlations were obtained and comparison of heat transfer correlations between single-phase water and oil cross flow was carried out.

EXPERIMENTAL SETUP AND DATA-PROCESSING METHOD

Experimental setup

Fig.1 is the test loop and Fig.2 is the test section of this study. The inner and outer diameter of the vertical tube is 50 mm and 60 mm respectively. The equipment that can measure the temperature difference is composed of two parts. Part one is a heater rod made up of two jointed steel tubes with the inner and outer diameter of the tubes being 5 mm and 6 mm, respectively. A Pt10 resistance coiled thread is put into one of the steel tubes, and a Pt100 resistance coiled thread is put into the other. Part two is a rod without heater; it is made up of a single steel tube with a Pt100 resistance coiled thread inside. The tube's inner and outer diameter is also 5 mm and 6 mm respectively. An amplifier and processing circuit connects the two parts, and produces a voltage signal. The

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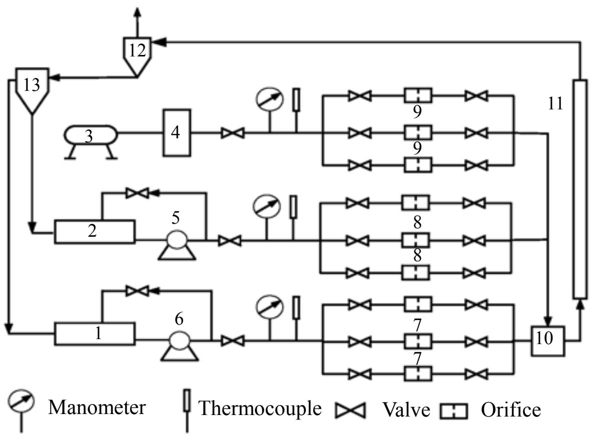
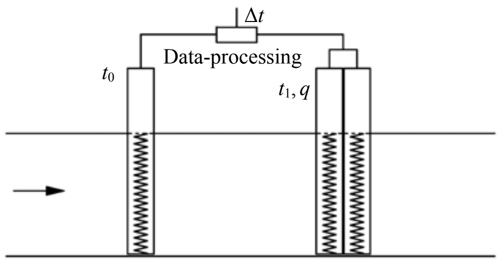
voltage signal was put into the computer for data processing, and the temperature difference was obtained between the rod surface and the mainstream flow.



1: Oil tank; 2: Water tank; 3: Compressor; 4: Pressurizer; 5: Water pump; 6: Oil pump; 7: Oil flowmeter; 8: Water flowmeter; 9: Gas flowmeter; 10: Mixer; 11: Test section; 12: Gas/liquid separator; 13: Oil/water separator

Fig.1 Test loop



t_0: Fluid temperature; t_1: Wall temperature; q: Heat flux; Δt: Temperature difference

Fig.2 Sketch map of the temperature difference measurement equipment

The calculation of heat flux density

The flow will change when liquid flows across the rod. Some assumptions are adopted: (1) The flow is stable; (2) The time of heat transfer from inside to outer side of the rod is short enough; (3) Liquid flowing across the rod absorbs the whole heat from inside to the outer side of the rod.

Then the average heat transfer coefficient between the rod and liquid can be obtained according to the heat transfer theory:

$$h=q/\Delta t, \quad (1)$$

where h is average heat transfer coefficient, q is heat flux density, Δt is the temperature difference between the rod wall temperature and fluid temperature and can be obtained directly by the equipment mentioned above. q can be calculated by the heating power and the effective surface area of the rod, that is:

$$q=W/A_s, \quad (2)$$

where W is the heating power, A_s is the effective surface area of the rod. In this study the rod is heated by constant circuit flow. The output circuit is 0.6 A, and the value of the Pt resistance is 20 Ω, so the heating power is:

$$W=I^2R=0.6^2\times 20=7.2 \text{ W} \quad (3)$$

The heat flux of the heating rod surface is:

$$q=W/A_s=7.2/0.0015755\approx 4570 \text{ W/m}^2 \quad (4)$$

In this study, the combination of heating unit and temperature measurement unit successfully obtained the measurement of the temperature difference between the fluid and the rod; it is of great significance in practice.

Data processing method

The study of the cross flows and heat transfer outside the round tubes has been carried out for decades; during this process the analogical theory was proposed. It provides not only the direction of experiment and data processing method, but also the common base of different investigators' experimental results. Extensive efforts were exerted in recent years to study the two phase cross-flow heat transfer inside vertical upward tubes and were summed up by Zhukauskas (1987), but the heat transfer of single phase cross flow like that in this study has not been reported yet.

Most of the studies showed that the cross flow situation varies with the Reynolds number, and that the characteristic of the heat transfer is determined by the growth and the departure of the boundary layer. It is proposed that the local heat transfer coefficients vary along the wall of the tubes. Although the variation of heat transfer is very complicated, the gradual change of the heat transfer is very obvious from the average heat transfer coefficient (Yang and Tao, 1998).

Analogical theory was employed in the data processing in this study because of previous successful experience. According to the analogical theory, the heat transfer experimental results should be expressed as a function of dimensionless numbers. For convenience, we adopt the form of Nusselt number correlation proposed by Holman:

$$Nu = hL/\lambda = C \cdot Re^m \cdot Pr^n, \quad (5)$$

where h is the average heat transfer coefficient, L is the width of the rod facing the stream, λ is the conductive coefficient of liquid, Re is the Reynolds number, Pr is the Prandtl number, C and m are empirical constants which can be determined experimentally and n is equal to 1/3 that suggested by Holman.

EXPERIMENTAL RESULTS AND DISCUSSION

Heat transfer of single water phase cross flow

The cross flow between liquid and gas phase has similar characteristics. In the front part of the rod, laminar boundary layer develops gradually and becomes thicker, and then leaves the rod and produces reversals and eddies. The back part of the rod is under complicated reversals and eddies, which strengthen the heat transfer significantly.

In this study, the water's superficial velocity is 0.06~0.65 m/s, and the Reynolds number is 1000~11000, then the dimensionless correlation of heat transfer in single water phase cross flow is obtained as follows:

$$Nu_{sw} = 3.97Re^{0.34} \cdot Pr^{1/3}, \quad (6)$$

where Nu_{sw} is the Nusselt number of water cross flow. The measurement results are given in Fig.3. Fig.4 compares the calculated and experimental results of the average heat transfer coefficient showing that the error is below ±4%.

Heat transfer of single oil phase cross flow

Due to the limitations of the experimental conditions, the oil superficial velocity in this study is 0.037~0.40 m/s, and the Reynolds number is 1.15~12.5. The conductive coefficient of oil is obviously much lower from that of water, which is about three times that of the oil conductive coefficient. Processing

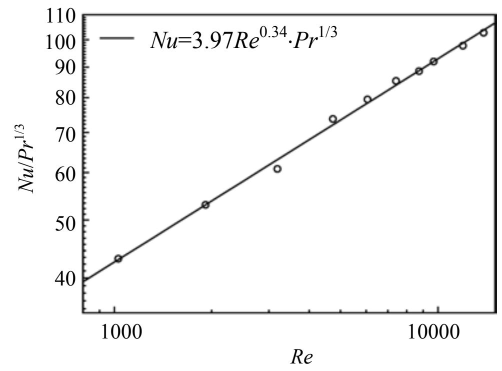


Fig.3 Correlation of heat transfer data on water in single phase cross flow

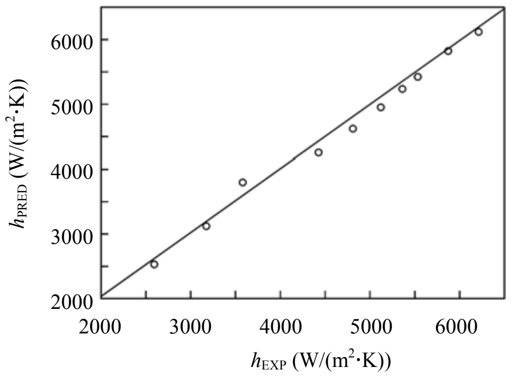


Fig.4 Comparison between experimental and calculated water data

of the heat transfer experimental data yielded the dimensionless correlation of oil below:

$$Nu_{so} = 6.27Re^{0.23} \cdot Pr^{1/3}, \quad (7)$$

where Nu_{so} is the Nusselt number of oil cross flow. The measurement results are given in Fig.5. Fig.6 shows comparison between calculated and experimental water data.

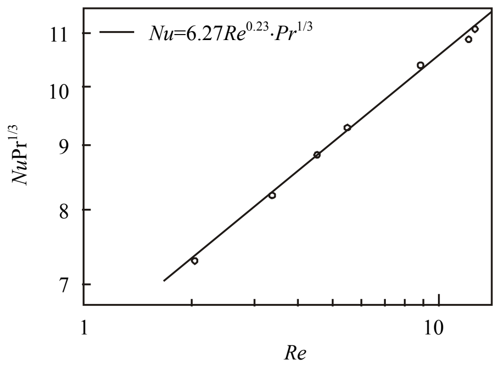


Fig.5 Correlation of heat transfer data on oil in single phase cross flow

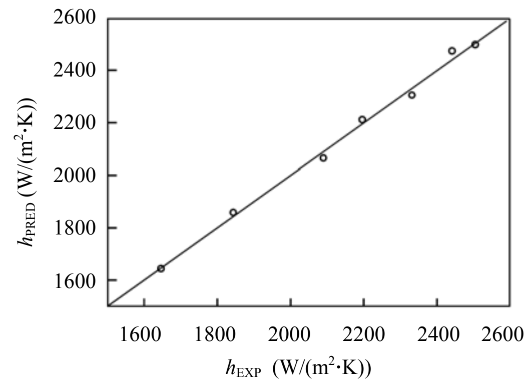


Fig.6 Comparison between experimental and calculated oil data

DISCUSSION

Although the new correlation is similar to the correlation proposed by Holman, one can see that large difference exists between the magnitude of the coefficient and the two exponents. It is suggested that this difference is caused by the special construction of the heating rod and special flow situations. The heat transfer correlation of Holman was obtained for cross-flow heat transfer with a large space; in this study the front area of the rod is nearly a square surface area, and the heat transfer of liquid cross flow is in a narrow space inside the vertical upward tube.

From this difference of the coefficient and the two exponents, it is concluded that the dependence of heat transfer on liquid Reynolds is much smaller in a narrow space than that in a wide space. As the resistance against heat transfer is mainly due to the presence of a viscous boundary layer at the wall of the rod, this conclusion can be readily explained by the fact that the reversals and eddies penetrate into this viscous boundary layer and reduce its effective thickness, which proves experimentally that the heat transfer of cross flow in a narrow space is obviously different from that in a wide space, so that the heat transfer correlation obtained in a wide space may not be applicable to the heat transfer of cross flow in a narrow space.

As mentioned above, the conductive coefficient of water is four times that of oil, and the specific heat is 2.2 times that of oil, therefore, the heat transfer is significantly different between water and oil in cross flows. Fig.7's comparison of average heat transfer coefficient of water and of oil in cross flows shows that the average heat transfer of water in cross flow is about 2~3 times that of oil.

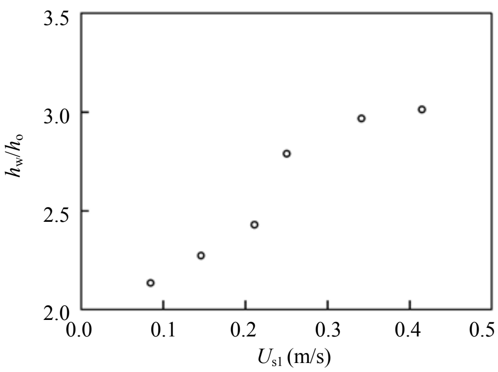


Fig.7 Comparison of average heat transfer between water and oil in single phase cross flow at the same superficial velocity

CONCLUSION

In this study, the combination of heating unit and temperature measurement unit successfully achieved measurement of the temperature difference between the fluid and the rod. The heat transfer of water and oil cross flow was studied, and corresponding correlations were obtained.

It is concluded that the dependence of heat transfer on liquid Reynolds is much smaller in a narrow space than that in a wide space. As the resistance against heat transfer is mainly due to the presence of a viscous boundary layer at the wall of the rod, this conclusion can be readily explained by the fact that the disturbance and eddies penetrate into this viscous boundary layer and reduce its effective thickness.

The heat transfer capabilities of water and oil cross flow was compared. The experimental results showed that the average heat transfer coefficient of water is about 2~3 times as that of oil when they have the same superficial velocity.

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