Experimental Analysis on Effect of Temperature on Performance Testing for Heat Exchangers

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Abstract. Heat exchangers are utilized to transfer or recover thermal energy in different industrial, domestic and commercial uses. With the outbreak of oil crisis, new type heat exchangers and heat transfer enhancement technology have gained more and more attention. Performance testing is the only approach to get heat transfer and flow resistance characteristics. Compared with testing standard GB/T 27698-2011, the qualitative temperatures of hot and cold fluid in TSG R0010-2019 are set as 60±1℃ and 30±1℃. In this paper, the effect of qualitative temperature on performance testing for heat exchangers was investigated experimentally. The heat transfer and flow resistance correlations were obtained using Wilson plot method when the qualitative temperatures of hot water were 60℃ and 70℃. And these two correlations were also developed by equal flowing velocity method at the qualitative temperatures of 50℃ and 60℃. The results showed that qualitative temperature had scarcely any effect on fitting heat transfer and flow resistance correlations. The research results will provide a foundation for the actual performance testing and standard revision for heat exchangers.

1. Introduction

Heat exchangers are devices that transfer heat between hot and cold fluids. They are utilized to convert or recover thermal energy in different industrial, domestic and commercial uses [1-3]. With the outbreak of oil crisis, heat exchangers as the energy-saving devices have gained more and more attentions. New type heat exchangers have been invented, such as welded plate heat exchangers, plate and shell heat exchangers, spiral wound heat exchangers, etc. In addition, the enhanced heat transfer technologies used for traditional heat exchangers have been developed into the third generation [4-6]. Enhanced heat transfer technology can be divided into passive enhanced heat transfer technology without direct external power supply and active enhanced heat transfer technology with external power supply.

The adoption of new technology is mainly to increase thermal performance of heat exchangers and save material and cost. It is well know that any enhancement technique will introduce additional flow resistance, and usually the ratio of pressure drop enhancement is larger than that of heat transfer enhancement. The overall performance of heat exchangers using new technology cannot be obtained only by theoretical or numerical methods. The original performance can be measured only by experimental testing. Meanwhile, performance testing can also evaluate the performance degradation owing to the fouling thermal resistance [7]. And the heat transfer criteria for both cold and hot fluids separated from overall performance can be used to design and select heat exchangers.
GB/T 27698.1-8-2011 is the only national standard of performance testing for heat exchangers in China. This series of standards specifies testing methods and procedures for tubular heat exchanger, plate heat exchanger, spiral plate heat exchanger, heat transfer element, fine tube and air-cooled heat exchanger [8]. In addition, this series of standards stipulates the change range of the flowing velocity of hot and cold fluids without requirement of qualitative temperature. However, in TSG R0010-2019, the qualitative temperature of hot fluid is set as 60±1℃ and the qualitative temperature of cold fluid is set as 30±1℃ [9]. Qualitative temperature requirement for cold fluid is difficult to achieve in southern laboratory, especially in summer. So, the effect of qualitative temperature on performance testing for heat exchangers was investigated experimentally.

2. Testing system and methods

2.1. Testing system

There are five testing systems in GB/T 27698.1-8-2011, respectively for convective heat transfer, condensation, flow boiling, pool boiling and fin tube heat transfer. Single-phase liquid-to-liquid heat transfer is the most heat transfer mode encountered in actual testing, and is also the heat transfer mode specified in Appendix A of TSG R0010-2009. Therefore, only testing system and testing methods of convective heat transfer are introduced in this paper. The testing system is shown in Fig. 1, in which device 1 is a cooling tower, device 2 is a cooler, device 3 is the heat exchanger waiting to be tested, device 4 is a heater, device 5 is a gas-liquid separator, device 6 is a sub-cooler, and device 7 is a tank.

![Testing system for convective heat transfer](image)

Steam is served as the heating source and air is served as the cooling source. The hot fluid is heated by steam before entering the testing sample. Then the hot fluid transfers heat to the cold fluid in the testing sample. After leaving the testing sample, the cold fluid is finally cooled by air, thereby completing a cycle of heat transfer. The testing instruments are used to measure the flow rates, temperatures, pressures and pressure drops of cold and hot fluid.

The contact-type flow rate sensor is used to measure the flow rate of liquid. It needs to be mounted on a straight tube. The length of straight tube should be twenty times tube diameter in upstream direction and fifteen times tube diameter in downstream direction. The steam flowmeter is used to measure the volume flow rate of steam. The temperature sensor is used to measure temperature, which should be mounted in the center of the tube. And the distance between temperature sensor and flange sealing surface or screwed nipple should be less than 150 mm. The pressure transmitter and pressure difference transmitter are used to measure pressure and pressure drop, which should be vertically mounted. And the distance between pressure measuring holes and disturbances (such as elbow, variable diameter tube and valve) should be greater than five times tube diameter in upstream direction and two times tube diameter in downstream direction. Accuracy level is the absolute value of the ratio of maximum measurement error to range of instrument. The accuracy levels of industrial instrument in China are usually 0.1, 0.2, 0.4, 0.5, 1.0, 1.5, 2.5, 4.0, etc. The smaller this value means the higher
accuracy of the instrument. The accuracy levels and ranges of all the measuring instruments are specified in GB/T 27698.1-2011.

2.2. Testing methods

There are two testing methods in GB/T 27698.1~8-2011, including Wilson plot method and equal flowing velocity method. When using Wilson plot method, the flowing velocity of one fluid is fixed and velocity of the other fluid is varied. When using equal flowing velocity method, the flowing velocity of the fluid on both sides is set as the same value and varies simultaneously.

The overall thermal resistance consists of convective resistance on one side of the wall, conductive thermal resistance through the wall and convective resistance on the other side of the wall:

$$R_{\text{total}} = R_a + R_w + R_b$$

Here, these three thermal resistances can be described as:

$$R_a = \frac{1}{K}$$

$$R_b = \frac{1}{C_2 \cdot \frac{1}{Re_a^{n_a}} + C_1}$$

When using Wilson plot method, the heat transfer coefficient of fluid b is kept constant. Then the sum of last two terms on right of Eq. (1) can be considered a constant. And Eq. (1) can be written as:

$$\frac{1}{K} = \frac{1}{C_2 \cdot \frac{1}{Re_a^{n_a}} + C_1}$$

If the Re exponent $n_a$ in Eq. (5) is assumed as initial value, the overall thermal resistance can be represented as a linear function, in which $1/K$ is the dependent variable and $1/Re_a^{n_a}$ is the independent variable. $1/C_2$ is the slope of straight line and $C_1$ is the intercept [10-12]. By linear regression, constants $C_1$ and $C_2$ can be obtained. The final $C_1$ and $C_2$ can be obtained by modifying value of $n_a$.

When using equal flowing velocity method, owing to $u_a = u_b = u$, Eq. (1) can be written as:

$$C \cdot u^n = \frac{1}{1/K - R_w} \left[ \frac{1}{(d / \nu_a)^{n_a} \cdot Pr_a^{0.3} \cdot (\lambda_a / d_a)} \right] + \frac{1}{(d / \nu_b)^{n_b} \cdot Pr_b^{0.4} \cdot (\lambda_b / d_b)}$$

If the right term of Eq. (6) is expressed as $Y$, after logarithm fetch on both sides, the above equation can be written as:

$$\ln(Y) = \ln(C) + n \cdot \ln(Re)$$

Equation 7 is also the linear form and $C$ and $n$ can be obtained by the least square method [13-15]. It should be noted that the final $n$ is obtained by iterative approach because $Y$ also contains $n$.

2.3. Restrictions of testing methods

Performance testing using Wilson plot method should meet two requirements. The thermal resistance for one fluid should be a constant. The correlation for the convective coefficient of the other fluid should be known, which is usually in the form of power of the velocity or Reynolds number. And the exponent of reduced velocity and Reynolds number in early Wilson plot method should also be assigned. But in most cases the exponent is unknown and must be calculated by an iterative procedure [16]. A modified Wilson plot method has been proposed to avoid the requirement of a constant thermal resistance [17]. The constant thermal resistance is substituted by a functional form for the coefficient of fluid (b).

The equal flowing velocity method is based on equal Reynolds number method. They all require that the geometry of the cold fluid channel is similar with that of hot fluid channel. Meanwhile, the fluid on both sides is the same medium. The double-pipe and plate heat exchangers meet the requirement of the geometric similarity of the fluid channels. The Reynolds number of both fluids should be the same value when using equal Reynolds number method. However, it is difficult to adjust the Reynolds number of cold fluid equal to that of hot fluid in practical testing, because the Reynolds number is related to both velocity and physical properties. To satisfy this condition, the flowing
velocity and inlet temperature of fluid on both sides need to be adjusted repeatedly, which is troublesome and time-consuming. When using equal flowing velocity method, it only needs to control the same velocity of fluid on both sides, which is more convenient, feasible and practical. It is should mentioned that the geometry of fluid channel of plate heat transfer is easy to deform. Therefore, the pressure of the cold and hot fluid should be kept basically the same, in order to reduce the deformation of the plate and ensure the geometric similarity of fluid channels.

3. Results and discussion

3.1. Verification of testing system and methods

The replication experiments were carried out to verify whether the testing system and methods were functioning properly. The heat transfer rate of hot fluid was compared to that of cold fluid and only tests with differences in energy balance within ±5% were valid. The experimental Nusselt numbers were compared with that calculated from Dittus–Boelter correlation [18]. The experimental friction factors were compared with that calculated from Filonenko correlation [18]. As it can be found from Ren’s work [19, 20], all of the experimental Nusselt numbers and friction factors agree well with the predicted values.

3.2. Effect on Wilson plot method

When using Wilson plot method, device 3 was a double-tube heat exchanger. The hot water flowed inside the tube while the cold water flowed inside the annular channel countercurrently. The flowing velocity of hot water varied from 0.3~1.8 m/s and the qualitative temperature was 60°C and 70°C. The flowing velocity of cold water was fixed at 0.5 m/s and the inlet temperature was fixed at 18°C. The fitted correlations of Nusselt numbers were Eq. (8) and Eq. (9) at the qualitative temperature of 60°C and 70°C. The experimental Nusselt numbers at the qualitative temperature of 60°C were compared with that calculated from Eq. (9). Then the experimental Nusselt numbers at the qualitative temperature of 70°C were compared with that calculated from Eq. (8). As it can be seen from Figure 2, all of the experimental Nusselt numbers agree well with the calculated values with the maximum deviation of ±5%, showing that temperature has no effect on fitting heat transfer correlations when using Wilson plot method.

\[
\begin{align*}
Nu_h &= 0.0184 \cdot Re_h^{0.823} \cdot Pr_h^{0.3} \\
Nu_h &= 0.0266 \cdot Re_h^{0.769} \cdot Pr_h^{0.3}
\end{align*}
\]

(8)

(9)

Figure 2. Comparison between experimental and calculated Nu based on Wilson plot method

The fitted correlations of Euler numbers were Eq. (10) and Eq. (11) at the qualitative temperature of 60°C and 70°C. The experimental Euler numbers at the qualitative temperature of 60°C were compared with that calculated from Eq. (11). Then the experimental Euler numbers at the qualitative
temperature of 70℃ were compared with that calculated from Eq. (10). In Figure 3, it can be found that all of the experimental Euler numbers agree well with the calculated values with the maximum deviation of ±5%, showing that temperature has no effect on fitting flow resistance correlations when using Wilson plot method.

\[ Eu_e = 18.177 \cdot Re_e^{-0.249} \]  
(10)

\[ Eu_e = 17.402 \cdot Re_e^{-0.246} \]  
(11)

3.3. Effect on equal flowing velocity method

When using equal flowing velocity method, device 3 was a plate heat exchanger. The hot water flowed in one side of the plate while the cold water countercurrently flowed in the other side of the plate. The flowing velocity of the fluid on both sides was set as the same value and varies from 0.2~0.9 m/s. The qualitative temperature of hot water was 50℃ and 60℃. The inlet temperature of cold water was 30℃. The fitted correlations of Nusselt numbers were Eq. (12) and Eq. (13) at the qualitative temperature of 50℃ and 60℃. The experimental Nusselt numbers at the qualitative temperature of 50℃ were compared with that calculated from Eq. (13). Then the experimental Nusselt numbers at the qualitative temperature of 60℃ were compared with that calculated from Eq. (12). It is found from Figure 4 that all of the experimental Nusselt numbers agree well with the calculated values with the maximum deviation of ±5%, displaying that temperature has no effect on fitting heat transfer correlations when using equal flowing velocity method.

![Figure 3. Comparison between experimental and calculated Eu based on Wilson plot method](image3)

![Figure 4. Comparison between experimental and calculated Nu based on equal velocity method](image4)
The fitted correlations of Euler numbers were Eq. (14) and Eq. (15) at the qualitative temperature of 50°C and 60°C. The experimental Euler numbers at the qualitative temperature of 50°C were compared with that calculated from Eq. (15). Then the experimental Euler numbers at the qualitative temperature of 60°C were compared with that calculated from Eq. (14). In Figure 5, it can be seen that all of the experimental Euler numbers agree well with the calculated values with the maximum deviation of ±5%, displaying that temperature has no effect on fitting flow resistance correlations when using equal flowing velocity method.

\[
\begin{align*}
Nt_h &= 0.2015 \cdot Re_h^{0.7099} \cdot Pr_h^{0.3} \\
Nt_h &= 0.1994 \cdot Re_h^{0.7143} \cdot Pr_h^{0.3}
\end{align*}
\]  

Figure 5. Comparison between experimental and calculated Eu based on equal velocity method

4. Conclusions
In this paper, the effect of qualitative temperature on performance testing for heat exchangers was studied experimentally. The testing system and testing methods in GB/T 27698.1~8-2011 were introduced firstly. Then the heat transfer and flow resistance correlations were obtained using Wilson plot method when the qualitative temperatures of hot water were 60°C and 70°C. These two correlations were also developed by equal flowing velocity method at the qualitative temperatures of 50°C and 60°C. The results indicated that qualitative temperature had scarcely any effect on fitting heat transfer and flow resistance correlations. The research results will provide a basis for the actual performance testing and standard revision for heat exchangers.

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