Experimental Equipment for Forced Convection Heat Transfer with Equilibrium Tracking

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Abstract. Based on the principle of forced convection heat transfer in a single tube with air transverse sweep, an experimental device of forced convection heat transfer with equilibrium point tracking was developed. The device controls wind speed, heating power and other experimental working parameters by MCU, synchronously adjusting, collecting and analyzing working parameters in real time, to realize the tracking of thermal balance point. Newton cooling formula and criterion relation are adopted to calculate Nusselt number and Reynolds number automatically, to fit criterion relation and to display correlation curve automatically, and to realize automatic data analysis. The test results show that the experimental results are in good agreement with the empirical correlation formula within the Reynolds number range of 40 ~ 4000, which realizes the automatic tracking of thermal equilibrium point and meets the requirements of real-time automatic measurement in forced convection heat transfer experiment.

Keywords: Convection heat transfer, Single pipe sweep, Reynolds number, Criterion relation.

1. Introduction
Convective heat transfer is the most basic and important research field in heat transfer. Forced convection heat transfer technology has been a research hot spot of domestic and foreign scholars in recent years. In general, the experiment device of forced convection outside the tube mainly adopts potentiometer, temperature patrol and u-type pressure gauge to control the experiment parameters and obtain the experiment data [1]. It cannot automatically judge and prompt whether the heat transfer process reaches the thermal equilibrium state, resulting in large error of experimental data. The obtained data cannot be timely processed, and most of it need to be sorted out after the experiment. Therefore, the possible problems in the experimental process cannot be found and eliminated in time, and even the obtained experimental data can be invalidated. Therefore, on the basis of the existing experimental equipment, this paper optimizes the experimental operation flow, and discusses the experimental
equipment development method in which the hot equilibrium point can be automatically tracked, and the data can be automatically analyzed and displayed.

2. Experimental principle and method

2.1. Principle of forced convection heat transfer by air across a single pipe

According to Newton's cooling formula, the convective heat transfer coefficient can be expressed as:

\[ h = \frac{Q}{F(T_w - T_f)} \]  

(1)

In formula (1), \( Q \) is the heat flow of convective heat transfer; \( H \) is the convective heat transfer coefficient; \( F \) is the surface area of the object in contact with the fluid; \( T_f \) is the average temperature of the fluid; \( T_w \) is the surface temperature of the object. According to the heat transfer theory, the convective heat transfer coefficient is related to the flow velocity, pipe diameter, temperature, fluid physical properties, etc. When the air traverses a single pipe for heat transfer, the experimental correlation formula is:

\[ N_u = C R e^n \]  

(2)

In equations (2) and (3), the Nusselt number and Reynolds number can be expressed as:

\[ N_u = \frac{hD}{\lambda} \]  

(3)

\[ R e = \frac{uD}{v} \]  

(4)

In equations (3) and (4), \( D \) is the outer diameter of the circular tube; \( \lambda \) is the thermal conductivity of air; \( u \) is the air inlet velocity; \( v \) is the kinematic viscosity of air; Through experiments, the constants \( C \) and \( n \) in the relation between \( N_u \) and \( R e \) in the case of air transverse across a single circular tube are determined. Under the condition that the outer diameter \( D \) of the circular tube is fixed and constant, the change of convective heat transfer coefficient \( h \) in the case of different flow rates \( u \) and different heat flow \( Q \) should be measured and the data should be sorted to obtain the criterion relation of convective heat transfer.

2.2. Thermal equilibrium point criterion

Considering that the convective heat transfer between the outer surface of the tube and the surrounding air is accompanied by radiation heat transfer between the tube and the surrounding environment, the heat transfer per unit time can be expressed as [2]:

\[ dQ = \rho c \frac{dT_W}{d\tau} + hF(T_w - T_f) + \frac{F_0(T_w^4 - T_0^4)}{\varepsilon_1 F_0 \varepsilon_0 (1/\varepsilon_0 - 1)} \]  

(5)

In equation (5), \( T_0 \) is the temperature of the air duct, which can be considered to be the same as the fluid temperature \( T_f \). \( \rho c \times dT_W/d\tau \) is the heat gain of the circular tube, \( hF(T_w - T_f) \) is a heat gain of the pipe itself, \( hF(T_w - T_f)/\varepsilon_1 + F/F_0 (1/\varepsilon_0 - 1) \) is the radiation heat exchange between the air and the circular tube, \( F_0 \) is pipe area, \( \varepsilon_0 \) is the exterior blackness of air duct, \( \varepsilon_1 \) is the exterior blackness of circular tube. Since the radiation heat transfer is very small, it can be ignored. When the system reaches the steady state of heat conduction, \( dT_W/d\tau = 0 \); namely circular tube temperature does not change with time, it can be considered as system of balanced judgement conditions.

2.3. Criterion relevance fitting principle

Under the constant temperature, the logarithm of both sides of the experimental formula for the heat transfer of a single tube is obtained:

\[ \log(Nu) = a + k \log(Re) \]  

(6)
Type (6) in $a = \log(C)$ If $x=\log(Re)$ and $y=\log(Nu)$, equation (6) can be expressed as:

$$y = a + kx$$

(7)

The logarithm of Nu and Re has a linear relation in the experimental correlation of the heat transfer in a single tube. The linear equation of Nu and Re in the experimental data is analyzed and fitted by using unitary linear regression equation, and the fitting curve of criterion correlation is obtained. According to the principle of least square method, the coefficients $a$ and $k$ can be expressed as:

$$a = (\sum xy \sum x - \sum y \sum x^2)/(\sum x^2 - k \sum x^2)$$

(8)

$$k = (\sum x \sum y - m \sum xy)/(\sum x^2 - m \sum x^2)$$

(9)

In equations (8) and (9), $m$ is the number of experimental points; $xy = \log(Re)\log(Nu)$; $x^2 = \log^2(Re)$.

3. Design method of equilibrium tracking and data processing

3.1. System hardware circuit design

The hardware system of equilibrium point tracking and automatic data analysis is composed of three parts, namely, measurement module, control module and display module. The system structure is shown in figure 1.

3.2. System software design

Master controller monitors the real-time system status, in order to prevent the deformation of PMM plate in the air duct because of overheat. When the temperature of the circular tube wall is over the protection range, heating stick is shut by force and the fan is set to work on the largest output. After the circular tube wall temperature reaches below cooling temperature, the experiment is continued. The system software design process is shown in figure 2.

Figure 1. Structure of measurement control system
When the main controller judges that the system has reached the thermal equilibrium point, the operator is prompted by the screen, and the measurement data can be recorded as required. By selecting the recorded data, the convective heat transfer coefficient is calculated, and the parameters in the preset air physical parameters table in the system are automatically searched according to the qualitative temperature \[4\]. The values of \( \text{Nu} \) and \( \text{Re} \) are calculated based on the flow density \( \rho_f \), thermal conductivity \( \lambda \) and kinematic viscosity \( \nu \) of the searching results, combined with the heat input \( Q \) and the wall temperature \( T_W \) of the tube. When the operator requests to view the experimental data curve, the system will automatically fit the criterion relation according to the least square method and display the fitting curve.

4. The development of experimental equipment and experimental results

4.1. Experimental device parameters
The adjustment range of air volume and heating power of the experimental equipment designed in this paper is shown in table 1, and the range of measurement parameters and measurement errors of the equipment are listed in table 2.

| Parameter            | Regulating Range | Units | Mode       | Step Size |
|----------------------|------------------|-------|------------|-----------|
| Air Volume           | 0~5.5            | \( m^3/min \) | percentage | 0.5%      |
| Heating Power        | 0~400            | \( W \)         | percentage | 0.5%      |

| Measurements         | Range            | Units | Measurement Error |
|----------------------|------------------|-------|--------------------|
| Tube Wall Temperature| 10~200           | \( ^\circ\text{C} \) | \( \pm1.5 \) |
| Air Temperature      | 10~200           | \( ^\circ\text{C} \) | \( \pm1.5 \) |
| Stagnation Pressure Difference | 0~100 | Pa | \( \pm0.05 \) |
| Stagnation Point Speed | 0~80        | m/s   | \( \pm0.05 \) |
| Heater Voltage       | 0~220            | V     | \( \pm0.01 \) |
| Heating Current      | 0~2              | A     | \( \pm0.005 \) |
4.2. Experimental structure

In the experimental device designed in this paper, the material of the experimental tube is red copper, and the length of the tube is 258 mm, the outer diameter \( d \) is 18 mm, and the inner diameter is 10 mm. A heating rod of 200 mm and outer diameter 9.8 mm is inserted in the middle to heat the tube. Figure 3 is a schematic diagram of the box wind tunnel structure, which mainly consists of air inlet, rectifier, test area, contraction area, measurement area, rubber connecting pipe and centrifugal fan [5-8].

![Figure 3. Structure of experimental apparatus](image)

The wind speed in the wind tunnel can be adjusted by the power of the fan adjusted by the output voltage of the ac voltage regulator. The wall temperature of the tube can be adjusted by controlling the heating power of the heating rod by its voltage [9]. The cross-section of the wind channel in the test area is rectangular, with a width \( L \) of 250 mm and a height \( H \) of 90 mm. The experimental circular tube is located in the center of the cross section, and the effective length \( l \) is 250 mm. Figure 4 is a cross-section of the wind channel in the test area.

![Figure 4. Diagram of duct section in test area](image)

When measuring the wall temperature of the circular tube, a thermocouple probe with a diameter of 1 mm is inserted into a 360° quadrilateral slot on the wall of the tube, and 4 thermocouple probes are used to measure the mean temperature as the wall temperature of the tube.

4.3. The experimental results

According to the experimental method of forced convection heat transfer in a single tube, the experimental data of experimental conditions were adjusted within the effective working range of the experimental device. The experimental data basically covered the adjustable wind speed and heating temperature range of the experimental device. The experimental data are listed in Table 3.
Table 3. Experimental results of forced convection heat transfer by air across a single tube

| $T_f/°C$ | $T_w/°C$ | $u/\text{m/s}$ | Re | Nu | $T_f/°C$ | $T_w/°C$ | $u/\text{m/s}$ | Re | Nu |
|---------|---------|---------------|----|----|---------|---------|---------------|----|----|
| 22.7    | 72.2    | 1.37          | 1347.80 | 17.25 | 24.0    | 86.2    | 2.22          | 2096.43 | 22.56 |
| 23.2    | 49.4    | 5.51          | 3765.60 | 30.53 | 23.0    | 90.2    | 1.98          | 1855.08 | 21.41 |
| 24.2    | 114.4   | 5.87          | 4152.07 | 30.87 | 23.0    | 73.3    | 0.60          | 588.04  | 10.62 |
| 23.6    | 58.0    | 4.99          | 3091.57 | 27.23 | 23.3    | 105.5   | 5.77          | 4191.78 | 30.98 |
| 23.5    | 75.3    | 4.96          | 3854.99 | 28.86 | 22.6    | 105.5   | 4.62          | 4164.47 | 28.51 |
| 23.2    | 78.1    | 0.91          | 879.94  | 15.53 | 22.8    | 96.5    | 2.91          | 3362.41 | 27.73 |
| 23.3    | 57.5    | 1.60          | 1636.20 | 19.58 | 23.0    | 110.4   | 3.67          | 3074.44 | 28.72 |
| 22.6    | 93.6    | 5.17          | 3805.91 | 29.15 | 23.4    | 86.0    | 6.94          | 3967.58 | 31.29 |
| 22.9    | 116.4   | 1.22          | 1068.90 | 14.87 | 21.9    | 52.3    | 5.63          | 2764.31 | 28.04 |
| 23.1    | 71.4    | 6.91          | 3805.39 | 31.2  | 23.4    | 104.7   | 5.82          | 3246.16 | 29.06 |
| 22.9    | 64.0    | 1.08          | 1085.96 | 14.94 | 23.3    | 145.3   | 2.60          | 2119.93 | 21.99 |
| 22.2    | 78.6    | 6.52          | 6968.32 | 42.05 | 23.9    | 77.0    | 4.33          | 2691.45 | 24.43 |

Figure 5 shows the comparison of experimental data, fitting correlation and empirical correlation. The fitting correlation coefficient is 0.979, and the fitting correlation and experimental data fit well.

When the Re value is small, the experimental results in this paper have a higher coincidence with the empirical correlation, while the larger Re value has a greater deviation from the empirical correlation. On the one hand, there is heat dissipation on the top of the heating rod without heat preservation treatment, resulting in a certain difference between the heat added by the tube and the load of the heating rod. On the other hand, when the incoming air flow is large, the Re value has exceeded the use range of the empirical correlation, resulting in a low degree of coincidence with the empirical correlation.

5. Conclusion
In this paper, an experimental device for forced convection heat transfer in a single tube with air crossing is studied and implemented. An automatic control and automatic measurement system is designed, and the functions of automatically calculating feature numbers Nu and Re, fitting of criterion correlation and drawing of correlation curve are realized. The test results of the device show that, within the effective working range, the experimental results are in good agreement with the empirical correlation, and can well realize the tracking of the equilibrium point and the automatic analysis and display of the data. It is useful for the experimental research and teaching of the equilibrium point tracking forced convection heat transfer.
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