Research and Design of Heat Transfer Coefficient Measuring Instrument for Vacuum Glass

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Abstract: In order to solve the problem of building energy loss and actively respond to the implementation of the national energy conservation and emission reduction policy, this system, according to the international standard of vacuum glass JC/T1079-2008, combined with the development status and production demand of the measuring instrument, developed a set of instruments that can meet the design requirements to quickly and accurately measure the heat transfer coefficient of vacuum glass. At the same time, the constant pressure measurement conditions are put forward and implemented on the basis of the system. The circuit, software and mechanical structure of the system are studied and designed. Through the above design, the design and test of the vacuum glass heat transfer coefficient measuring instrument are completed. The experimental data show that the measurement error is 0.34% under the condition of adopting effective control strategy, which is about 16 times lower than the measurement error of low-end control method, which is 5.6%. The conclusion shows that the instrument can be used to measure the target more accurately, which is of economic and practical significance.

1. Introduction

With people's huge demand for energy in daily life, non-renewable energy is overutilized, and the surface environment pollution is becoming increasingly serious. The development and consumption of energy have caused serious damage to nature, and energy conservation and consumption reduction has become a top priority, but people have been paying little attention to building energy consumption. According to statistics, about 30% of China's social energy consumption is building energy consumption. To solve this problem, vacuum glass can be used for good thermal insulation performance to reduce the indirect energy loss caused by heat flow through glass, which is an efficient and feasible energy saving method.

As a new and good way to save energy, it can not only reduce energy consumption and environmental pollution, but also replace insulating glass to reduce building energy consumption. Besides, it also has many advantages, such as long life. At present, although vacuum glass has been applied in China's architecture, there is a lack of theoretical research on vacuum glass, which makes it unable to be applied in a better and more standard way to give full play to its advantages. Based on these reasons, the research and design of vacuum glass thermal resistance tester will enable vacuum...
glass to be used in the construction field in a standardized and effective way, thus reducing the consumption of other energy sources and environmental pollution.

2. The principle of measuring instrument

2.1. Heat transfer principle and calculation of heat transfer coefficient

For vacuum glass, heat transfer is mainly through these three ways, namely, heat transfer of the internal support of vacuum glass, heat transfer of residual gas, heat transfer of radiation. The approximate vacuum environment inside the vacuum glass reduces the convective heat transfer to a large extent. At the same time, because the volume of the micro-support inside the vacuum glass is very small, the heat passing through the support is also very small, so the thermal conductivity and heat transfer can also be greatly reduced. Schematic diagram of heat transfer through vacuum glass is shown in Figure 1.

![Figure 1. The specific heat transfer diagram of vacuum glass](image)

From the above analysis, it can be seen that the heat transfer value inside the vacuum glass can be theoretically calculated by radiation heat transfer, support heat transfer and residual gas heat transfer [1], and the thermal conductivity at the center of the vacuum glass is represented by

\[ C_{\text{Vacuum}} = C_{\text{Radiation}} + C_{\text{Supports}} + C_{\text{Gas}} \]  \hspace{1cm} (2-1)

Type:

The radiant thermal conductivity of two parallel glass surfaces \( C_{\text{Radiation}} \) can be estimated by the following formula:

\[ C_{\text{Radiation}} = e_{\text{Effective}} \sigma \left( T_1^4 - T_2^4 \right) / \left( T_1 - T_2 \right) \]  \hspace{1cm} (2-2)

The thermal conductivity value generated by the tiny cylindrical support inside the vacuum glass can be calculated by the following formula:

\[ C_{\text{Supports}} = \frac{2\lambda_{\text{Glass}}a}{b^2 \left( 1 + \frac{2\lambda_{\text{Glass}}h}{\lambda_{\text{Supports}} \pi a} \right)} \]  \hspace{1cm} (2-3)
Considering the gap between two pieces of glass, the height of the finished support should be much smaller than its radius. The purpose of this is to reduce the thermal conductivity of the support by increasing the denominator and decreasing the numerator according to the mathematical relationship described in Equations 2-5. Formula 2-5 is simplified as follows:

$$C_s = \frac{2\lambda_{\text{glass}}a}{b^2} \quad (2-4)$$

According to the composition of heat transfer coefficient, the calculation formula of heat transfer coefficient K value of vacuum glass can be obtained:

$$\frac{1}{K} = \frac{1}{C_{\text{Internal}}} + \frac{1}{C_{\text{Vacuum}}} + \frac{1}{C_{\text{External}}} \quad (2-5)$$

The thermophysical characteristics of matter are as follows:

The thermophysical properties of substances are called thermophysical properties. It is a material property directly related to the heat transfer process and the increase or decrease in the heat content of the object. Characteristics of thermal properties: The thermophysical property is the derived amount of the basic quantity; The measurement of thermophysical properties is related to a fixed thermal process; The measuring methods and measuring devices of thermophysical properties are diversified. The key to the test of thermal properties lies in the design of the thermal process.

2.2. The principle of thermostatic measurement

From the above discussion, it can be seen that to obtain the heat transfer coefficient K value, only the thermal resistance of vacuum glass should be obtained. In the actual measurement process, the internal pressure of a qualified vacuum glass is very small, about 0.1~0.3Pa, and usually the residual gas thermal resistance can be ignored. In fact, the sealing part of vacuum glass can also conduct heat transfer, but in general, only the middle part of vacuum glass is taken as the effective measurement part, and the heat transfer effect of the edge is not included in the calculation scope. In this way, residual gas and edge heat transfer are not included in the final calculation of K value. Therefore, according to the heat flow method stipulated in THE national standard JC/T1079 of vacuum glass, the heat resistance $R_{\text{vacuum}}$ of vacuum glass can be indirectly obtained by means of relevant measurement, and then the heat transfer coefficient K value can be calculated according to the relevant formula. The measurement principle of specific heat transfer coefficient [2] is shown in Figure 2.

Fig 2. The measuring principle diagram of the measurement instrument
Figure 2 shows the main components of the measuring instrument and the principle measured by the measuring instrument. In this experiment, the heat flow successively passes through the above plane plate. After a certain period of time, the heat flow will stabilize and form a dynamic equilibrium process. If the temperature difference between the two surfaces of the vacuum glass to be tested is \(T_M - T_C\), and the temperature difference between the two surfaces of the standard plate is \(T_H - T_M\), then the dynamic equilibrium equation established is:

\[
C_M = \frac{T_H - T_M}{T_M - T_C} C_S
\]  

(2-6)

According to the regulations, under the condition that the ambient temperature in the laboratory is 20℃, the temperature of hot plate and cold plate is generally controlled to 40℃ and 10℃ in the actual production of the measuring instrument, and the specified error is no more than ±0.1℃. After the heat flow is stable, the temperature on the measuring plate is measured [3]. The actual calculation is to convert the Celsius temperature to the Kelvin temperature. The final formula of heat transfer coefficient can be obtained:

\[
K = \frac{1}{\left( 0.1584 + \frac{1}{C_M} \right)}
\]  

(2-7)

3. Design of testing device for heat transfer parameters of vacuum glass

3.1. Circuit hardware design of the measuring instrument

3.1.1. Design of central control circuit module  The main control circuit module mainly includes the main control chip and its required peripheral circuit, key circuit, communication circuit, reset circuit and so on. This design uses STC series single chip microcomputer. The main control circuit is composed of the main control circuit and its peripheral circuit, which are the micro controller minimum system, the key circuit and the communication circuit respectively. The minimum system is the minimum configuration required by the MCU when it is working normally. S1 is the reset button, through which the MCU can be reinitialized; S2 and S3 are used to control the stepping motor so as to control the rise and fall of the pressure device. Introduce the communication circuit emphatically: there are many kinds of communication mode of single chip microcomputer, this design chooses external serial port communication[4], divided into two ways: serial communication and parallel communication. Parallel communication can transmit the data that need to be transmitted simultaneously and in several bits, so the parallel data transmission is faster but the cost is higher in the long distance communication. Serial communication is to transfer the data to bits, data transmission speed is slower than parallel transmission speed. In this paper, serial asynchronous communication is finally chosen as the communication mode of this design. After testing, this communication mode can reach the experimental purpose. The main control circuit diagram of the system is shown in Figure 3.
3.1.2. Temperature control design circuit In the thermostatic control circuit, the hot plate temperature is mainly controlled to 40±0.1°C, and the cold plate temperature is controlled to 10±0.1°C. Back specific measures is to use sensors to collect real-time temperature and set temperature, the PID algorithm, and finally the results output to a switching device, cycle through certain circumstances make switching devices and has different duty ratio, control switch device opened and shut off time, thus to achieve temperature control. The main function of the measuring circuit is to collect the real-time temperature of the cold plate, hot plate and measuring plate into the main control chip for data processing through the sensor. Because the load capacity of the core chip is limited, the controlled object cannot be driven directly. In the middle, the output control signal must be amplified by a suitable driving circuit, so as to realize the switch control from weak current to strong current. At this time, the necessary protection measures must be taken to isolate the strong and weak electricity through the line, and the actual circuit adopts the optocoupler isolation. The following is the design drawing of the thermostat control circuit, as shown in Figure 4.
3.1.3. Power circuit design This section firstly analyzes the voltage and current required by each module of the system, and requires +5V power supply in the main control circuit, display circuit, serial port communication, temperature difference measurement circuit and motor control circuit. The heating device USES screw plus hot wire, which needs ~220V power supply; The cooling plate, stepping motor, water pump and cooling fan used in refrigeration equipment need +15V power supply. Based on the above analysis, the refrigeration unit USES a +15V switching power supply and the maximum allowable current is greater than 10A, because the power required for refrigeration is large. The heating device adopts commercial power ~220V. Other circuits adopt +5V, and the specific implementation method is to pass +15V through filtering and step-down conversion to +5V through LM7805 three-terminal voltage regulator chip, and then filter to supply the required circuit for use. The power circuit design is shown in Figure 5.

Figure 4. Schematic diagram of thermostatic control circuit

Figure 5. Power circuit
3.2. Software design of measuring instrument

3.2.1. The system overall control software design According to the real-time temperature and the comparison of goal setting temperature, heating heating device to start, start refrigeration refrigeration equipment, if the real-time temperature and target temperature of the temperature difference value is greater than 10 °C, the main control chip control switch device connected to the power of heating and cooling, if the temperature difference value is less than 10 °C, then into PID temperature control mode, the main control chip control switch device for constant temperature control the opening of the duty ratio. The control flow chart of the system is shown in Figure 6.

![Control Flow Chart](image)

3.2.2. Design of thermostatic control software The key to temperature control lies in PID control strategy. Due to its simple algorithm, stable operation, high reliability and other excellent performance, it has been widely used in many control occasions since its inception in the field of industrial control. PID control strategy is the most commonly used one in the simulation control system, and its control system principle block diagram is shown in Figure 7.
The specific control process of PID controller is as follows: firstly, the system is a closed loop structure with negative feedback. The output value \( Y_{out}(t) \) at the last moment is fed back to the input end, and then compared with the given value \( R_{in}(t) \). Deviation will occur after the comparison, and then the PID algorithm is entered, and then the result is output. The control rule of PID is:

\[
 u(t) = k_p \left( \text{error}(t) + \frac{1}{T_i} \int_{0}^{t} \text{error}(t)dt + \frac{1}{T_d} \frac{d\text{error}(t)}{dt} \right) \tag{3-1}
\]

The result of the position PID algorithm measured by the experiment is related to the state value of the system at the past time, and the position algorithm uses the accumulated value of the deviation in the equation. However, the output result of incremental PID algorithm is only related to the last and last penultimate deviation, so the error of the output result of positional PID algorithm related to the past state is relatively large. Both of these two control methods can achieve good results, but considering the design of the control object is temperature, temperature has a large inertia, time-varying, large hysteresis characteristics, so choose incremental PID. Its temperature control flow chart is shown in Figure 8.

**Figure 7. PID model**

**Figure 8. The flow chart of PID control**
3.2.3 Software design of temperature acquisition module DS18B20 is adopted in the design to collect temperature, which can convert analog quantity into digital quantity in real time and transmit it to SCM. DS18B20 is the data exchange between DS18B20 and MCU through the communication protocol of single bus. It works by converting the collected temperature into 12 bits of data, stored in two 8-bit bits of RAM. DS18B20 works at a strict time sequence, reading the temperature of the sensor is to refer to relevant technical data and strictly follow the official instructions to write the program. For the temperature sensor, we are mainly concerned about how to read the measured temperature by software. The flow chart of reading temperature is shown in Figure 9.

![Flow chart of reading the temperature](image)

Figure 9. The flow charts of reading the temperature

3.2.4 Liquid crystal display software design The LIQUID crystal display driver mainly displays the temperature and other related characters or Chinese characters collected by the temperature sensor to the liquid crystal display screen in real time through software. LCD12864 has a total of 20 pins, of which 4 are control pins and 8 are bidirectional data transmission pins. Where PSB is a serial or parallel selector, PSB is grounded in the display hardware design, that is, serial data transmission is selected in this design. Selecting serial can save I/O port and simplify the production of PCB board. The other three control pins are CS chip selector, which can read and write to LCD only during high level. SCLK is a clock signal, or pulse input, that provides a steady pulse that never causes the STD end to send commands and data; STD is the serial data command port, in which the serial data transmission is completed in three bytes, the first byte represents write or read LCD, if it is write, it is divided into write data or write command, the second byte sends the high four bits of data, and the third byte sends the low four bits of data.
3.3. Introduction to mechanical system of measuring instrument

In this paper, three-end open-ended structure is adopted. Because the mechanical structure system of heat transfer coefficient measuring instrument is mainly divided into two kinds: closed structure and three-end open structure. Most of the measuring instruments adopt closed structure, but the closed structure can only measure several kinds of vacuum glass with fixed area, so the size of the sample is limited. The mechanical structure design of the vacuum glass heat transfer coefficient measuring instrument is mainly based on the measurement method stipulated in the national standard JC/T1079-2008, and combined with the experience in the actual production process. It can be divided into three parts: heating machinery module design, refrigeration module design and constant pressure machinery module design.

In the mechanical design of thermostatic module, it mainly includes hot plate mechanical design, cold plate mechanical design and measuring plate mechanical design. In order to ensure high efficiency of heat transfer, each module adopts aluminum as the contact surface between the three flat plates. The cold plate and hot plate are designed with insulation shell, and the empty part is filled with foam filler with insulation property. The design of the mechanical structure of the measuring plate should be based on the structure stipulated in the national standard. The mechanical structure mainly consists of the measuring head and its concentric side isolation ring.

For constant pressure mechanical design is called working platform mechanical mechanism. The model places the cooling fan and water pump under the working platform, so as to avoid the influence of fan vibration. The hot plate, standard plate and measuring plate shall be placed in the lower space of the working platform in sequence, and the upper surface of the measuring plate shall be on the same plane as the surface of the working platform. In addition, a bright spot of the mechanical design is the three-end opening formed by the clamping of the movable plate of the mechanical structure and the working platform. The three-end opening will not limit the size of the vacuum glass to be measured during the measurement [5].

Through this figure, we can intuitively understand the placement position and structure model of each module of the system, as shown in Figure 10.

![Figure 10. The mechanical structure diagram](image-url)
4. Test and results of vacuum glass heat transfer coefficient measuring instrument

4.1. Debugging of upper computer of measuring instrument
The upper computer software displays the temperature information collected by the temperature sensor under the software in real time through the serial port, and draws the temperature curve on the main interface of the software. In the experimental stage, there is a parameter input box on the right side of the software, which can realize on-line tuning of PID parameters and improve the experimental efficiency [6]. PID output value is designed for professional technicians to perform parameter tuning and debugging.

4.2. The measured results
In the laboratory environment specified by the national standard, a standard plate with known thermal conductivity coefficient 1 was made and vacuum glass to be tested was selected. The same vacuum glass was repeatedly measured under the same experimental conditions, and the constant pressure realized by the natural counterweight was 1.29bar. The final data is represented by the red data in FIG. 11. Under the condition that the vacuum glass sample to be tested is subjected to a pressure of 0.129mpa, an intelligent PID thermostatic control strategy is adopted for temperature change. Figure 11 is shown below.

Figure 11. Measurement parameters of vacuum glass heat transfer

Similarly, the measured heat transfer parameter value of the vacuum glass sample is taken as the calculation standard $1.030 \text{Wm}^{-2}\text{k}^{-1}$, and the test error is calculated based on the actual measured value, so as to ensure that the measured value and measurement error meet the requirements permitted by the national standard [7]. By comparing the test data parameters of the red and blue broken lines, the following test rules are obtained: when the effective control strategy is adopted and the measurement times are N=50, the measurement error value is 0.34%, which is 16 times lower than that of the low-end control method, which is 5.6%. In this state, the error between the test value and the real value is almost 0.34%.

5. Conclusions
The mechanical structure of the measuring instrument is designed according to the measurement method stipulated in the national standard JC/T1079-2008 and combined with the experience in the actual production process. The instrument can be used to test various kinds of vacuum glass samples.
under the national standard under the experimental environment for many times, realizing the design function of accurate, rapid and fully automated test of vacuum glass heat transfer parameters [8]. Nowadays, our country building materials or the existence of a large number of loss that cause environmental pollution problems, and for the application of vacuum glass is still not widely, but the use of the instrument by vacuum glass heat insulation heat preservation method to reduce the loss of other energy sources, not only can solve the present problems, but also the application of vacuum glass research and talent training provides a good platform, in the construction field and quality and mass production, the application of vacuum glass has have a certain economic value and practical significance.

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