Research on the Theory and System for Testing Thermal Conductivity of Materials

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Research on the Theory and System for Testing Thermal Conductivity of Materials

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Abstract. Thermal conductivity is one of important indexes of material's quality evaluation. This material's thermal conductivity detection system was designed and made based on the least square support vector machine algorithm. The system hardware was made mainly by microcontroller ATmega64, the temperature detection circuit and heating and refrigeration circuit. The system software was based on virtual instrument development platform of Labwindows/CVI and the least square support vector machine algorithm, which has data collection and processing, and the results display and control functions. Application shows that this system has advantages of reliable operation, precise temperature control and high thermal conductivity detection accuracy.

1. Introduction

With the development of economy, the global energy consumption grows with each passing day. Building energy consumption[1] accounted for about 30% of total energy consumption. With the higher demand of indoor environment, luxury, style and aimless abuse also makes the building energy consumption becoming higher. In order to reduce building energy consumption, building energy conservation has become a long-term strategic principle for China's economic development. External wall insulation is an important link in construction field. The external wall insulation and related systems directly affect the effect of energy saving building[2]. So to determine the thermal conductivity of materials plays a decisive role on the significance of saving energy and raw materials and improving the quality of the products.

On the basis of the guarded hot plate method[3], a new type of the double plates material thermal conductivity detection system was developed in this paper. The test object was a low thermal conductivity thermal insulation material represented by the building materials. The mathematical model for the steady-state thermal conductivity of double plates was established, and the overall design of the system was carried out for mathematics model. The system intelligent measurement and control system took the microprocessor Atmega64 as the core. Based on the least square support vector machine algorithm (LS-SVM) and Labwindows/CVI, the software designed a simple hardware circuit, friendly interface, and high measurement precision double plates material thermal conductivity detection system.

2. Detection Principle and Control Algorithm of System

2.1Detection Principle of System

In this paper, the steady-state method is adopted, which is primarily based on the Fourier heat conduction law[4] of the guarded hot plate method. That is, at any time, the local heat conduction density formed by heat conduction is numerically proportional to the temperature gradient at the same time and in the opposite direction. The mathematical expression is:

$$q = -\lambda \frac{\partial t}{\partial n} \vec{n} \quad (1)$$

In the formula: The negative sign in (1) indicates that the heat transfer direction is opposite to the positive direction of the temperature gradient, which is the same direction as the temperature drop. The proportional coefficient λ is called the thermal conductivity(W/(m·k)). Expression (1) is obtained by transformation:

$$q = \frac{\lambda}{d}(t_2 - t_1) \quad (2)$$

Here q - the heat flux(W/m^2), d - thickness of the specimen(mm).

Expression (2) stands for the heat flux through single-layer flat wall. After (2) is transformed, we can get (3) for calculating the thermal conductivity of a single-layer flat wall.

$$\lambda = \frac{qd}{t_2 - t_1} = \frac{Qd}{F(t_2 - t_1)} \quad (3)$$

Here Q - the heat flux(W/m^2), F - the measurement area of the specimen.

Combined with the power calculation formula of electrotechnics, expression (3) is transformed to obtain the thermal conductivity equation:

$$\lambda = \frac{U^2}{R} \cdot \frac{d}{F(t_2 - t_1)} \quad (4)$$

Here U - the heating zone voltage, R - the heater resistance in the heating zone.

Since the double plates thermal conductivity instrument has two identical specimens and two cold plates, the energy released in the heating zone is transmitted by two specimens, so expression (4) should be rewritten as:

$$\lambda = \frac{U^2}{R} \cdot \frac{d}{F(t_2 - t_1)} = \frac{P \cdot d}{2F(t_2 - t_1)} \quad (5)$$

2.2Heating Control based on LS-SVM Model

This article adopts the least square support vector machine algorithm(LS-SVM) as modelling method to control the heating of the metering zone and the cold zone. Taking heating in the metering zone as an example, this article adopts the LS-SVM to construct a nonlinear regression model with the six inputs and one output. The input variables are six nodes temperature differences of the hot plate. The output variable is the voltage value of PWM signals output by Atmega64. The input process variables are trained by LS-SVM to obtain the heating control model of the metering zone. Discrimination technology was used to process the samples, and the unreasonable sample were removed. A total of 2000 groups of data were collected during the experiment, of which 1000 groups were used for training and another 1000 groups were used for testing.

The specific steps for establishing a temperature control model of the metering zone by using the LS-SVM training are as follows:

Step1: Determine the characteristic variables that reflect the status of the metering zone and pre-process the data;

Step2: The common radial basis kernel function is used as the kernel function;

Step3: The adjustable parameters$\gamma$and radial basis parameters$\sigma$are optimized by Cross-Validation;

Step4: Input 1000 groups of samples to support vector machine for training to obtain the mapping relationship between input and output;

Step5: Input another 1000 groups of samples for model prediction;

Step6: The value of adjustable parameters γ and radial basis parameters σ are changed according to the prediction results until the model has achieved good results.

According to the above process, the model simulation was carried out through Matlab, and the function fitting between the predicted value and the actual value was realized. Finally, the parameter γ=5×104, σ=200. Figure.1 shows the relative error diagram of the trained LS-SVM model. It can be seen from Figure 1 that the maximum relative measuring error is less than 3%, which indicates that the model has a high precision.

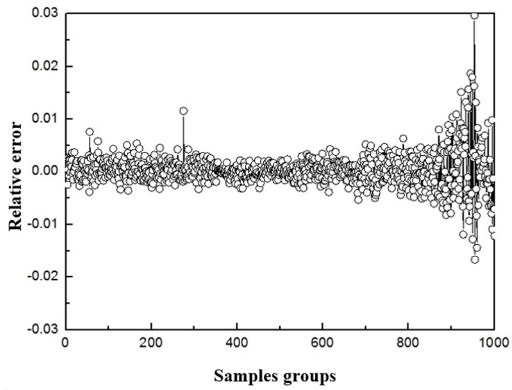

Figure 1. The relative error of testing samples

3. System Hardware

The hardware system of thermal conductivity meter consists of the furnace body part and the intelligent measurement and control part. The furnace body should comply with the requirements of the measurement principle, and guarantee the necessary conditions for accurate measurement from the device structure. The design of intelligent measurement and control part implements the human-computer dialogue, measurement and control.

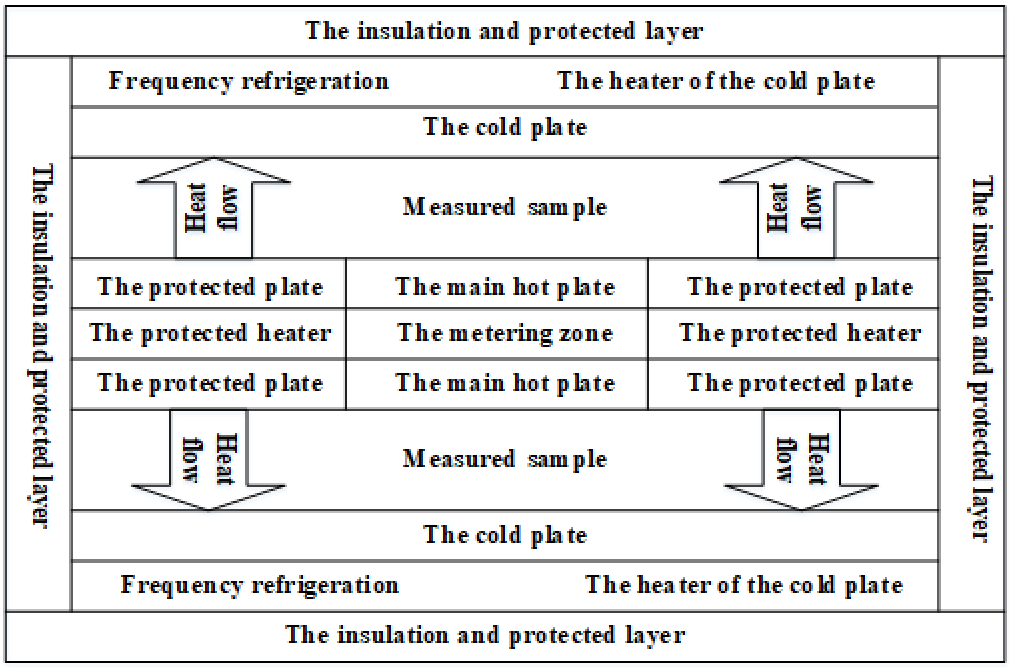

Figure 2. Chart of protective panel structure

The schematic diagram of the furnace section is given in Figure 2. The main hot plate has a heater, which mainly supplies heat to the test piece to make the specimen reach the set temperature. 16 temperature sensors are uniformly arranged at the protected plate. Between the cold plate and the insulation layer are the refrigerator, cold plate heater and 6 temperature sensors, in order to guarantee the cold plate at the setting temperature. Two specimens of the same material are measured for thermal conductivity at the same time, and the average value are taken after measurement. The specimen is the same size as the protective plate and is located between the cold plate and the hot plate. The specimen size is the same as the guard plate, which is placed between the cold plate and the hot plate.

The above analysis demonstrates that the intelligent measurement and control part should include an intelligent processor module, a heating and refrigeration control circuit, a power detection circuit, and a temperature detection circuit. The system intelligent measurement and control system took the microprocessor Atmega64 as the core. In order to accurately measure temperature signals in the metering zone, protected zone, and both sides of the cold plate, the system adopts the multi-point temperature detection method[5]. In order to accurately detect the voltage and current output by the programmable power, the system adopts the 10-bit AD of the ATmega64 as an analog-to-digital converter to measure the voltage.

3.1Design of Heating and Refrigeration Control Circuit

About this system, the cold zone heating and cooling control and the protected zone heating control with the relay control mode, while the hot zone heating unit involves the collection of the heating power. In the test process, the temperature in the hot zone should not only remain constant, but also collect power in real time. Therefore, the heating unit in the heat zone adopts the method of DC voltage regulation. First, detected temperature information is converted into the duty cycle of the PWM by the least square support vector machine algorithm. Second, the PWM wave is filtered by the high-frequency filter, follower, voltage comparator and differential amplifier. Through the control of LM2576HV[6] of the adjustable power supply, the adjustable range of output voltage reaches 0-60v, and finally the adjustable heating control can be realized. The circuit diagram of this unit is shown in figure 3.

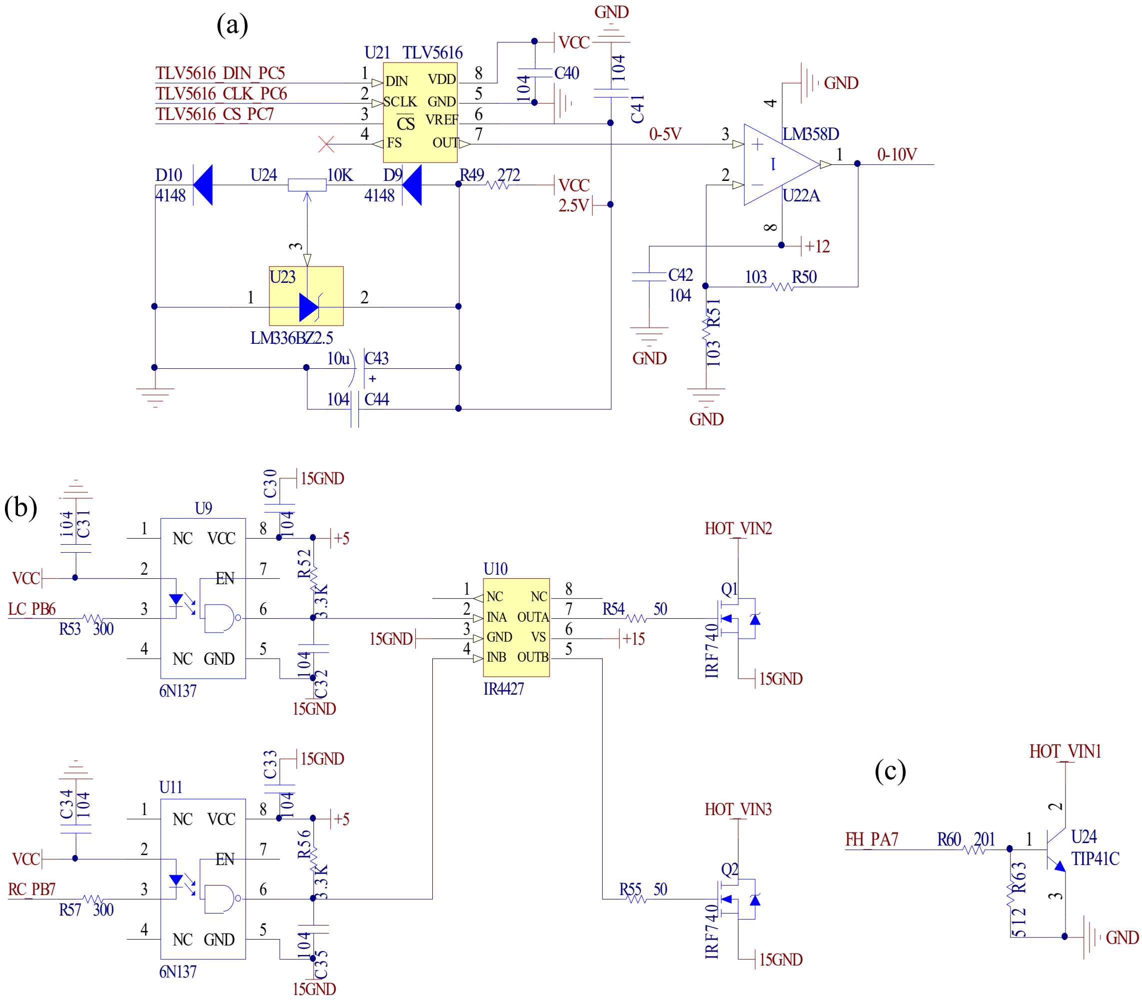

Figure 3. (a) The refrigeration control circuit, (b) The heating control circuit of cold zone, (c)The heating control of protected zone

4. System Software

The selected upper computer is Labwindows/CVI. The upper computer mainly completes the measurement of thermal conductivity and thermal resistance, the algorithm operation to achieve the temperature control of the hot plate and the cold plate, the temperature display of each zone and report printing function. The main interface of this system is given in Figure 4.

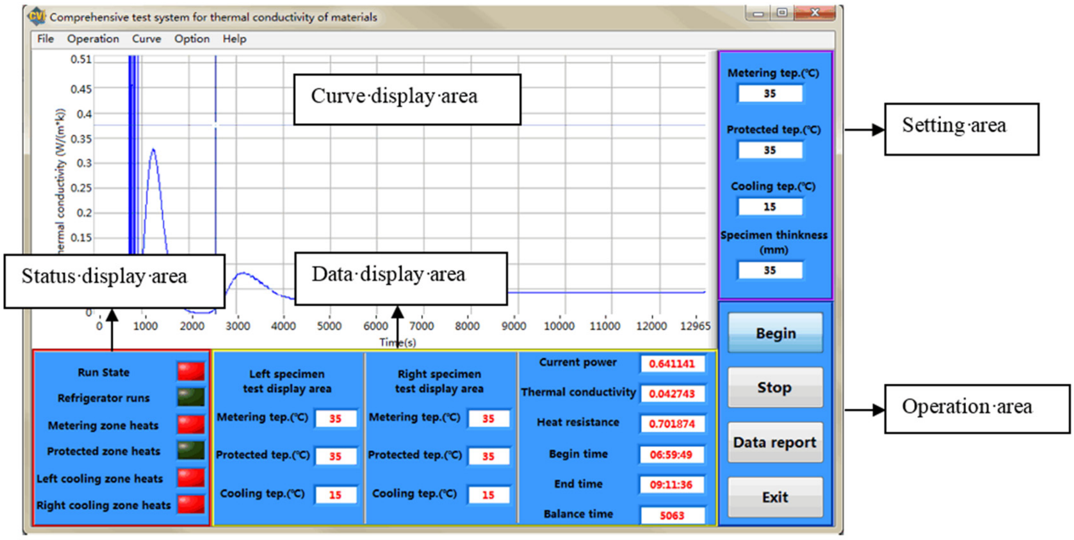

Figure 4. The software of thermal conductivity detection system

The main interface can be divided into five functional units according to the functions realized: menu bar, curve display area, instrument status display area, data display area, data setting area and operation area. The main function of the "status display area" is to view the equipment operation status of the cold zone and the hot zone. "Data display area" is mainly a display of some physical quantity such as temperature, power, thermal conductivity, balance time of the current instrument. "Data setting area" mainly completes the setting of the sample detection environment.

5. Results and Discussion

In order to verify the accuracy of the system, we verified by repeatedly measuring the thermal conductivity of standard specimens, and took the standard specimen slag rock wool as an example to analyze the measurement results. According to the national standard GB/T 11835-2007, the thermal conductivity of slag rock wool is 0.03812. The size of the specimen is 150 (mm)× 150 (mm). The thickness d of the specimen is 30mm. The temperature of the hot plate and the cold plate are 35.0℃ and 15.0℃ by DS18B20 measured after thermal equilibrium. The F0 and F1 port voltage of ATmega 64 are 0.5004 V and 0.5131V, so the thermal conductivity is

$$\lambda = UI \cdot \frac{d}{2F(t_2 - t_1)} = \frac{12.0094 \times 0.1196 \times 0.03}{2 \times 0.0225 \times (35.0 - 15.0)} = 0.038301\ w/(m \cdot k) \tag{6}$$

After 10 repeated measurements, the measured thermal conductivity and relative error are presented in Table1. From the analysis of Table 1, it can be observed that the test error of the system is less than 0.5%, which fully satisfies the user's requirements for thermal conductivity detection system.

Table 1. Test Results and Relative Error

Number	Normal Value $W/(m \cdot k)$	Measurement $W/(m \cdot k)$	Relative error(%)
1	0.03812	0.038301	0.475
2	0.03812	0.038286	0.420
3	0.03812	0.038315	0.498
4	0.03812	0.038292	0.446
5	0.03812	0.038312	0.472
6	0.03812	0.037956	-0.43

7	0.03812	0.037957	-0.46
8	0.03812	0.037938	-0.50
9	0.03812	0.038310	0.498
10	0.03812	0.038293	0.446

6. Conclusions

This article designed a new type of double plates material thermal conductivity detection system which can not only accurately and reliably detect the performance of thermal conductivity of building insulation materials, but also reduce artificial operation error. The thermal conductivity meter is the core of microcontroller Atmega64, which is more intelligent. The LS-SVM model is adopted to achieve the measurement accuracy of 0.5 level. Using the virtual instrument development platform Labwindows/CVI makes the human-computer dialogue interface very user-friendly. This thermal conductivity meter provides a basis for how to better effectively reflect the thermal performance of the materials, and also provides a direction for the development of the thermal insulation materials towards the light and efficient target development. The system has been successfully applied to detecting the thermal conductivity of a factory in Tianjin. The practice proves that the measurement accuracy can reach 0.5 level, which completely satisfies the requirements of the detection of the thermal conductivity of the materials.

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