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Experimental Research on Physical Parameters Inside Hardy-Plant Leaves

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Abstract: With the development of bio-heat transfer technology, the research into the thermal effect mechanism of hardy plants, as well as the heat exchange between the plant and the surroundings has become another emerging issue in the field of heat transfer. Specific heat capacity and thermal conductivity are two important physical parameters during the study of material thermal properties, which play important roles in the analysis of mechanism of heat and mass transfer within plants. In this paper, the leaves of Camellia, Tarajo holly and Jasper were selected as the research object and the specific heat capacity of their detached leaves were measured by DSC, the thermal conductivity of leaf tissue was measured based on thermal probe method of hotline source instantaneous model. Conclusions are as follows: the specific heat and thermal conductivity of hardy plant leaves surged within a narrow temperature range around 0°C and peaked at 0°C, but the peak value of different plants was quite different. Each physical parameter values measured from experiments were within the permissible range, it was also verified that the experimental equipment and methods used before were reasonable and operational.

Keywords: Temperature, Specific Heat, Thermal Conductivity Coefficient, Hardy, Leaf

1. Introduction

Hardy plants can still survive in cold winter. This raises the question of how plants can regulate themselves to resist cold winter. A large number of scholars have carried on researches on cold-resistant mechanism of Hardy plants. Maximov set out to study the plant hardiness early in 1912 [1]. Lyons put forward the theory of "Phase transition of membrane lipids" in the next year [2], which marks the beginning of cold-resistant mechanism of Hardy plants. In 1932, the conductometry analysis method was proposed for the first time in determination of the cold resistance of plants by Dexter [3]. Therefore, a great process had been achieved in the field of cold resistance of plants. However, all of the researches above have analyzed the cold resistance of plants just from the aspects of the structure and function of originals, desaturation of plasma membrane and so on. That is to say the studies on properties of physiology and biochemistry were conducted from the perspective of physiology and cell biology. Environment temperature has a serious influence on the growing development of plants and plants proceed under highly non equilibrium state during the whole life. With the change of seasons and the shift of day and night, plant morphological structure and physiological characteristics are always changing. Currently, researchers focus on how heat effect the plants are mainly concentrated in the influence of temperature on physiological function of plants. As we all know, there are water and minerals transportation and at the same time accompanied by photosynthesis, respiration, and other important metabolism, combined with the limitations of measurements. For the above reasons, the mechanism of thermal effect within plant is not very clear under microscale level. Plants exist as living organisms with its own thermal effect mechanism [4]. So researches on the heat and mass transfer inside plants and with the surrounding environment will be a new biological direction in the field of heat and mass transfer of plants from multiscale level.

The heat and mass transfer inside plant tissues are based on the studies of thermo-physical properties which have a strong impact on plant organisms, especially of viable tissues. As we all know, thermo-physical properties are essential to lucubrate the heat transfer characteristics and mass transfer mechanism, the reasonable and accurate evaluation of thermo-physical property give a great guarantee to obtain a precise temperature and flow field. In order to quantitative describe the heat transfer characteristics and mass transfer mechanism within plant tissue and to discover the heat and mass transfer inside plants and with the surrounding environment, as well as to analyze the cold resistance of plant from heat and mass transfer indirectly and to measure the physical property parameter of corresponding tissue including summarize their varying patterns are essential. Nevertheless, the metrical data of plant tissue, especially of viable tissue are seriously inadequate, and subject to limitations of measurement technology these data differ greatly, which hinder the development of heat and mass transfer studies in plants. The appropriate object and method were selected to measure the specific heat and the thermal conductivity in this article, hopefully to enrich the existing theoretical data and lay a theoretical foundation for the research of cold resistance and mechanism of heat and mass transfer in plants.

2. Experimental System and Measurement Methods

2.1. Experimental Materials

A Camellia tree of five years was selected as the main research object in this experiment, and the reasons are as follows: 1) Camellia is high hardy, green through all four seasons and bloom in winter, which could be very representative to discuss the cold resistance of plants. 2) The elliptical leaves of Camellia with distinct veins and appropriate thickness are convenient for experiments and mathematical modeling. In addition, Tarajo Holly and Jasper (non-hardy plant) blades which are similar to Camellia blades were selected as the verification group and contrast group respectively to ensure the accuracy and reliability of the experiment in this paper. Both of the two trees are five years.

In consideration of the thermal adaptability of plants and high accuracy of experiment, Camellia and Tarajo Holly were placed in phytotron of - 6°C for two weeks, the contrast group Jasper was cultivated in the 2°C environment for the same amount of time before tests. Then the three plants adapted to the new surrounding environments by means of their own ability of adjustment. Some mature leaves which have similar shape and size were picked to do experiments.

2.2. Experimental Methods

Leaves have uniform structure and anisotropic material. What's more, the thermo-physical properties of living plants differ essentially from in vitro tissue. All these results in great difficulty during measurement. Considering the measurement technology was limited, the differential scanning calorimeter (DSC204F1, Nestal Company of Germany) was chose in this paper to measure the specific heat of Camellia, Tarajo Holly and Jasper leaves at different temperatures, and a new thermal probe method based on hot line source instantaneous model was used in measuring thermal conductivity of living plants.

2.3. Preparation of Test Specimens

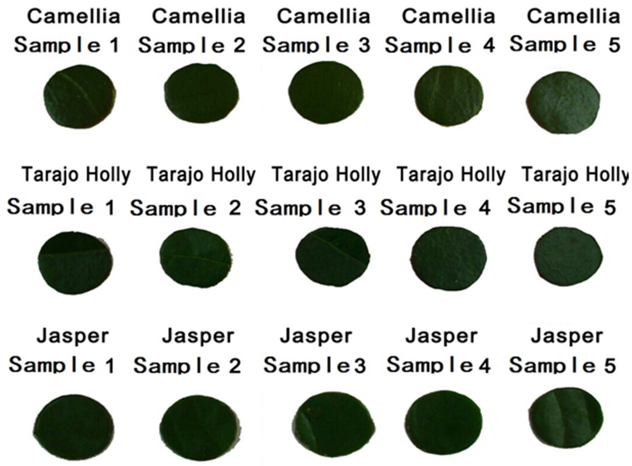

Fig. 1. *Sample leaves.*

Fig. 2. *Arrangement of thermal probes.*

In order to get the specific heat of in vitro tissue, some circular specimens with corresponding size should be prepared before tests. Firstly，five leaves in good condition and with similar outline shape and size from that three trees were picked respectively. Then washed these leaves with demonized water and dried by filter papers. Finally, these leaves were clipped into circular specimens with 50 mm in diameter, just shown as figure 1.

2.4. Experimental Principles and Steps

(1) The differential scanning calorimeter measuring the specific heat

The differential scanning calorimeter (DSC) do thermal analysis at controlled temperature by measuring the energy difference input into samples and references varies with temperature or time [5]. At the beginning of tests, samples were kept in a constant temperature of - 6°C for 3 minutes, and then warmed up to 24°C with the rate of 2°C/min. After all of these operations, the specific heat of each sample could be obtained in the temperature range. In order to increase the accuracy of the results, all the samples were measured twice and gross errors were eliminated. Take the average as the specific heat of each plant at particular temperature.

(2) Thermal probe method for the determination of thermal conductivity

Thermal probe method for the determination of thermal conductivity of leaves is a technique which based on non-steady measurement principle, and it comes from heating line source theory. The device mainly includes thermal probes, stabilized voltage supply and 34972A Agilent data acquisition instrument. Of which, the thermal probe made by stainless steel was a self-made device which contains a 0.05 mm enameled copper wire was used as heating elements embraced by copper wire for 20 circles. The space between copper and stainless steel was filled with silicone grease with good insulated and thermal conductivity. Both of the ends were fixed by resin adhesive. The arrangement of probes was shown in Figure 2. The voltage across of copper was supplied by APS3003S-3D DC stabilized power supply, and the 34972A Agilent data acquisition instrument was used for collection of experimental data. The collected output voltage signal ΔU and heating time were entered into the computer.

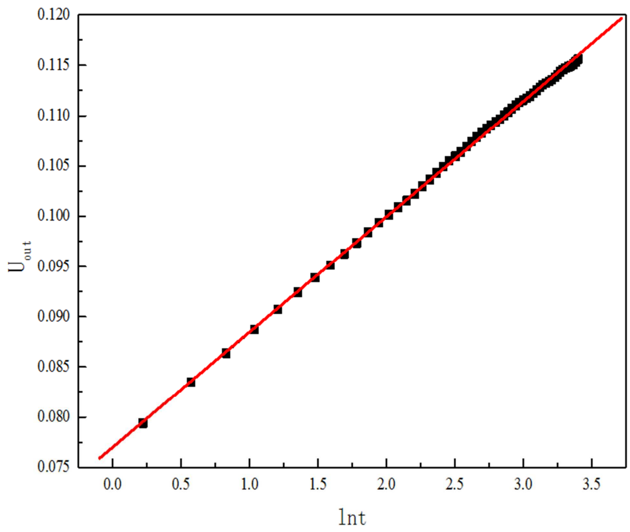

Fig. 3. *Calibration curve of output voltage Uout and logarithmic time (lnt) (Glycerol, at 21.2°C).*

Table 1. *Rate of change of voltage with logarithmic time (Glycerol, at 21.2°C).*

	1	2	3	4	5	Average
dU/d(lnτ)	0.01147	0.01108	0.01120	0.01081	0.01106	0.011124

The determination of the thermal conductivity of leaves following these steps:

(1) The thermal probe constant should be tested before measuring the thermal conductivity of leaves. The glycerol was continuously kept at 21.2°C by water-bath heater in this experiment. Take notes of the changes of output voltage U_{out} with time τ at the rate of 200ms for acquisition interval. The calibration curve of output voltage Uout and logarithmic time ($\ln\tau$) could then be obtained, as shown in Figure 3. The software of Origin is the availability of increasingly powerful tools to process the data. Repeated 5 times less and got the voltage variation rate with the logarithm time $dU/d(\ln\tau)$ respectively, as shown in Table 1. Took the average 0.011124 and calculated thermal probe constant for 0.0971.

(2) Inserted the probes into leaves and sealed the port with sealant.

(3) Started the Agilent data acquisition instrument until the self-test had finished. The channel of Agilent software was configured to DC voltage type. Set the scan control intervals to 200 ms and sweep time for 30 s.

(4) Turned on the power supply after setting up the channel. At the same time clicked on "Start" and get the voltage for 3.0 V and current for 0.32 A.

(5) Started the program to register and save the experimental results. Meanwhile, recorded the parameter values of ambient temperature, wind speed, atmospheric humidity and so on.

(6) Repeated steps 3~5 every 15 minutes and got 25 groups of thermal conductivity.

3. Experimental Results and Analysis

3.1. Specific Heat

3.1.1. The Specific Heat Data and Analysis of Camellia Samples

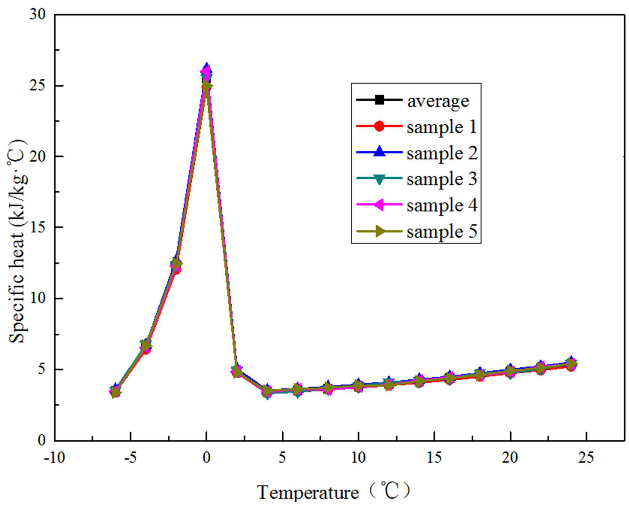

Fig. 4. *Specific Heat Curves of Camellia Leaves.*

The specific heat curves of Camellia leaves under different temperature were shown in Figure 4. From this picture some results could be obtained: 1) The specific heat of Camellia has a small increased as temperatures go up in the temperature range of -6°C~-4°C. 2) The specific heat of Camellia leaves increases rapidly with cubic parabola relationship when the ambient temperature range in -4°C~0°C, and reaches the maximum at 0°C for about 25 J/(kg°C). 3) Within an ambient temperature range of 0°C ~ 2°C, the specific heat of Camellia leaves decline sharply to about 5 J/(kg°C). 4) Values of the specific heat decrease slowly at the range of 2°C~4°C and then as the temperature increases, the specific heat increases gradually. But the increase amplitude is very small.

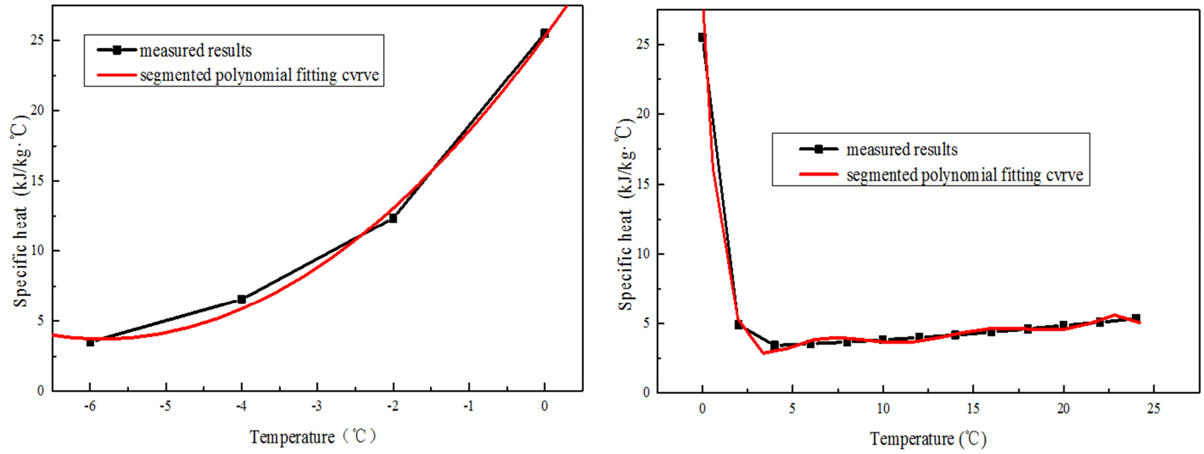

Fig. 5. *Segmented polynomial fitting curve of Specific Heat of Camellia Leaves.*

There are many reasons for causing the specific heat of Camellia leaves change dramatically at about 0°C. But from the point of heat and biological view, reasons are as follows:

(1) The content of bound water inside leaves is rich. Although there is no solid-liquid phase transition occurs, the latent heat that comes from water itself prompts specific heat peak at 0°C.

(2) There are biochemical reactions occur within leaves, that is to say hardy plants do have cold mechanisms. The antifreeze proteins are quickly produced within leaves under low temperature, which can hinder the formation of ice through physiological effects such as thermal hysteresis activity [6-7]. But the antifreeze protein disappears gradually above 0°C, which results in the reduction of the cold resistance and the specific heat of leaves will decline.

(3) The membrane lipid within leaves will have a phase transition from flowing liquid crystal state into curing gel state while at the state of freezing injury [8].

The approximate relationship between the specific heat of Camellia leaves and temperature was available after adopting the segmented polynomial fitting curves of specific heat among different ranges of temperature. As shown in Figure 5.

$$c = 25.3 + 7.38t + 0.63t^2 \quad (1)$$

The applicable temperature range for Formula (1) is - 6°C~ 0°C.

$$c = 25.47 - 19.47t + 6.43t^2 - 1.05t^3 + 0.09t^4 - 0.005t^5 \quad (2)$$

The applicable temperature range for Formula (2) is above 0°C, but in the growth temperature range.

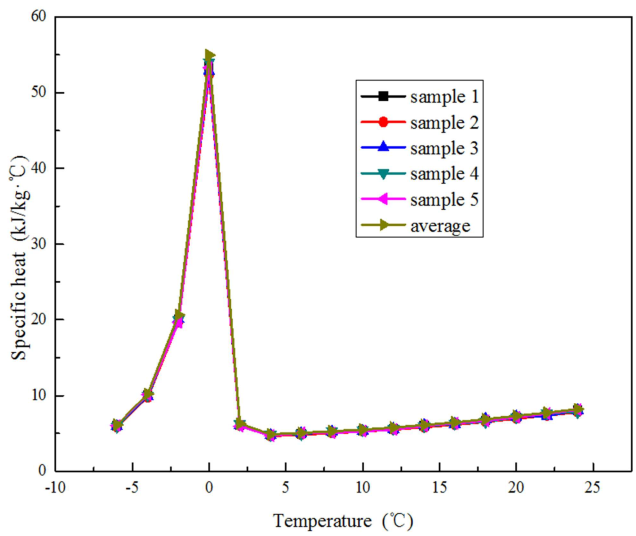

Fig. 6. *Specific heat curves of Nex latifolia thunb leaves.*

Comparing the specific heat curve of Camellia leaves (Figure 4) and Tarajo Holly (Figure 6) you will find that both of these two parameters have similar properties. At the beginning of the experiment the temperature is very low, the specific heat just about 5 J/(kg·°C). The specific heat increase rapidly with the temperature rise and reaches the maximum at 0°C for about 52 J/(kg·°C). A sharp decline of specific heat occurs in the range of 0°C~2°C to about 5 J/(kg·°C). Then as the temperature increases, the specific heat increases slightly. But the increase amplitude is very small. It is identified that the specific heat of hardy leaves do really have similar features, that is specific heat increase to a peak at 0°C.

The approximate relationship between the specific heat of Nex latifolia thunb leaves and temperature was available after adopting the segmented polynomial fitting curves of specific heat among different ranges of temperature. As shown in Figure 7.

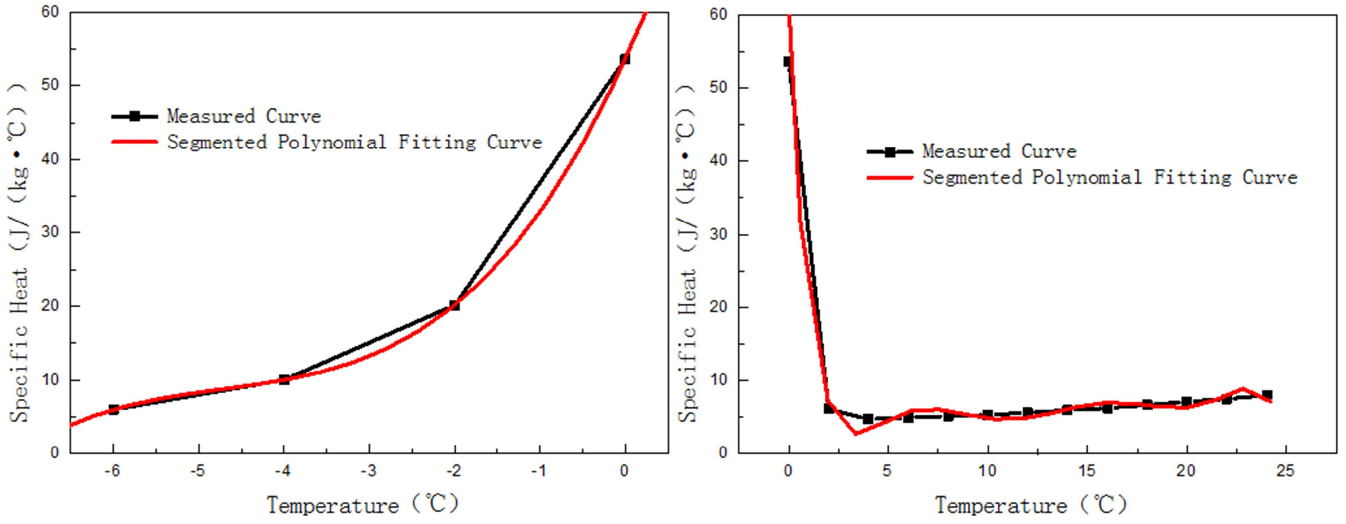

Fig. 7. Segmented simulation of specific heat on Nex latifolia thunb leaves.

$$c = 53.64 + 25.43t + 5.06t^2 + 0.36t^3 \quad (3)$$

The applicable temperature range for Formula (3) is –6°C~0°C.

$$c = 53.48 - 45.96t + 15.79t^2 - 2.65t^3 + 0.24t^4 - 0.01t^5 \quad (4)$$

The applicable temperature range for Formula (4) is above 0°C, but in the growth temperature range.

3.1.2. Data Processing and Analysis for the Specific Heat of Jasper Leaves

The specific heat of Jasper leaves is shown in Figure 8. The specific heat curves of Jasper (non-hardy plant) vary greatly from hardy plants. The specific heat increases steadily with warmer temperatures at all test temperatures.

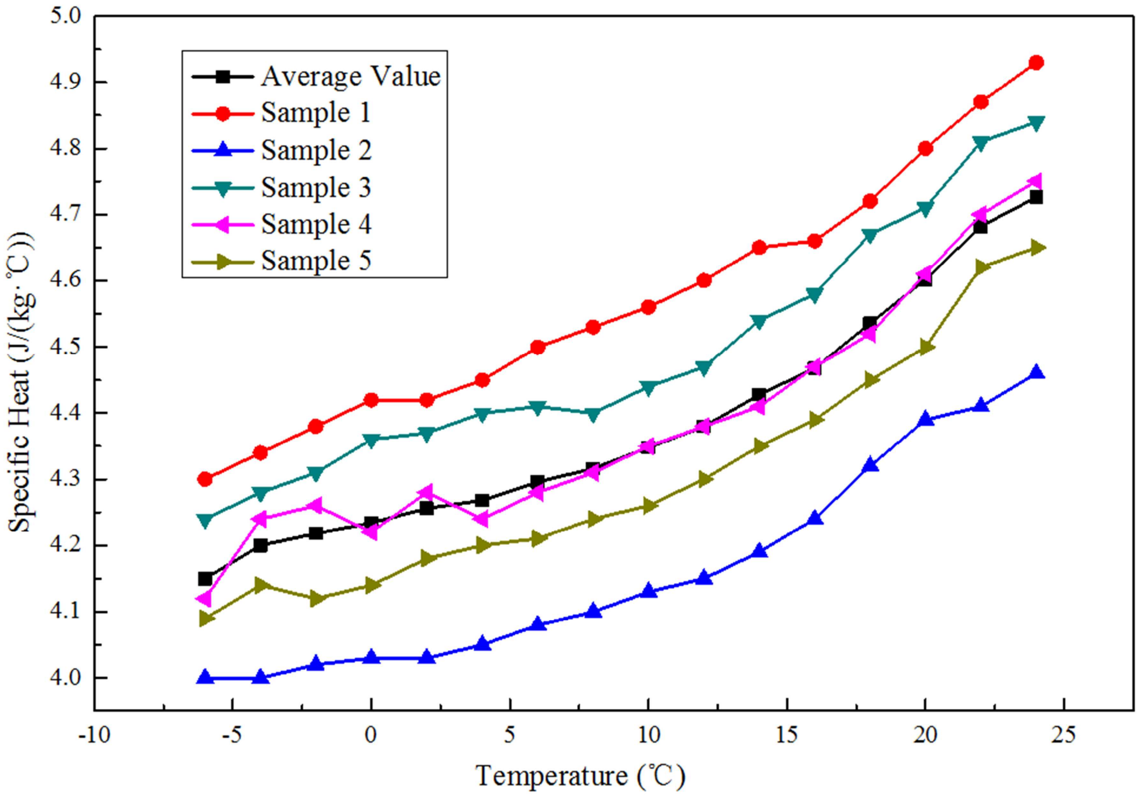

Fig. 8. Specific heat curve of Jasper leaves.

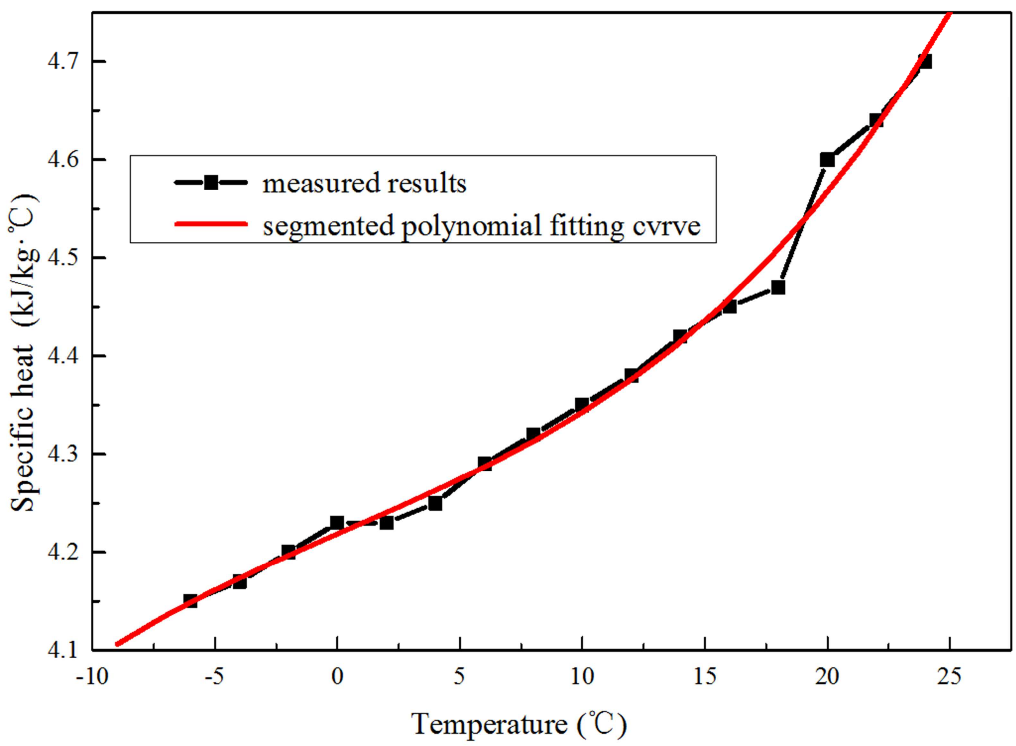

Fig. 9. *Segmented simulation of specific heat on Jasper leaves.*

The quadratic function was used for fitting the specific heat curves of Jasper leaves. As is shown in Figure 9.

$$c = 4.21 + 0.009t \tag{5}$$

The applicable temperature range for Formula (5) is all the growth temperature.

3.1.3. Contrastive Analysis

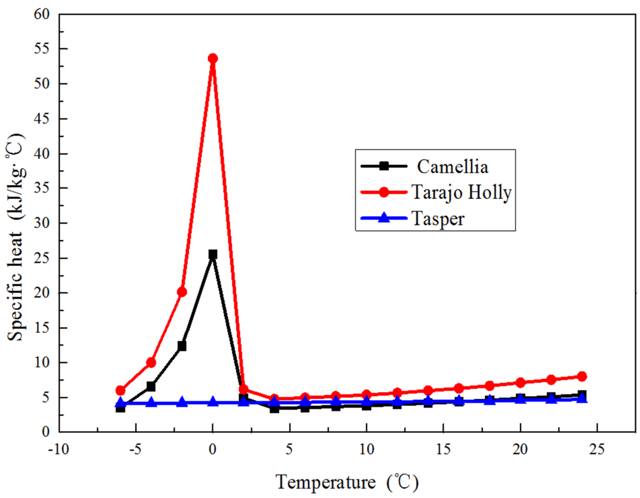

Fig. 10. *Comparison of Average Specific Heat Curves.*

The average specific heat curves of Camellia, Tarajo Holly and Jasper leaves in different temperatures were plotted in Figure 10. Some useful conclusions could be drawn from this figure 1) The specific heat of three plants leaves extremely close to each other while the temperature is higher than 4°C and increases with the rise of temperature slightly. But the two types of plants differ greatly as temperature in the range of -6°C~ 4°C. 2) The specific heat of hardy plants (Camellia and Tarajo Holly) increase rapidly in the temperature range of -4°C ~ 0°C and reach the maximum at 0°C, but a sharp decline appears in the range of 0°C ~ 2°C. In contrast, the specific heat of Jasper leaves increases with warmer temperatures gradually. By inference, the specific heat of hardy plants change dramatically at about 0°C, while the non-hardy plants increase in gentle linear. 3) By comparing the specific heat curves of Camellia and Tarajo Holly leaves, you will discover similar shapes but large differences in the peak of specific heat with about twice times.

Measurement errors could hardly be avoided in the measurement of the specific heat by the ways of DSC. Accidental error will affect the reproducibility of the measurement results, that is, the measurement accuracy. Some causes of accidental errors by DSC in measuring the specific heat of leaves at different temperatures include [8] baseline stability, the quality difference of the sample dish, the amount of sample, heating rate, atmospheric velocity and stability. System error will affect the authenticity of the measurement results, namely measurement accuracy. The main reasons causing system errors are as follows: 1) the leaves are anisotropic material, by contrast, the sapphire as reference samples is isotropic material. So the heat transfer coefficient are different. 2) The functional relationship between specific heat and temperature is nonlinearity which can also bring errors. 3) Thermal resistance exists between sample dishes and temperature-sensitive elements, as well as the samples and the sample dishes itself, resulting in a measurement error caused by thermal hysteresis.

3.2. Thermal Conductivity

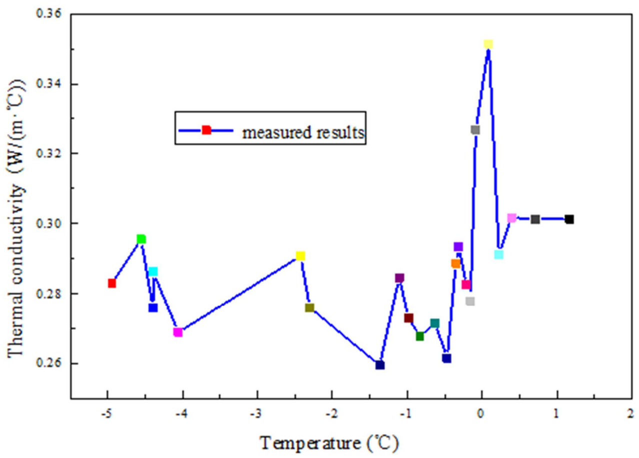

Fig. 11. *Thermal conductivity of Camellia leaves.*

Thermal conductivity values of Camellia leaves at different temperatures were plotted in Figure 11 ranging from 0.26 to 0.36 W/(m·°C). That is well within the expected range of thermal conductivity range for plants from 0.04 to 0.4 W/(m·°C). In addition, it was verified that the test program can be used to determine the thermal conductivity of different parts of viable body. As we can see from the figure that the thermal conductivity values of Camellia leaves fluctuate around 0.28 W/(m·°C) in the growth environment of less than 0°C. In a small range around 0°C, a peak of the thermal conductivity of Camellia leaves can be achieved for 0.351 W/(m·°C). While the growth environment higher than 0°C, the thermal conductivity is about 0.3 W/(m·°C) or so. The changes of the thermal conductivity curves are similar to the specific heat that the physical parameters appear to soar or drop suddenly at 0°C.

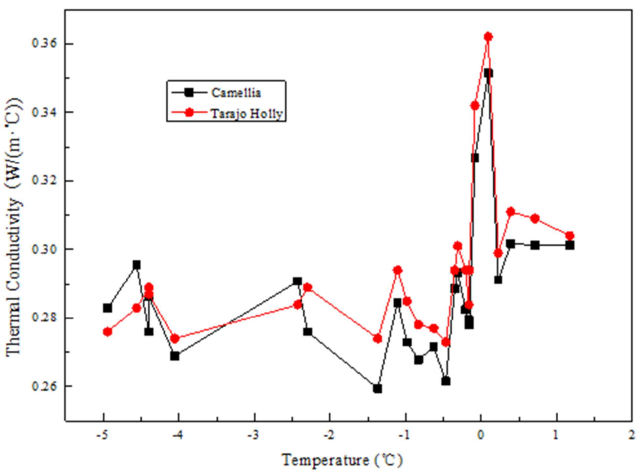

Fig. 12. *Comparison of the thermal conductivity curve of Camellia and Tarajo Holly leaves in different temperatures.*

As can be seen from the figure that the thermal conductivity curves vary greatly, the main causes of this phenomenon can be concluded as the following three points: 1) Leaves belong to porous media and there are many factors which affect the thermal conductivity of leaves, for example, blade porosity, moisture content, environment temperature, composition. These factors are indirectly affected by light intensity, concentration of carbon dioxide, atmospheric humidity and water supply, etc. Due to all this combined effects, it is difficult to guarantee the stability of the thermal conductivity of leaves. 2) Although continuous operations were adopted in our tests, the experiment conducted in an open-air environment that makes the measured temperature discontinued. 3) Errors were caused when processing the data.

Both of the thermal conductivity of Camellia and Tarajo Holly leaves are plotted in Figure 12 and they have similar properties. The thermal conductivity of Tarajo Holly leaves in the growth environment below 0°C is about 0.29 W/(m·°C) with a slight fluctuation which bigger than Camellia leaves. The thermal conductivity of Tarajo Holly leaves reach the maximum in a small temperature range of 0°C for about 0.365 W/(m·°C) which is higher than camellia leaves. The peak values of specific heat and thermal conductivity of Tarajo Holly leaves are all bigger than Camellia leaves, possible reasons for this phenomenon are as follows:

(1) The cuticle of Tarajo Holly leaves is thicker [9], and the content of antifreeze protein goes over that in Camellia leaves.

(2) The richer content of bound water inside leaves, the stronger ability to tolerate low temperature [10]. While the bound water content within Tarajo Holly leaves are higher than that within Camellia leaves.

4. Conclusion

The heat and mass transfer inside plant tissues is based on the studies of thermo-physical properties which are essential to lucubrate the heat transfer characteristics and mass transfer mechanism. The reasonable and accurate evaluation of thermo-physical property give a great guarantee to obtain an a precise temperature and flow field. Based on routine determination of physical parameters, some improvement of experimental apparatus and methods were made in this paper and selected Camellia as research objects, Tarajo Holly as verification group and Jasper (non-hardy plant) as contrast group. The heat specific and thermal conductivity were measured and fitting analysis of heat specific curve was made. From the experiments and discussion, some useful conclusions could be obtained:

(1) The specific heat of hardy leaves (Camellia and Tarajo Holly) increase rapidly in the temperature range of -4°C~ 0°C and reach the maximum at 0°C. A sharp decline of specific heat occurs in the range of 0°C~2°C. Then as the temperature increases, the specific heat increases slightly.

(2) The specific heat of non-hardy leaves increases steadily with warmer temperatures at all test temperatures.

(3) The changes of the thermal conductivity curves are similar to the specific heat that the physical parameters appear to soar or drop suddenly at 0°C and reach the maximum at 0°C.

(4) Although the curves of specific heat and thermal

conductivity are similar for hardy plants, the peak varies greatly.

(5) Each physical parameter values measured from experiments were within the permissible range, it was also verified that the experimental equipment and methods used before were reasonable and operational. In addition, all the tests were carried out by a series of group operations to meet the repeatability requirement.

References

[1] Huang Liqun, Li Zhihui. Research progress on cold resistance of landscape plant [J]. Hunan Forestry Science & Technology, 2004, 31 (5): 19-21.

[2] James M. Lyons. Chilling injury in plants [J]. Ann rev Plant Physiol, 1973, (24): 445-466.

[3] Tang Yaohua. Study on the early selection of cold-resistance eucalyptus trees [D]. Zhu Zhou: Centural South University of Forestry and Technology, 1999.5.

[4] Zuo Airen. Physiological mechanism of plants adapt to variable temperature adversity [J]. Journal of biological teaching, 2000, 25 (6): 38-39.

[5] Yuan Kaijun, Han Xiaoqiang, Chen Guojin, et, al. Determination the heat capacity of the crude oil by DSC [J]. Gas Storage and Transportation, 2012, 29 (11), 864-867.

[6] Yang Yuzhen, Lei Zhihua, Peng Fangren. Research Advances about Low-temperature-induced Proteins and the Cold Tolerance in Plants [J]. Acta Botanica Boreali-Occidentalia Sinica, 2007, 27 (2), 421-428.

[7] Lu Hong, Feng Dachun, Yang Jiyou. Comparison of Differential Scanning Calorimetry and Modulated Differential Scanning Calorimetry in Measurement of Specific Heat Capacityies [J]. Analysis Instruments, 2011, (3), 70-74.

[8] Xu Kangsheng. Air temperature is proportional to the plant transpiration [J]. Biological Bulletin, 2003, 38 (5): 9-10.

[9] Guo Jianzao, Yuan Honggang. Study of Individual Screening on tea plant cold resistance [J]. Journal of Tea, 1995, 21 (1), 34-38.

[10] Wang Ning, Wu Jun, Xia Pengyun, et al. Physiological Responses of Ilex Latifolia to Low Temperature and Its Cold Tolerance [J]. Journal of south China agricultural university, 2011, 32 (3), 82-86.