QUANTIFICATION MODEL FOR ESTIMATING TEMPERATURE FIELD DISTRIBUTIONS OF APPLE FRUIT

Min Zhang[1,*], Le Yang[1], Huizhong Zhao[2], Leijie Zhang[1], Zhiyou Zhong[1], Yanling Liu[1], Jianhua Chen[1]

[1] *College of Food Science and Technology, Shanghai Ocean University, Shanghai, P. R. China 201306*

[2] *College of Urban Construction and Environment Engineering, University of Shanghai for Science and Technology, Shanghai, P. R. China 200093*

[*] *Corresponding author, Address: College of Food Science and Technology, Shanghai Ocean University, Shanghai, 201306, P. R. China, Tel: +86-21-61900392, Fax: +86-21-61900392, Email: zhangm@shou.edu.cn*

Abstract: A quantification model of transient heat conduction was provided to simulate apple fruit temperature distribution in the cooling process. The model was based on the energy variation of apple fruit of different points. It took into account, heat exchange of representative elemental volume, metabolism heat and external heat. The following conclusions could be obtained: first, the quantification model can satisfactorily describe the tendency of apple fruit temperature distribution in the cooling process. Then there was obvious difference between apple fruit temperature and environment temperature. Compared to the change of environment temperature, a long hysteresis phenomenon happened to the temperature of apple fruit body. That is to say, there was a significant temperature change of apple fruit body in a period of time after environment temperature dropping. And then the change of temerature of apple fruit body in the cooling process became slower and slower. This can explain the time delay phenomenon of biology. After that, the temperature differences of every layer increased from centre to surface of apple fruit gradually. That is to say, the minimum temperature differences closed to centre of apple fruit body and the maximum temperature differences closed to the surface of apple fruit body. Finally, the temperature of every part of apple fruit body will tend to consistent and be near to the environment temperature in the cooling process. It was related to the metabolism heat of plant body at any time.

Keywords: apple fruit, thermocouple, temperature, quantification model

1. INTRODUCTION

Precision agriculture is one of the tendency of modern agriculture. Temperature is an important factor of affecting plant's growth. So the plant body's temperature should be described as accurately as possible when the environmental around plant was regulated and controlled. For example, it is obviously more accurate using the body temperature of plant than the air temperature to judge whether the plant was suffering chilling injury in the chilling process. Ansari and Haghighi studied the problem of heat transfer of the fruits and vegetables under cold storage environmental conditions(Ansari et al.,1999). Lisowa and Shyam studied the impact parameters and measurement methods of the thermal properties of the fruits(Lisowa et al., 2002; Shyam et al., 2003). Becker studied the models of thermophysical property of Food(Becker, 1999). Miklos studied simultaneous heat and mass transfer within the maize kernels during drying(Miklos et al., 2000). Li and Yang studied heat and mass transfer characteristics of the vegetables and seeds in the drying process(Li Yebo et al., 1996; Yang Junhong et al., 2001). However, most of these studies neglected specific lives characteristics of the fruits and vegetables. In the modern scientific research of plant life, using physics model, many complex phenomena of lives successfully could be explained. Moreover, the present phenomenological science of plant life could be quantified as it as possible. The operating mechanism of the environment in living creature and the processes and principles of biological adaptation could be further understood. Also it could provide new models and ideas for revealing and resolving other complex issues of plant life science.

The object of this work was to develop a more accurate mathematical model to describe the dynamics temperature distribution of fruits and vegetables under different conditions. It could prove up the mobile forms of the internal heat of fruits by combination of thermal physics methods. It would be verified through the experimental and theoretical research of apples' internal temperature distribution of each moment in the cooling process. The results would find out the general rules of characteristics of heat transfer and lay a theoretical foundation to further explore plant stress physiology, including plant burn and heat resistance, plant frost damage and frost resistance, plant chilling injury and chilling resistance and even low-temperature preservation of vegetables and fruits.

2. THEORY AND METHODS

2.1 Theoretical analysis on temperature field

The heat transfer thoery of engineering thermo-physics was used to study the energy change within apple fruit. It took into account heat exchange of representative elemental volume, metabolism heat and external heat. The fruit organization was considered as a heat exchange control volume. A quantification model of transient heat conduction was bulit through the analysis of micro-control volume heat exchange by the heat conduction theory and the energy conservation law. The basic model could be expressed in Eqution(1)

$$\rho_m c_m \frac{\partial T_m}{\partial t} = k_m \nabla^2 T_m + q_m + q_a \qquad (1)$$

Where: $\rho_m c_m \frac{\partial T_m}{\partial t}$ is the energy change from the change of organization temperature, $k_m \nabla^2 T_m$ is the heat exchange between micro-control volume and the environment by thermal conductivity, q_m is the metabolic heat of organization, q_a is the absorption external heat by absorption.

For the sphere fruit with radius *R*, which is under the third boundary condition, with uniform inner heat source and with variable properties, a complete mathematical description of non-steady-state thermal conductivity of fruit was given as follows

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + \frac{q_v}{\rho c} \qquad (t > 0,\ 0 \le r \le R) \qquad (2)$$

Initial condition,

$$T(r,0) = T_0 \qquad (t=0,\ 0 \le r \le R) \qquad (3)$$

Boundary conditions,

$$-\lambda \frac{\partial T(r,t)}{\partial r}\Big|_{r=R} + \alpha(T_\infty - T_0) + \frac{q_v}{2} = \rho c \cdot \frac{\Delta r}{2} \cdot \frac{\partial T}{\partial t} \qquad (t=0,\ r=0) \quad (4)$$

$$\frac{\partial T(r,\tau)}{\partial r}\Big|_{r=0} = 0 \qquad (t=0, r=0) \qquad (5)$$

Where: T is sample temperature, τ is heating time, λ is thermal conductivity of the sample, a is temperature coefficient of the sample, ρc is sample specific heat capacity of sample, $q_v$is the respiratory heat of unit volume, α is convection heat transfer coefficient of boundary, R is sample radius.

In order to simplify the numerical calculation, apple organization was regarded as the same quality uniformly. The equivalent thermal parameters of thermal property was adopted to calculate. Properties of fruit were only affected by temperature(Zhang Min et al., 2004). However, in a range of temperature difference, they could be regarded as homogeneous. In the cooling process, major components were not changed from biochemical reactions. Some parameters of thermal property of apple and environment were shown in Table 1.

Table 1. Parameter of thermal properties of apple and environment

parameters	reference values
diameter （m）	0.09
water content (%)	87.6
initial temperature (℃)	20
frozen storage temperature (℃)	3
thermal conductivity (W/mK)	0.0032T- 0.5703
specific heat capacity(KJ/m^{3}K)	10.581T+799.85
respiratory heat (W/m^3)	$e^{0.0958T-23.884}$
convective heat transfer coefficient (W/m^{2}K)	30

2.2 Measurement system

The measurement system was shown in Fig.1. It mainly included constant temperature box(VELP Scientifica, Italy)with ±0.5℃ precision, thermal probe measurement system and data acquisition system. The thermal probe measurement system mainly included micro-thermocouple probe, thermos full of ice water with 0℃, transformer-oil vessel for heat transfer enhancement, compensation terminal in the mixture of ice and water, and so on. The data acquisition system mainly included 2700 data acquisition instrument (Keithley Instruments, USA), computer interface, and corresponding computer memory system.

At first, the micro-thermocouple probe should be calibrated to determine the test error. Low temperature thermostat bath DC2006(produced by Shanghai Instrument Factory) was used to calibrate measurement terminal of each thermocouple at the temperature of 0℃～30℃. And then the actual measured temperatures were amended. Computer P, I, D was used to control for DC2006. The Pt100 was used as temperature sensor. The circulating pump in the DC2006 flew in 10L/min.

Secondly, the calibrated micro-thermocouple probe was penetrated the apple sample vertically at 20℃ environment . Point 1-4 were put into sample, Point 5 was on the epidermal position of the sample, Point 6 was exposed in constant temperature box to obtain its environmental temperature. Then the test system and computer systemwas turned on and stabilized for 60 min, which was adjusted at the temperature of 3℃ ±0.5℃ and relative humidity of 85 ~ 90%.

Thirdly, the apple sample penetrated by the calibrated micro-thermocouple probe was put into the constant temperature box with temperature of 3℃ ±0.5℃ and relative humidity of 85 ~ 90%.

Finally, the temperature data at each moment and each section of apple fruit were collected by the Keithley acquisition instrument and stored on the computer to deal with at the same time.

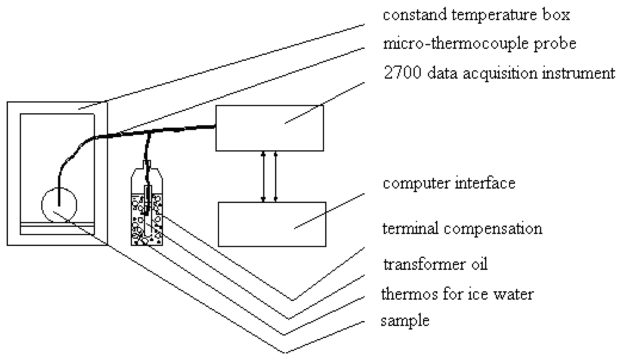

Fig.1: Experimental equipment of the refrigeration apple's inner temperature distribution

3. MEASURED RESULTS AND DISCUSSION

3.1 Probe calibration

The calibration results of multipoint temperature measurement probe in the low temperature thermostat bath DC2006 were listed in Table 2. It shown that the average temperature deviation of every point was less than 1.5℃ at the range of 0℃ and 30℃. The maximum fluctuation temperature deviation after amended could be controlled less than 0.03℃(see Table 3).

Table 2. Calibration deviation of multipoint temperature measurement probe

Temperature	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
0℃	-0.80	-0.89	-0.98	-1.05	-1.07	-0.87
5℃	-0.93	-1.02	-1.21	-1.03	-1.25	-1.06
10℃	-0.87	-1.15	-1.36	-1.22	-1.15	-1.02
20℃	-0.90	-1.16	-1.44	-1.21	-1.36	-1.23
30℃	-1.03	-1.17	-1.38	-1.23	-1.45	-1.27

Table 3. Calibration deviation of multipoint temperature measurement probe after amended

Temperature	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
0℃	0.02	0.02	0.02	0.02	0.02	0.02
5℃	0.02	0.02	0.02	0.02	0.01	0.02
10℃	0.01	0.01	-0.02	-0.02	-0.01	-0.01
20℃	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02
30℃	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02

3.2 Experimental value of temperature distribution and calculated value of quantification mode of apple fruit

The determined temperature distribution of apple fruit in constant temperature box was shown in Fig.2. The calculated temperature value by the quantification model including Formula(2) to Formula(5) was shown in Fig.3. So the following conclusions could be obtained:

First, the quantification model can satisfactorily describe the tendency of apple fruit temperature distribution at the cooling process.

Then, there was obvious difference between apple fruit temperature and environment temperature. Compared to the change of environment temperature, a long hysteresis phenomenon happened to the temperature of apple fruit body. That is to say, there was a significant temperature change of apple fruit body in a period of time after environment temperature dropping. And then the change of temerature of apple fruit body in the cooling process became slower and slower. This can explain the time delay phenomenon of biology.

After that, the layer temperature differences increased from centre to surface of apple fruit gradually. That is to say, the minimum temperature differences closed to centre of apple fruit body and the maximum temperature differences closed to the surface of apple fruit body. Finally, the temperature of every part of apple fruit body will tend to consistent and be near to the environment temperature in the cooling process. The temperature distribution of apple fruit body was related to the metabolism heat of plant body.

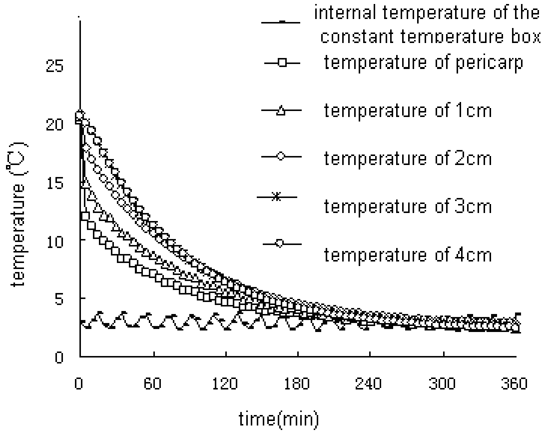

Fig. 2: The experimental temperature variation of apple fruit

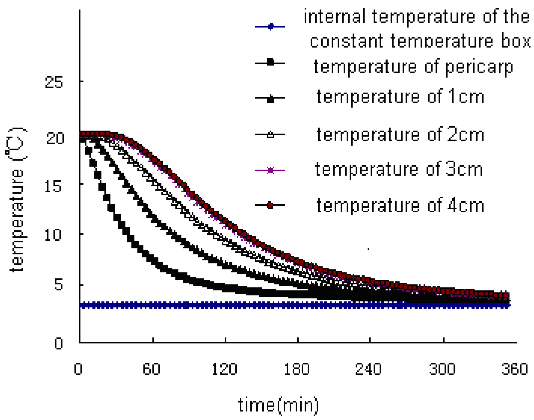

Fig. 3: The simulation temperature variation of apple fruit

4. CONCLUSION

In this paper, the heat transfer theory of thermal physics is applied. It takes into the characteristics of life-activity apple. A computer quantification model of transient heat conduction was provided to simulate apple fruit temperature distribution in its temperature dropping process. Contrasted between the results of numerical analysis and the temperature field distribution of actual test, the conclusion could be got by experiment: the quantification model can satisfactorily reflect the tendency of apple fruit temperature distribution at the dropping temperature process. And we can further explore plant stress physiology, including plant burns and heat resistance, plant frost damage, plant chilling injury and frost resistance and vegetables, fruits and other low-temperature preservation, and so on.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Natural Science Foundation of China, Grant No 30771245 and the key construction course project of Shanghai Educational Committee, Grant No 6700308.

REFERENCES

B. R. Becker, B. A. Fricke. Food Thermophysical Property Models. INt.Comm. Heat Mass Transfer, 1999, 26:27-35

F. A. Ansari, S. Y. Khan. Application concept of variable effective surface film conductance for simultaneous heat and mass transfer analysis during air blast cooling of food. Energy Conversion and Management, 1999, 40(5): 567-574

H. Lisowa, M. Wujec, T. Lis. Influence of temperature and variety on the thermal properties. Int.Agrophysics, 2002, 16: 43-52

J. H. Yang, Z. D. Chu, X. L.Meng. Internal moisture content diffusion diffusion mechanism of seeds drying. Journal of Tianjin University, 2001, 34(2): 142-145

N. Miklos, C. István, K. Attila. Investigation of simultaneous heat and mass transfer within the maize kernels during drying. Computers and Electronics in Agriculture, 2000, 26(2): 123-135

S. Shyam, M. Sablani, R. Shafiur. Using neural networks to predict thermal conductivity of food as a function of moisture content, temperature and apparent porosity. Food Research International, 2003, 36: 617-623

Y. B. Li, Q. L. Yu, L. H .Zhao. Experiment and Study on the Heat and Mass Transfer in Potato During Drying. Transactions of The Chinese Society of Agricultural Engineering, 1996, 12(4): 62-65

Zhang Min, Zhang Bailing, Sun Zhiqiang. Heat Transfer Analysis in Postharvest Fruit. Journal of Northeast Agricultural University, 2004,（35）4：418-421(in Chinese)