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THERMAL CONDUCTIVITY OF FOOD PRODUCTS

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Abstract. The presented work is focused on the food thermal characteristics calculation methods (heat conductivity coefficient λ and thermal diffusivity coefficient *a*). Thermal characteristics of food are important in food industry and define the intensiveness of technological processes of food refrigeration and thermal treatment, energy consumption for their realization and technological equipment production rate. They are also needed for the building and validation of mathematical models of heat transfer in food products which are useful in the design and optimisation of freezing, heating, cooking and cooling processes and equipment. It is not easy to define the food thermal characteristics. Difficulties arise from their heterogeneity, high labour consumption and complexity of experimental sets. Methods for experimental determination of heat conductivity coefficient λ and thermal diffusivity coefficient *a* based on the regular method mode require the $\alpha \to \infty$ condition, which is the case of high speed of the environment which flows around the test sample, as in the case of boiling or condensing. Using the method presented in this article it is possible to determine the heat conductivity λ and thermal diffusivity coefficient *a* even in the absence of the condition $\alpha \to \infty$.

Keywords: food products, thermal conductivity, thermal diffusivity coefficient

INTRODUCTION

Thermal characteristics (TC) of food products define the intensiveness of technological processes of their refrigeration and thermal treatment, energy consumption for their realization, and technological equipment production rate. Thermal characteristics are also needed in the building and validation of mathematical models of heat transfer in food products (Almonacid-Merinoand Torres 1993, Karunakar *et al.* 1998, Sablani *et al.* 2002, Sun 2007), which are useful in the designing and optimisation of freezing, heating, cooking and cooling processes and equipment (Simpson and Cortes 2004, Marcotte *et al.* 2008).

The definition of thermal characteristics presents certain difficulties due to their heterogeneity, high labour consumption and complexity of experimental sets. Special difficulties are encountered while defining the TC of systems which are composed of separate products placed into one container, e. g. in the form of fish or meat blocks.

Substantial difficulties occur when defining the TC of products in a frozen state, because their TC change, depending on the temperature due to turning moisture into ice.

Such TC as specific heat capacity c and density ρ are additive values and may be defined for food products by the calculation method based on the known mass and chemical composition of the products.

Heat conductivity coefficient λ and thermal diffusivity coefficient a are not such as that, and they are defined exclusively in an experimental way, using methods such as e.g. the Bock device and the thermistor camera. In comparative inter-laboratory studies of the same material samples very large differences were found between the conductivity coefficients λ determined by means of the Bock device and the thermistor camera (Pogorzelski and Firkowicz-Pogorzelska 1998).In the article an alternative approach based on the regular mode method is presented.

THEORETICAL PART

The classical regular mode method, based on the heat conductivity theory developed by Kondratiev (Kondratiev 1957, Staniszewski 1979), allows a rather simple way of defining the thermal diffusivity coefficient in the process of cooling or heating

$$a = \frac{\lambda}{c\rho} \tag{1}$$

However, its application is valid on the condition that surface heat transfer coefficient from the product sample to a medium during refrigeration or from the medium to the products during heat transfer tends to infinity ($\alpha \to \infty$). Additionally, the low thermal conductivity coefficient results in that the Biot number also tends to infinity

$$Bi = \frac{\propto \cdot l}{\lambda} \tag{2}$$

(in practice Bi > 100). In the case of slabs having a thickness dimension of the linear characteristic

$$l = \frac{\delta}{2}. \quad (3)$$

It means that constant predetermined temperature ″t_0″ should be kept on the outer surface ″F″ of the sample being investigated and marginal condition of the third order is secured.

On this condition the graph of excessive temperature logarithm change on time $\ln(t - t_0) = f(\tau)$, where t is temperature within the sample, presents a direct line, and the thermal diffusivity coefficient is calculated according to the formula:

$$a = Km_\infty, \quad (4)$$

where K – sample form coefficient, m^2;
m_∞ – sample cooling rate → ∞, and equals:

$$m_\infty = \frac{\ln(t_1 - t_0) - \ln(t_2 - t_0)}{\tau_2 - \tau_1}, \quad (5)$$

Where t_1 and t_2 – temperature in any point of sample at time moments τ_1 and τ_2, °C.

Condition $\alpha \to \infty$ may be obtained only to a certain precision. Selection of α value when using the regular mode method was developed by Kondratiev (1957) and is based on a universal dependence between criterion M and modified criterion H, described by the formulas

$$M = \frac{m}{m_\infty}, \quad (6)$$

$$H = \frac{\propto}{\lambda} \frac{KF}{V}, \quad (7)$$

Where: m – sample cooling rate at final value of α;
V – sample volume, m^3,
F – heat exchange surface, m^2.

It follows from formula (7) that surface heat transfer coefficient equals:

$$\alpha = H \frac{\lambda V}{KF}, \quad (8)$$

The relation between criteria H and M may be taken from the detailed table which is given in the paper (Kondratiev 1957), excerpts of which are presented below:

Table 1. Relation between criteria H and M

H	∞	25	20	15	10	0
M	1	0.972	0.965	0.954	0.931	0

At $H = 15$ criterion M is other than one, which corresponds to an ideal condition $H \to \infty$ and $\alpha \to \infty$, at $\frac{1-0.954}{1} \cdot 100\% = 4.6\%$. It we take an error due to non observance of condition $\alpha \to \infty$ 4.6% then at $H \geq 15$, or as follows from equation (6) at $\alpha \geq 15\frac{\lambda V}{KF}$ we may consider $M \approx 1$ and take $\alpha \to \infty$ with the error 4.6%.

In practice, when carrying out experiments, the condition $\alpha \to \infty$ is secured by way of high speed medium flushing the sample being investigated either at boiling or condensing, or by selecting sample dimensions defining values *K*, *F* and *V*, which follows from equation (8).

METHODS OF RESEARCH

In a number of cases it is not possible to provide condition $\alpha \to \infty$, or the graph of dependence of excessive temperature logarithm on time $\ln(t - t_0) = f(\tau)$ presents a curve concaved upward. It takes place at defining the thermal diffusivity coefficient of products in the frozen state, when we have TC with the sample temperature changes.

In the case of impossibility to create conditions $\alpha \to \infty$ with the predetermined accuracy, it is possible to determine coefficients of temperature and thermal conductivity of products with the known specific product thermal capacity based on dependencies underlying the regular method mode.

For that purpose cooling rate ″m″ is determined from graph $\ln(t - t_0) = f(\tau)$, obtained experimentally at the final value of surface thermal transfer coefficient α_κ, which is considerably different from the condition $\alpha \to \infty$. Then thermal diffusivity coefficienta_0 is determined by expression (4) and thermal conductivity coefficient $\lambda_0 = a_0 c\rho$ is determined by equation (1). By means of dependency (7) criterion H is determined

$$H = \frac{\alpha_\kappa}{\lambda_0}\frac{KF}{V}, \tag{9}$$

by means of which criterion M is determined from the table (Kondratiev 1957). The M value can be determined by equation

$$M = \frac{\mathrm{H}}{\sqrt{\mathrm{H}^2 + 1.437\mathrm{H} + 1}}. \tag{10}$$

Then the true value of refrigeration rate at α→∞ will be equal to

$$m_\infty = \frac{m}{M}. \tag{11}$$

For the purpose of verification of validity of using regular mode for defining thermal diffusivity and thermal conductivity coefficients at considerable error, breach of condition $\alpha \to \infty$ the experiments for cooling paraffin were carried out.

Paraffin in the form of parallelepiped (block) with the dimensions of 0.598 × 0.255 m and thickness $\delta = 0.07$ m were placed between two plates of aluminum alloy with the internal ducts filled with a coolant (Freon R22) by means of a pump. The side walls of the block were insulated.

Experimental set (Fig. 1) allowed regulation of coolant supply to the plates and its passage through the ducts in the super cooled state, which made it possible to carry out the experiment at different thermal transfer coefficients and to define their value by the calculation method.

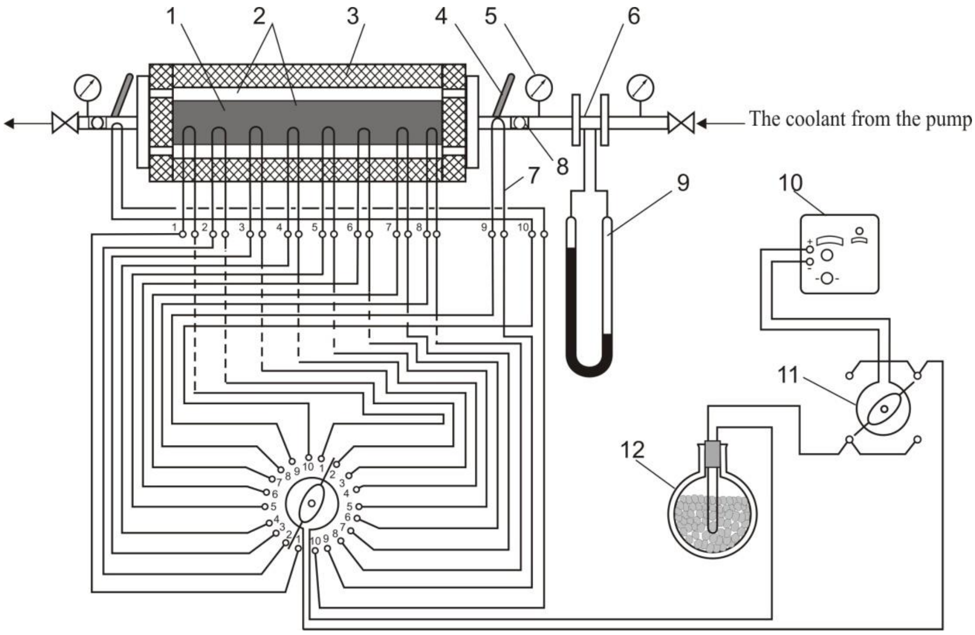

Fig. 1. Experimental unit chart. 1 –investigated material; 2 – refrigeration plates; 3 – heat insulator; 4 – thermometer; 5 – manometer; 6 – chamber diaphragm; 7 – heat couple; 8 – observation glass; 9 – differential manometer; 10 – potentiometer; 11 – switch; 12 – Dewar vessel

For the experimental paraffin sample, its volume, mass and density were $V = 0.011$ m^3, $m_n = 9.23$ kg and $\rho = 865$ kg m^{-3}, respectively, and at bilateral removal of heat from the sample during the experiment the surface of thermal transfer and form coefficient were equal to:

$$F = 2 \cdot 0.598 \cdot 0.255 = 0.305 \text{ m}^2 \text{ and } K = \frac{\delta^2}{\pi^2} = \frac{0.07^2}{3.14^2} = 4.97 \cdot 10^{-4} \text{ m}^2.$$

Experiments for determining thermal diffusivity coefficient were made at surface thermal transfer coefficients $\alpha = 686$ W m^{-2} K^{-1} and $\alpha = 150$ W m^{-2} K^{-1}.

For the purpose of assessment of the obtained experimental results validity, the TCs of paraffin were used, obtained from different sources, and they differed considerably. Thus some papers give out the following paraffin TC:

$$a = 1.25 \cdot 10^{-7} \text{m}^2 \text{ s}^{-1},\ \lambda = 0.1465 \text{ W m}^{-1} \text{K}^{-1},\ c = 1.37 \text{ kJ kg}^{-1} \text{K}^{-1}$$
$$\text{and } \rho = 850 \text{ kg m}^{-3}.$$

while some other papers give data for specific thermal capacity and thermal diffusivity coefficient of paraffin at $t = +20$°C, $\lambda = 0.27$ W m^{-1} K^{-1}, $\rho = 920$ kg m^{-3}.

RESULTS AND DISCUSSION

The experiments demonstrate that at surface thermal transfer coefficient $\alpha = 686$ W t m^{-1} K^{-1} the mean value of refrigeration rate was $m = 2.85 \cdot 10^{-4}$ s^{-1}. Then, using formulas(4), (1) and (9) and taking specific thermal capacity $c = 1.37$ kJ kg^{-1} K^{-1} we get

thermal diffusivity coefficient

$$a_0 = Km = 4.97 \cdot 10^{-4} \cdot 2.85 \cdot 10^{-4} = 1.42 \cdot 10^{-7} \text{m}^2 \text{ s}^{-1},$$

thermal conductivity coefficient

$$\lambda_0 = a_0 c\rho = 1.42 \cdot 10^{-7} \cdot 1.37 \cdot 10^3 \cdot 865 = 0.168 \text{ W m}^{-1} \text{K}^{-1},$$

criterion

$$H = \frac{\alpha}{\lambda_0} \frac{KF}{V} = \frac{686}{0.168} \cdot \frac{4.97 \cdot 10^{-4} \cdot 0.305}{0.01067} = 58.0.$$

It follows from the table of dependency between criteria H and M (Kondratyev 1957) that value $H = 58$ corresponds to $M = 0.987$. It means that error from non-observing condition $\alpha \to \infty$ in the experiments was $\frac{1-0.987}{1} \cdot 100\% = 1.3\%$ and the value of refrigeration rate in the experiments was $m \approx m_\infty$. The actual value of m_∞ at $\alpha \to \infty$, as it follows from equation (11), equals

$$m_\infty = \frac{m}{M} = \frac{2.85\cdot10^{-4}}{0.987} = 2.89\cdot10^{-4}\ \text{s}^{-1}.$$

In the experiments carried out at $\alpha = 150$ W m^{-2} K^{-1}, the mean value of refrigeration rate was $m_\kappa = 2.75\cdot10^{-4}$ s^{-1}

$$a_0 = Km_\kappa = 4.97\cdot10^{-4}\cdot2.75\cdot10^{-4} = 1.367\cdot10^{-7}\text{m}^2\,\text{s}^{-1},$$

$$\lambda_0 = a_0 c\rho = 1.367\cdot10^{-7}\cdot1.37\cdot10^3\cdot865 = 0.162\ \text{W m}^{-1}\,\text{K}^{-1},$$

$$H = \frac{\alpha_\kappa}{\lambda_0}\frac{KF}{V} = \frac{150}{0.162}\cdot\frac{4.97\cdot10^{-4}\cdot0.305}{0.01067} = 13.2.$$

It follows from the table of dependency that $M = f(H)$ (Komdtatyev 1957) at $H = 13.2$ criterion $M = 0.947$. Then the refrigeration rate is

$$m_\infty = \frac{m_\kappa}{M} = \frac{2.75\cdot10^{-4}}{0.947} = 2.90\cdot10^{-4}\ \text{s}^{-1},$$

which practically coincides with the value ofm_∞ obtained from the experiments carried out at $\alpha = 686$ W m^{-2} K^{-1}.

The final thermal diffusivity coefficient and thermal conductivity coefficient of paraffin will be obtained.

$$a = Km_\infty = 4{,}97\cdot10^{-4}\cdot2{,}90\cdot10^{-4} = 1{,}44\cdot10^{-7}\text{m}^2\,\text{s}^{-1},$$

$$\lambda = ac\rho = 1{,}44\cdot10^{-7}\cdot1{,}37\cdot10^3\cdot865 = 0{,}17\ \text{W m}^{-1}\,\text{K}^{-1})$$

CONCLUSIONS

1. The demonstrated experimental-calculation method allows to determine thermal diffusivity coefficient and thermal conductivity coefficient by regular mode method even in the case of impossibility to observe condition of $\alpha\rightarrow\infty$.
2. Thermal conductivity coefficient can be determined and, prior to that, the specific thermal capacity was obtained, e.g. by calorimetric method.
3. When determining products thermal diffusivity and thermal conductivity coefficients being in the frozen state by means of the regular mode method the graph of changing excessive temperature logarithm on time represents convex upward curve owing to TC changes due to ice formation. Thermal conductivity coefficient λ increases in the process of ice formation and criterion value H decreases, which determines impossibility to observe condition $\alpha\rightarrow\infty$. In this case

this method allows to overcome the predicament on the condition of defining refrigeration rate in the narrow range of temperatures.

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PRZEWODNOŚĆ CIEPLNA PRODUKTÓW SPOŻYWCZYCH

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S t r e s z c z e n i e. W pracy opisano metodę pozwalającą na obliczeniowe wyznaczenie charakterystyk cieplnych produktów spożywczych – współczynnika przewodzenia ciepła λ oraz współczynnika wyrównania temperatury (dyfuzyjności cieplnej) *a*. Współczynniki te wpływają na przebieg procesów obróbki termicznej produktów, a także na zużycie energii i produktywność urządzeń technologicznych. Znajomość tych współczynników jest konieczna do tworzenia modeli matematycznych wymiany ciepła w produktach spożywczych, użytecznych w projektowaniu i optymalizacji procesów i urządzeń do mrożenia, ogrzewania, gotowania czy schładzania produktów. Określenie właściwości cieplnych żywności nie jest łatwe. Trudności wynikają z różnorodności produktów spożywczych, pracochłonności i złożoności stanowisk badawczych. Sposoby eksperymentalnego wyznaczania ww. współczynników oparte na metodzie stanu uporządkowanego wymagają spełnienia warunku $\alpha\rightarrow\infty$, co ma miejsce w przypadku dużych prędkości środowiska omywającego badaną próbkę, przy gotowaniu lub kondensacji. Za pomocą przedstawionej w pracy metody możliwe jest wyznaczenie współczynnika przewodzenia ciepła λ i współczynnika dyfuzyjności cieplnej a nawet w przypadku braku spełnienia warunku $\alpha \to \infty$.

Słowa kluczowe: produkty spożywcze, przewodność cieplna, współczynnik dyfuzyjności cieplnej