HEAT CONDUCTIVITY OF SOME FOOD PRODUCTS: THEORETICAL MODELS AND PRACTICAL MEASUREMENTS

Radu ROŞCA[1], Aida ALBU, Petru CÂRLESCU[1], Ioan ȚENU[1]

e-mail: rrosca@uaiasi.ro

Abstract

Thermo-physical properties are necessary for the design and prediction of heat transfer operation during handling, processing, canning, and distribution of foods. Thermal conductivity is defined as the ability of a material to conduct heat. There are steady-state and transient-state methods for measurement of thermal conductivity. The most commonly used transient methods are the thermal conductivity probe method, transient hot wire method, modified Fitch method, point heat source method, and comparative method. In this paper the modified Fitch method was used in order to measure thermal conductivity; the results were compared with the one predicted by some heat conductivity models: series model, parallel model, the weighted geometric mean method. Experimental tests and calculations were applied to the following food items: dry salami (salam uscat CrisTim); Transylvanian salami (salam ardelenesc); rustic sausage (parizer ţărănesc Caroli). The experimental tests were performed immediately after the products were purchased and then repeated after they were stored for one week, at 6°C. The results show that the series model adequately describes the heat conductivity for dry salami and rustic sausage, while the weighted geometric mean model is more appropriate Transylvanian salami, which has the lowest water content and the highest fat content.

Key words: heat conductivity, composition, Fitch method

Thermo-physical properties are necessary for the design and prediction of heat transfer operation during handling, processing, canning, and distribution of foods. Thermo-physical properties of foods include different types of parameters associated with the heat transfer operations of food processing. Heat transfer involves the transfer of heat into or out of a food; thermal conductivity is defined as the ability of a material to conduct heat (Sahin S., Sumnu S.G., 2006).

In porous solids such as foods, thermal conductivity depends mostly on composition but also on many factors that affect the heat flow paths through the material, such as void fraction, shape, size and arrangement of void spaces, the fluid contained in the pores, and homogeneity (Sweat W.E., 1994).

Thermal conductivity in foods having fibrous structures such as meat cannot be the same in different directions (anisotropy) because heat flow paths through the material change with respect to direction.

Thermal conductivities of food materials vary between that of water (λ_{water} = 0.614 W/m·K at 27◦C) and that of air (λ_{air} = 0.026 W/m·K at 27◦C), which are the most and the least conductive components in foods, respectively. The thermal conductivity values of the other food components fall between these limits. Dry porous solids are very poor heat conductors because the pores are occupied by air. For porous materials, the measured thermal conductivity is an apparent one, called the effective thermal conductivity. It is an overall thermal transport property assuming that heat is transferred by conduction through the solid and the porous phase of the material (Sahin S., Sumnu S.G., 2006).

Due to the inherent biological variation of food products it is unreasonable to expect the accuracy of predicted thermal conductivities to be better than ±5%. For design purposes, accuracies to within ± 10% are usually sufficient for thermal conductivity data, which, depending on the food in question, can often be achieved with relatively simple thermal conductivity models (Carson J.K., 2017).

There are steady-state and transient-state methods for measurement of thermal conductivity. Although steady-state methods are simple in the mathematical processing of results, the long time necessary for the measurement makes transient methods more preferable for foods. The most commonly used transient methods are the thermal conductivity probe method, transient hot wire

[1] „Ion Ionescu de la Brad” University of Agricultural Sciences and Veterinary Medicine, Iasi

method, modified Fitch method, point heat source method, and comparative method (Sahin S., Sumnu S.G., 2006). In this paper the modified Fitch method was used in order to measure thermal conductivity; the results were compared with the ones predicted by some heat conductivity models.

MATERIAL AND METHOD

The schematic of the modified Fitch apparatus is shown in *figure 1*. The modified Fitch method is based on heat transfer through the disc-shaped sample, which is placed between a copper rod and a copper disc. The disc and rod act as a heat source and sink, respectively.

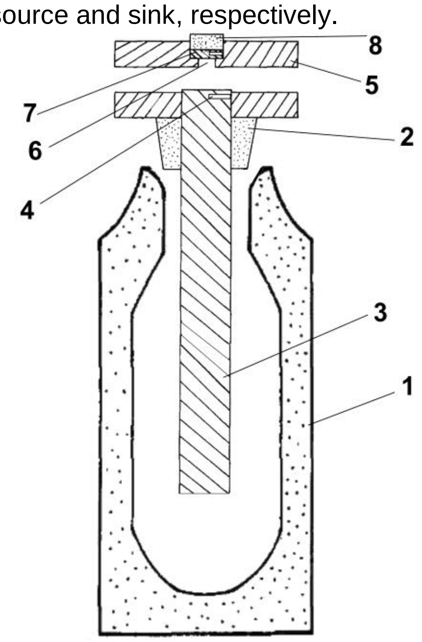

Figure 1 **Schematics of the modified Fitch apparatus**
1-vacuum flask; 2, 8-cork plugs; 3-copper rod; 4-thermocouple bore; 5-cork head; 6-sample compartment; 7-copper disc.

The product is placed in the sample compartment (6), being in direct contact with the copper disk (7); when the head (5) is placed over the cork plug (2), the product makes contact with the copper rod (3).

The copper rod (3) is inserted into a Dewar flask, filled with water and ice; after reaching the thermal equilibrium (at least 2 hours), the upper face of the copper rod reaches 0.7...1.2 ^{0}C.

The evaluation of the heat conductivity of the sample is based on the heat transfer from the copper disk (7), through the sample, to the copper rod. The temperature of the copper rod remains constant due to its mass, while the temperature of the product decreases during the heat transfer.

Type K thermocouples are used in order to measure the temperatures of the copper rod and product (the temperature of the product is assumed to be equal with the temperature of the copper disc 7).

Considering the steady-state, one-dimensional heat conduction from the copper disk through the product results in the following equation (Rahman, 1991; Singh et al., 1997):

$$S \cdot \frac{\lambda}{\delta} \cdot (T - T_s) \cdot d\tau = m \cdot c_{Cu} \cdot dT,$$

where S is the heat transfer area, λ is the conductivity of the product, δ is the thickness of the product, T is the instantaneous temperature of the product, T_s is the copper rod temperature (constant), $d\tau$ is the time needed for the product temperature to decrease with dT, m is the mass of the copper disk and c_{Cu} is the specific heat of copper. The left term represents the conductive heat transfer and the right term represents the sensible heat.

Solving the differential equation finally leads to:

$$\ln \frac{T_0 - T_s}{T - T_s} = \frac{\lambda \cdot S}{\delta \cdot m \cdot c_{Cu}} \cdot \tau,$$

where T_0 is the initial temperature of the sample (when τ=0, T=T_0).

From the above equation it is clear that the graphic representation of $\ln \frac{T_0 - T_s}{T - T_s} = f(\tau)$ is a first order polynomial and the term $\frac{\lambda \cdot S}{\delta \cdot m \cdot c_{Cu}} = M$ is the slope of the line representing the polynomial; based on the slope M, the thermal conductivity of the product is:

$$\lambda = \frac{\delta \cdot m \cdot c_{Cu} \cdot M}{S}.$$

In practice, in order to measure the thermal conductivity, the temperatures T_s and T are measured at equal time intervals and the function $\ln \frac{T_0 - T_s}{T - T_s} = f(\tau)$ is represented (*figure 2*). The slope M may be obtained using the equation of the regression line (as in *figure 2*, using only the linear part of the characteristic, without taking into account the initial non-linear part); a more precise method consists in calculating the arithmetic mean of the individual slopes between two successive points (i and i+1, *figure 3*):

$$m_i = \frac{\Delta i}{\Delta \tau_i}, \quad M = \frac{1}{n} \cdot \sum_{i=1}^{n} m_i.$$

The tests were performed until the product placed into the sample compartment (*6, figure 1*) has reached approximately the same temperature as the copper rod (3).

The modified Fitch apparatus which was used for performing the tests had the following features:

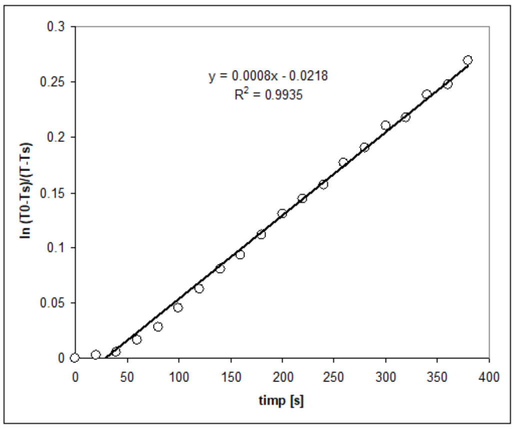

Figure 2 **Representation of the experimental data**
(M = 0.008)

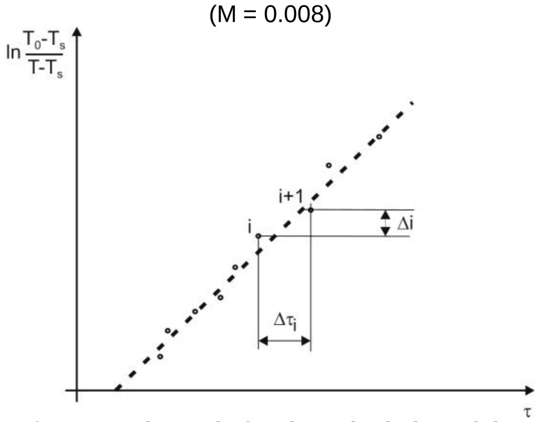

Figure 3 **Schematic for the calculation of the individual slope**

- height of the product sample compartment: $\delta = 7{\cdot}10^{-3}$ m;
- diameter of the product sample compartment: $d = 8{\cdot}10^{-3}$ m;
- area of the heat transfer surface: $S = 5{,}024{\cdot}10^{-5}$ m^2;
- specific heat of copper: $c_{Cu} = 385$ J/kg·K;
- diameter of the copper disk: $d_{Cu} = 16{,}4{\cdot}10^{-3}$ m;
- mass of the copper disk: $9{,}71{\cdot}10^{-3}$ kg;
- diameter of the copper rod: 20 mm.

The experimental results were used in order to verify and validate several mathematical models for thermal conductivity, based on food composition. The main components taken into account were water, carbohydrates, proteins, ash, fat; for temperatures below 0^0C, the ice fraction should also be considered.

The thermal conductivity of the individual components was calculated with the relations (ASHRAE 2006; Sahin S., Sumnu S.G., 2006):

$$\lambda_{H2O} = 0{,}57109 + 1{,}7625 \cdot 10^{-3} \cdot t - 6{,}7036 \cdot 10^{-6} \cdot t^2,$$

$$\lambda_{CHO} = 0{,}20141 + 1{,}3874 \cdot 10^{-3} \cdot t - 4{,}3312 \cdot 10^{-6} \cdot t^2,$$

$$\lambda_{proteins} = 0{,}17881 + 1{,}1958 \cdot 10^{-3} \cdot t - 2{,}7178 \cdot 10^{-6} \cdot t^2,$$

$$\lambda_{fat} = 0{,}18071 - 2{,}7604 \cdot 10^{-4} \cdot t - 1{,}7749 \cdot 10^{-7} \cdot t^2,$$

$$\lambda_{ash} = 0{,}32961 + 1{,}4011 \cdot 10^{-3} \cdot t - 2{,}9069 \cdot 10^{-6} \cdot t^2,$$

where t is the temperature [^{0}C].

Food products are poly-phase systems; some single-step heat conductivity models consider that food components are in layers parallel or perpendicular to the heat flow direction (Carson, 2006; Carson *et al.*, 2016).

For the parallel model (*figure 4a*), heat conductivity is given by the relation:

$$\lambda_{pa} = \sum_{i=1}^{n} \lambda_i \cdot \mu_i^v,$$

where λ_i is the heat conductivity of the component and μ_i^v is the volumetric fraction of the respective component.

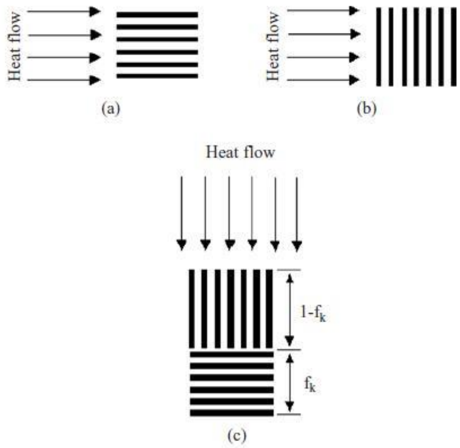

Figure 4 **Models for the calculation of heat conductivity**

The volumetric fraction is calculated using the mass fraction μ_i and density ρ_i of each component:

$$\mu_i^v = \frac{\mu_i / \rho_i}{\sum_{i=1}^{n} \mu_i / \rho_i}.$$

The mass fractions were obtained through direct chemical analysis of the products; the following formulae were used in order to evaluate the density (ASHRAE 2006; Sahin S., Sumnu S.G., 2006):

$$\rho_{H2O} = 997{,}18 + 3{,}1439 \cdot 10^{-3} \cdot t - 3{,}7574 \cdot 10^{-3} \cdot t^2,$$

$$\rho_{CHO} = 1599{,}1 - 0{,}31046 \cdot t,$$

$$\rho_{proteins} = 1329{,}9 - 0{,}51814 \cdot t,$$

$$\rho_{fat} = 925{,}59 - 0{,}41757 \cdot t - 1{,}7749 \cdot 10^{-7} \cdot t^2,$$

$$\rho_{ash} = 2423{,}81 - 0{,}36589 \cdot t.$$

The parallel model provides the upper limit of heat conductivity (Carson J.K., 2017).

The series model (*figure 4b*) takes into account layers which are perpendicular to the direction of heat flow; in the case, the heat conductivity is given by the relation:

$$\lambda_{sa} = \frac{1}{\sum_{i=1}^{n} \frac{\mu_i^v}{\lambda_i}}.$$

This model provides the lower limit of thermal conductivity (Carson J.K., 2017).

The Krischer model (*figure 4c*) combines the serial and parallel models using a phase distribution factor f_k (Sahin S., Sumnu S.G., 2006):

$$\lambda_{pa_k} = \frac{1}{\frac{1-f_k}{\lambda_{pa}} + \frac{f_k}{\lambda_{sa}}}.$$

It should be noted that, in this case, the phase distribution factor should be evaluated by the means of experimental tests.

Rahman developed a model based on the weighted geometric mean of the constituents (Fricke and Becker, 2001):

$$\lambda_a = \prod_{i=1}^{n} \lambda_i^{\mu_i^v}.$$

In this paper the above-mentioned models were used in order to calculate the thermal conductivity and the calculated results were compared with the ones obtained during the experimental tests performed with the modified Fitch apparatus.

The experimental tests and calculations were applied to the following food items:

- dry salami (salam uscat CrisTim);
- Transylvanian salami (salam ardelenesc);
- rustic sausage (parizer ţărănesc Caroli).

The experimental tests were performed immediately after the products were purchased and then repeated after they were stored in a refrigerator for one week, at 6^0C.

RESULTS AND DISCUSSION

Heat conductivity was measured with the modified Fitch apparatus. *Table 1* presents a sample of the experimental data recorded during the tests for rustic sausage; the corresponding graphic interpretation of the results is shown in *figure 5*. Graphical representations for the other two types of products are shown in *figure 6* and *7*.

Table 1

Experimental data for rustic sausage

Time	T_0 [^{0}C]	T_S [^{0}C]	T [^{0}C]
0	25.3	0.7	25.3
20″	-	0.7	25.2
40”	-	0.7	25.0
1’	-	0.7	24.8
1’20”	-	0.7	24.5
1’40”	-	0.7	24.2
2’	-	0.7	23.9
2’20”	-	0.7	23.5
2’40”	-	0.7	23.2
3’	-	0.7	22.9
3’20”	-	0.7	22.6
3’40”	-	0.7	22.3
4’	-	0.7	22.0
4’20”	-	0.8	21.8
4’40”	-	0.8	21.5
5’	-	0.8	21.2
5’20”	-	0.8	20.9
5’40”	-	0.8	20.7
6’	-	0.8	20.5
6’20”	-	0.8	20.2

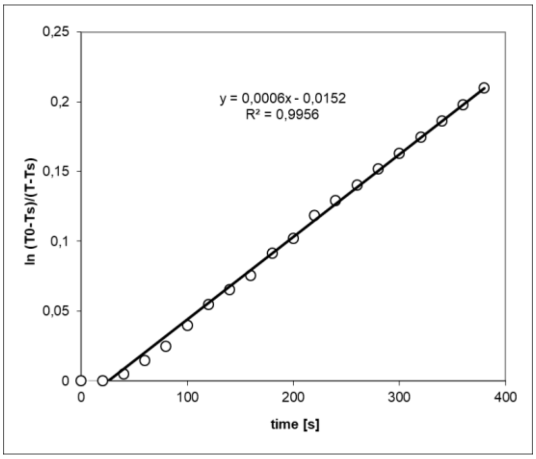

Figure 5 **Graphic representation of the experimental results for rustic sausage (λ=0.314 W/m·K)**

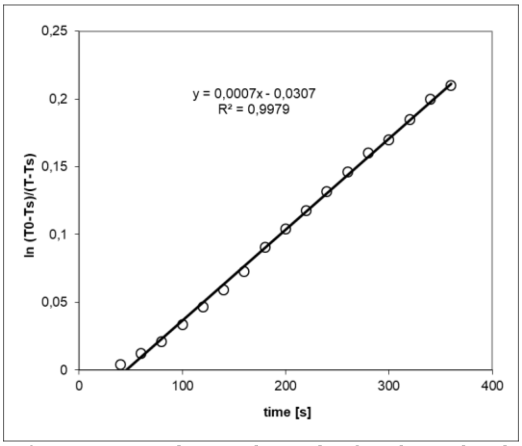

Figure 6 **Experimental results for dry salami (λ=0.321 W/m·K)**

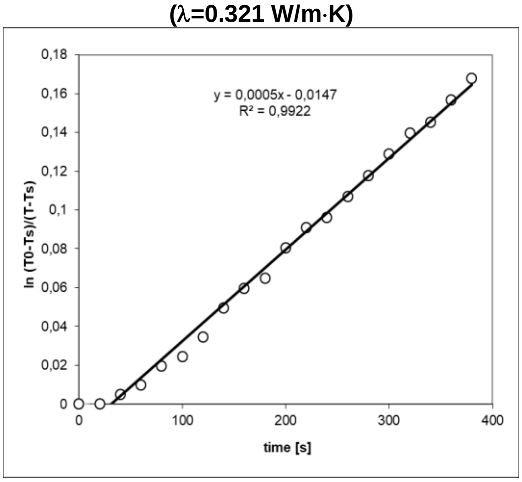

Figure **7 Experimental results for Transylvanian salami (λ=0.243 W/m·K)**

Table 2 summarizes the results of the experimental tests regarding the heat conductivity of the food products. The results show that that there was a slight increase of product heat conductivity after storage. However, the analysis of significance showed that there is no significant difference between the initial values and the ones recorded after storage. However, lower values of the standard error were recorded after long term storage, suggesting that the measurements should be performed some days after purchasing the food products.

Table 2

Experimental results regarding the heat conductivity of the products [W/m·K]

Product	Replicates			Mean	Rel. std. err. [%]
	1	2	3		
Initial					
Trans. salami	0.300	0.243	0.255	**0.266**	6.52
Dry salami	0.321	0.281	0.275	**0.292**	4.94
Rustic saus.	0.364	0.310	0.314	**0.329**	5.27
After 1 week storage at 6^0C					
Trans. salami	0.277	0.278	0.283	**0.279**	0.662
Dry salami	0.321	0.287	0.275	**0.294**	4.66
Rustic saus.	0.332	0.335	0.347	**0.338**	1.33

The results are in accordance with the findings of other authors, showing that the heat conductivity increases with moisture content (ASHRAE, 2006).

In order to apply the heat conductivity models the food products were analysed; *Table 3* summarizes the results of the chemical analysis.

Table 3

Results of the chemical analysis (average values)

Component	Transylvanian salami	Dry salami	Rustic sausage
Water, %	33.033	50.156	63.353
Ash, %	4.633	3.493	2.693
Fat, %	45.653	27.046	19.820
Proteins, %	16.380	17.743	11.117

Based on the product composition, heat conductivity was calculated using the parallel, series and geometric mean models; the results are summarized in *table 4*.

Table 4

Calculated results for heat conductivity [W/m·K]

Product	Parallel model	Series model	Geom. mean model
Trans. salami	0.328	0.239	**0.276**
Dry salami	0.408	**0.293**	0.347
Rustic sausage	0.463	**0.343**	0.406

An analysis of significance was performed over the measured and calculated results; the analysis led to the following conclusions:

- both the experimental and model data led to the conclusion that the rustic sausage has the highest thermal conductivity, probably because of its high water content;
- the other two types of salami have lower conductivities and the results are significantly different ($p<0.05$);
- for Transylvanian salami there was no significant difference between the value predicted by the geometric mean model and the measured value ($t_{calc} = 2.132<2.776=t_{0.05}$);
- for dry salami there was no significant difference between the value predicted by the series model and the measured value ($t_{calc} = 0.097<2.776=t_{0.05}$);
- for rustic sausage there was no significant difference between the value predicted by the series model and the measured value ($t_{calc} = 1.091<2.776=t_{0.05}$).

The results regarding the series and mean geometric models are in accordance with the findings of other authors (Carson *et al.*, 2016, mention the geometric mean model as being the most accurate for pork sausage meat; Fricke and Becker, 2001, confirmed the validity of the series model for other products than poultry, while mentioning that the parallel model over predicted the thermal conductivity of all foods taken into account).

For the abovementioned models the differences between the predicted values and the experimental data did not exceed 5%.

Using the results given by the series and parallel model, the phase distribution factor used in the Krischer model was calculated and the results are presented in *table 5*.

Table 5

Values for the phase distribution factor f_k

Product	Trans. salami	Dry salami	Rustic sausage
f_k	0.895	0.854	0.100

CONCLUSIONS

The modified Fitch method was used in order to measure the heat conductivity of three types of food items and the experimental results were then compared with the ones predicted by some heat conductivity models.

Although there were no significant differences between the values of heat conductivity before and after the one-week cold storage, the lower values of standard error recorded after storage suggest that it would be better not to perform the measurements immediately after the products were purchased.

The values given by the parallel model are significantly higher than the experimental ones, leading to the conclusion that this type of model is not adequate for predicting the heat conductivity of salami type food products.

The experimental data seem to suggest that the series model adequately describes the heat conductivity for dry salami and rustic sausage, while the weighted geometric mean model is more appropriate Transylvanian salami. At first glance it seems that the weighted geometric mean model would be more appropriate for food products with low water content and high fat content, but further tests should be performed in order to validate this assumption.

The values of the phase distribution factor in the Krischer model were roughly in the same range for dry salami and Transylvanian salami, while providing values eight times lower for rustic sausage.

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