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Investigation of thermal conductivity of orange and tangerine juices in non-stationary state

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Abstract. Thermal conductivity is one of the main thermophysical properties of liquid food products, including fruit and vegetable juices. Known experimental installations measure the thermal conductivity of stationary liquids. This results in significant deviations from the actual numbers. A method of determining the thermal conductivity of a fluid in motion and an experimental installation implementing the proposed method are suggested. The developed experimental installation consists of two coaxial cylinders: internal and external. A gap between cylinders is filled with analysed liquid. The object of the study was the juices of subtropical fruits, such as oranges, tangerines grown in the subtropical regions of the Republic of Azerbaijan. In this work, the thermal conductivity of juices was also investigated during forced movement on an installation also consisting of two coaxial cylinders. Experimental measurements of thermal conductivity for orange and mandarin juices were carried out. Experiments were carried out at frequencies from 50, 100, 150 and 200 s-. A general description of the dependence of thermal conductivity on temperature, dry matter concentration and rotational speed made it possible to develop a model, in particular for orange juice. The described method and experimental installation for measuring the thermal conductivity of a liquid in a non-stationary state made it possible to develop a mathematical model describing the dependence of thermal conductivity on temperature, dry matter content and cylinder speed.

1 Introduction

The thermophysical properties (TPP) of food products have a great influence on heat and mass transfer processes, especially such as density, viscosity, thermal conductivity, heat capacity of the product, etc., depending on the type of a product, its temperature, concentration and pressure over the product [1, p. 210; 2, p. 6; 3, p. 196-198].

The validity of the results of such calculations is closely related to the thermophysical characteristics (TPC) of food products of plant and animal origin [2, p. 7; 4, p. 125-132].

Although many alternative heat treatment approaches have been tested and successfully proposed for juices [5, p. 501-523], heat treatment remains the most cost-effective tool for ensuring microbial safety and enzyme deactivation [6, p.1875-1887]. Some disadvantages of thermal processes are slow thermal conductivity and convection heat transfer [7, p.299-

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304], as well as the negative effect of excessive processing on sensory, food and functional properties [8, p. 121-130]. In most cases, these effects are highly dependent on the food matrix [9, p. 33-43; 10, p. 380-389]. Moreover, the efficiency of the heat treatment can also be influenced by the complexity of the product and the presence of microorganisms [11, p. 981-986].

Preservation of organoleptic indices of food products is a key goal of the food industry. As a result, optimization of heat treatment is a key tool for maintaining balance between safety and nutritional qualities of raw materials [12, p. 7734-7743]. In addition to traditional heat treatment, there are some other unconventional thermal approaches (ohmic and microwave heating) which have some advantages, such as better energy efficiency, lower capital costs and shorter processing times [13, p. 43-51; 14, p. 83-88].

It is known that thermal conductivity (λ) is one of the main thermophysical properties of liquid food products, including fruit and vegetable juices [2, p. 6; 15, p. 668-691]. Information on the thermal conductivity of liquid food products is given in a number of works, in particular [2, p. 120-136; 16, p. 27-28; 17, p. 36-38; 18, p. 26-29; 19, p. 94-106; 20, p. 27-40].

However, in these works, experimental work was carried out only at atmospheric pressure, and many thermal devices and installations used in the technological processes of the food industry work at increased pressures. At the same time, there is no data on the thermal conductivity of the juices of subtropical fruits, especially orange and tangerine juices, characteristic of the Republic of Azerbaijan.

In addition, all experimental installations known to us measure the thermal conductivity of liquids in a stationary state. In devices used in various food processing lines and in particular in the production and processing of liquid food products, as a rule, the main substance is in a moving state. Since there is no data available in the literature for such liquids, in practice stationary liquid data have to be used. This leads to significant deviations in calculations from actual figures, especially in thermal calculations of process units and plants.

2 Objects and methods of research

Juices of subtropical crops, such as oranges and tangerines grown in subtropical regions of the Republic of Azerbaijan and meeting the requirements of existing standards, were used as the object of the study. Juices from these fruits were produced according to the generally accepted technology [21].

The following objects have been studied:

- orange juice at 278.1-393.1 K and concentrations of 14, 20, 25, 30 and 40%;
- tangerine juice 293.15-363.15 K and 10.7, 20, 30, 40 and 50%.

The thermal conductivity of juices was studied by the method of coaxial cylinders in a stationary mode. The measuring cell was placed in a massive copper block acting as a thermostat. Measurements were carried out by a relative method. The studied interval was 278... 393 K at pressures up to 5 MPa and a mass fraction of soluble dry substances up to 50% [2, p. 126-136].

In order to eliminate the above-mentioned drawbacks, we suggest a method for determining the thermal conductivity of a liquid in motion and an experimental installation implementing the proposed method. The developed experimental installation consists of two coaxial cylinders: internal and external. The outer cylinder is stationary. Rotation of the inner cylinder is carried out by a special motor with a controlled speed of cylinder rotation. Clearance between cylinders is filled with analysed liquid. The operating principle of the plant is described in [2, p. 122-125].

The weight fraction of dry soluble substances in the juices was determined by refractometric method.

3 Results of the experiment and discussion

The work carried out a study of the thermal conductivity of orange and tangerine juices using a cylindrical calorimeter. The experiments were carried out both at atmospheric pressure and at elevated pressures and temperatures above the normal boiling point.

The experimental data at different temperatures and concentrations are shown in Table 1.

Table 1. Thermal conductivity of orange juice (λ, Vt/m·K)

T, K	Solids content				
	14%	20%	25%	30%	40%
278.1	0.52	0.503	0.485	0.47	0.44
283.1	0.53	0.51	0.495	0.48	0.45
293.1	0.542	0.521	0.503	0.486	0.463
313.1	0.565	0.544	0.525	0.508	0.48
333.1	0.58	0.558	0.539	0.522	0.493
353.1	0.598	0.576	0.557	0.539	0.51
373.1	0.615	0.592	0.573	0.555	0.525
393.1	0.625	0.601	0.583	0.564	0.535

As shown in Table 1, the thermal conductivity is highly dependent on both the solids content and the temperature. From the results of the studies given in Table 1, it can be seen that per unit percentage of dry substances the change in thermal conductivity corresponds to 0.7%, or 0.003 *Vt/m·K*. Temperature also has a significant impact. So, according to the tables, by 10 K thermal conductivity increases on average by 0.01-0.012 *Vt/m·K*.

In the work, the thermal conductivity of juices was also studied during forced movement on the installation described in [2, p.126-127; 22, p. 277-278]. Experimental measurements of λ for orange and mandarin juices were carried out. Experiments were carried out at frequencies from 50, 100, 150 and 200 s^{-1}. For orange and tangerine juices, 45 experimental values of the thermal conductivity coefficient were obtained at temperatures of 293, 333 and 363 K. For the experiments, natural juice was used at a concentration of 14%, as well as concentrated at 25% and 45%.

Tangerine juice was studied at a concentration of 11.0%, 25.0% and 45.0% and temperatures of 293, 333 and 363 K.

Experimental values of thermal conductivity under forced motion are given in Table 2.

Table 2. Thermal conductivity with forced movement of orange and tangerine juices depending on temperature and frequency

Orange juice									
n, 1/s	C=14%			C=25%			C=45%		
	293	333	363	293	333	363	293	333	363
0	0.52	0.542	0.58	0.598	0.485	0.503	0.539	0.557	0.497
50	0.524	0.547	0.585	0.603	0.49	0.508	0.544	0.564	0.504
100	0.528	0.552	0.591	0.609	0.494	0.513	0.55	0.572	0.512
150	0.534	0.556	0.596	0.614	0.498	0.517	0.555	0.579	0.519
200	0.538	0.561	0.604	0.621	0.503	0.523	0.562	0.587	0.526
Tangerine juice									
n, 1/s	C=11,0%			C=25,0%			C=45,0%		
	293	333	363	293	333	363	293	333	363
0	0.530	0.58	0.607	0.515	0.55	0.575	0.445	0.474	0.497

50	0.542	0.585	0.614	0.52	0.556	0.582	0.45	0.479	0.504
100	0.549	0.59	0.622	0.525	0.562	0.59	0.454	0.484	0.512
150	0.555	0.595	0.63	0.529	0.567	0.597	0.457	0.49	0.519
200	0.56	0.6	0.637	0.534	0.573	0.605	0.463	0.494	0.526

The effect of temperature on the thermal conductivity of orange juice is shown in Figure 1.

Figure 2 shows how the thermal conductivity of fruit juices changes with increasing cylinder speed. Analysis of the obtained values λ shows that the thermal conductivity is significantly dependent on the rotation speed of the cylinder. With an increase in this parameter λ rises, and this dependence is more pronounced at room temperatures.

A diagram of thermal conductivity versus temperature and speed is shown in Figure 3. As the temperature increases, the slope of the curves $\lambda(n)$ decreases.

It is of interest to establish a correlation of the change in thermal conductivity from temperature with the increase in dry matter content. The analysis shows that in a more concentrated juice, the effect of S affects more.

The graph of the thermal conductivity of the juice versus temperature at different speeds (for different concentrations) shown in Figure 2 shows that the effect of S in the more concentrated juice is greater.

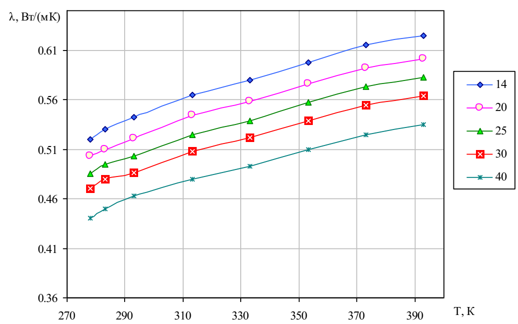

Fig. 1. Thermal conductivity of orange juice depending on temperature

A diagram of thermal conductivity versus temperature and speed is shown in Figure 3. As the temperature rises, the slope of the? (S) curves decreases. It is of interest to establish a correlation of the change in thermal conductivity from temperature with the increase in dry matter content.

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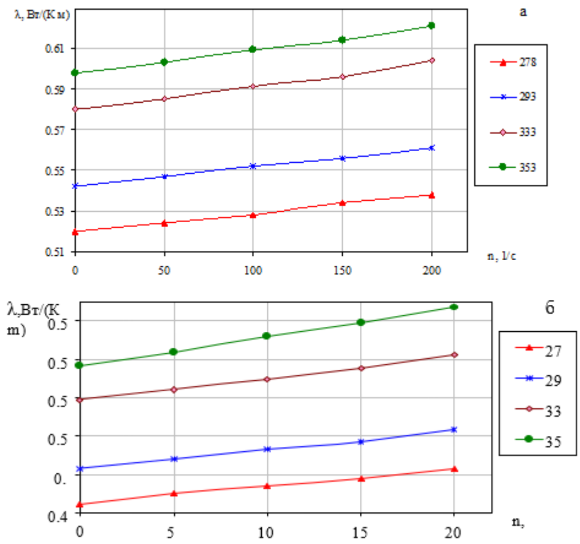

Fig. 2. The dependence on the rotation speed of the cylinders for orange juice at a dry matter content of 14% (a) and 25% (b)

For practical purposes, it is necessary to have an equation describing experimental data depending on the state parameters [2, p. 122-125; 23, p. 106-109]. Analysis of the obtained data made it possible to determine in an analytical form the dependence of the thermal conductivity of juices in a non-stationary state on the speed of rotation.

The proposed model has the form:

$$\lambda = A + Bn \tag{1}$$

The values of coefficients A and B are shown in Table 3.

Table 3.

Value of A and B coefficients					
Orange juice, 14,0%			Orange juice, 25,0%		
T, K	*A*	*B*	*T, K*	*A*	*B*
278	0.520	0.000092	278	0.0.485	0.000088
293	0.542	0.000094	293	0.503	0.000098
333	0.579	0.00018	333	0.539	0.00011
353	0.578	0.00011	353	0.557	0.00015

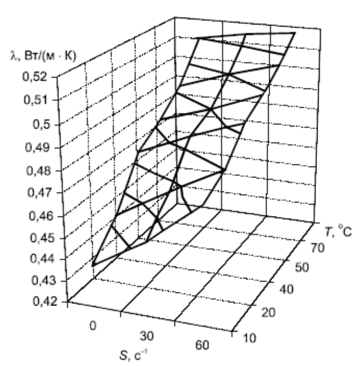

Fig. 3. Diagram of the Dependence on Temperature and Frequency

A general description of the dependence of thermal conductivity on temperature, dry matter concentration and rotation speed made it possible to develop a model, in particular for orange juice, the mathematical expression of which is:

$$\lambda = 0.572 + 9.4\ 10^{-4}\ T - 3.37\ 10^{-3}\ C + 3.5\ 10^{-4}\ S \tag{2}$$

The equations describe experimental data with an error of 1.5-2.0%.

4 Conclusions

Thus, for the first time, a method for measuring the thermal conductivity of orange and tangerine juices in a non-stationary state has been proposed and an installation implementing this method has been developed. With the help of this plant, for the first time, data on the thermal conductivity of juice in a non-stationary state were obtained, which make it possible to carry out the thermal calculation of devices more accurately, which reduces the energy consumption for the production of finished products. Based on the obtained experimental values of thermal conductivity values, we proposed an equation in an analytical form that establishes the connection of the two analysed properties with each other and with temperature.

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