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Thermophysical and chemical characteristics of tropical fruits

Características termofísicas y químicas de las frutas tropicales

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ABSTRACT

When developing canning technologies raw material processing processes thermophysical calculations are inevitably used. This work's purpose is to analyze the tropical fruits thermophysical characteristics. The research objects were the following fruits: kiwi, papaya, avocado and figs. The stationary flat layer method was used to analyze the thermal conductivity. The cryoscopic temperature was determined by the thermogram flat surface which was obtained during the product freezing. The hydrostatic weighing method was used to determine the density. The sugar content was determined using the refractometric method. The moisture content was determined by drying-out to a constant mass. As a result of the carried out work, the physical and chemical parameters of kiwi, avocado, papaya and figs were determined. The thermophysical properties of tropical fruits such as heat capacity, cryoscopic temperature, thermal conductivity, and the amount of frozen moisture, were calculated.

Keywords: papaya, kiwi, avocado; fig; thermophysical properties.

RESUMEN

Al desarrollar tecnologías de enlatado, los procesos de procesamiento de materias primas inevitablemente se utilizan cálculos termofísicos. El propósito de este trabajo es analizar las características termofísicas de las frutas tropicales. Los objetos de investigación fueron las siguientes frutas: kiwi, papaya, aguacate e higos. Se utilizó el método de capa plana estacionaria para analizar la conductividad térmica. La temperatura crioscópica fue determinada por la superficie plana del termograma que se obtuvo durante la congelación del producto. Se utilizó el método de pesaje hidrostático para determinar la densidad. El contenido de azúcar se determinó mediante el método refractométrico. El contenido de humedad se determinó por secado hasta masa constante. Como resultado del trabajo realizado se determinaron los parámetros físicos y químicos de kiwi, aguacate, papaya e higos. Se calcularon las propiedades termofísicas de las frutas tropicales, como la capacidad calorífica, la temperatura crioscópica, la conductividad térmica y la cantidad de humedad congelada.

Palabras claves: papaya, kiwi, aguacate; higo; propiedades termofísicas.

1. INTRODUCTION

The food production field is regularly updated with newly invented canned products types and names. When developing canning technologies thermophysical calculations of raw material processing processes are inevitably used (Cornejo et al., 2016; Zabalaga et al., 2016). Processing can be thermal (blanching, pasteurization, cooking, drying, etc.) and refrigeration (cooling, freezing, freezing, thawing, thawing). In order to perform the appropriate calculations it is necessary to know the raw material base thermophysical characteristics (Fontan et al., 2018; Korotkiy et al., 2020; Neverov et al., 2019a, 2019b, 2021; Yancheva et al., 2018). Such main characteristics include the thermal conductivity coefficient and thermal conductivity, as well as the specific heat capacity (Dalmoro et al., 2018; Paluri et al., 2018; Zielinska et al., 2017). The freezing point is rarely used in the calculations. There are such thermophysical characteristics as the respiration heat of food plant origin raw materials and the fats solidification heat. But in practice they are usually not used in calculations (Filippov & Stepanov, 2015).

Tropical fruits and vegetables are able not only expand the people diet. They can also be used as vitamin supplements in the functional products production. They are widely used, for example, as an additive in fermented dairy products-yoghurts, cheeses, curds, in the confectionery industry, when added to ice cream, etc. (Lima et al., 2017; Pereira et al., 2018) In many cases, heat or refrigeration treatment is used and thermophysical characteristics knowledge is necessary to calculate the corresponding technological processes (Mohd Ali et al., 2020; Nowak et al., 2018; Zocoler de Mendonça & Lopes Vieites, 2019). Thus the research of the tropical fruits thermophysical characteristics is an actual task.

One of the thermophysical characteristics is the thermal conductivity coefficient, it should be determined experimentally. There are some factors that distort the thermal conductivity coefficient obtained experimentally. Some of them depend on the properties of the test substance, some are associated with the measurement method.

These factors include:

Heat leakage. This problem exists in installations where the amount of heat passed through the product is measured using two devices an ammeter and a voltmeter. However, in our time, there are devices that can help solve these problems. These are the so-called electronic heat flow meters. The digital screen of such device shows the heat flow which is passing through the heat flow sensor in real time with changes every second, in W/m2. Multiplying this indication by the surface area coefficient of the test sample can accurately determine the heat flow passing through its surface in real time.

The next negative factor is the heat which is transmitted from the installation heater by radiation. However the correction for radiation in the research of non-gaseous substances is usually not taken into account.

When convective heat transfer occurs in the test substance layer it affects the measurements accuracy. It is easy to imagine that when studying a air layer with a height of several centimeters, as a convection result its temperature field will be equalized, that is, it will be the same throughout the entire volume. It is necessary to obtain the temperature difference on the product isothermal surfaces for proper analysis. This factor does not apply to fruit and vegetable products since it is represented by solid bodies and the gas component of such bodies as the fruits of pears, apples and others does not distort the indications of experimental data in any way due to its distribution over the volume of the product.

The temperature jump at the solid-gas interface also applies to the gases thermal conductivity measurement and does not apply to fruit and vegetable products. The problem in this case is that the real temperature gradient in the test substance layer is less than on its isothermal surfaces as a result of the small test substance density. This does not apply to solid bodies since their molecules are tightly adjunct each other and heat transfer is better.

The factors that affect the accuracy of fruit and vegetable products thermal conductivity measurements include the accuracy in reproducing geometric shapes. Otherwise even a thickness difference of 1 mm on the product surface with a product layer thickness of 20 mm significantly distorts the obtained values. When the samples are manually cutting difficulties with reproducing the geometric shape are revealed. This problem is solved by using special devices-pads that hold the cutting knives in a strictly parallel position with strictly specified dimensions between the knives. The second way to solve this problem is to use simultaneously with the measuring tool pads with high measurement accuracy up to 0.1 mm of a caliper. It allows you to achieve the most correct geometric shape of the product samples.

The purpose of this work was to determine the thermophysical properties of tropical fruits. The research objects choice is determined by the following. Currently there is an increase in the tropical fruit and vegetable products export. However, the thermal data bases for these products are lagging behind, and it is often difficult to find out important thermal characteristics. In our country tropical fruits are relatively studied a little and one of the main reasons remains their price and rarity. In a short time this may be changed the cultivation of some tropical fruits in subtropical areas of our country is being mastered, the tropical fruits export is increasing, and therefore the demand for them. The demand of the population for fortified products, products with a functional purpose is growing. Based on the studies which were conducted in 2011 (Dubtsov & Lazar, 2011), it can be concluded that tropical fruits are quite popular in our country, and the top ten most popular according to social surveys include the following fruits pineapple, kiwi, coconut, avocado, banana, mango, pineapple guava, papaya, tangerines, oranges. In descending order of popularity they can be arranged as follows pineapple, banana, kiwi, avocado, mango, coconut, tangerine.

The kiwi, avocado, and papaya were selected from these fruits for the application in the developed plant, which is due to their high biological value (avocado and papaya are among the three richest in chemical composition) (Dubtsov & Lazar, 2011) and are the least studied in terms of thermophysical properties. The most sugar-containing tropical fruit was also selected for research, it’s figs, the sugar content of which can exceed 30%.

2. MATERIALS AND METHODS

The research objects were the following fruits: kiwi, papaya, avocado, figs.

The stationary flat layer method was used to determine the thermal conductivity. The plant scheme in which this method is implemented is shown in Figure 1.

The heating element is an incandescent lamp with a power of 40 W. The product is installed in the hole 3. Hereafter the thermocouples 5 and the heat flow probe 4 are connected to the product and the lid is tightly closed. The main heater 8 is switched on. It works until the temperature in the measuring cell reaches the set value. After that the heater 8 is switched off, and the compensation heater 2 is connected. A flexible heating element with a capacity of 320 W is used as a compensation heater. It provides a stable heat flow through the product and a stable temperature at its surface. The heat flow density is recorded by the sensor 4. The heat flow meter TSIT-2 ITP of the UralPromTek company acts as the sensor 4. Thermocouples 5 fix the temperature field on the product surfaces. Thermocouples 6 and 7 control the temperature of the heating and cooling gas layers at the surfaces of the test sample. After the stationary mode is established, the obtained temperatures on the product surfaces and the heat flow through the product are set about.

The measuring cell in this plant is represented by a rectangular hole in the upper wall of the heating chamber. The sample which is installed in this hole is in contact with the internal and external air. During the experiment the outdoor air parameters are taken into account. At the same time if you need to conduct an experiment with a frozen product then the entire plant is placed in the freezing chamber and when the product is completely frozen the controller and the heating element are turned on. Then when the system comes to heat balance the readings of the thermocouples and the heat flow sensor are taken and calculations are made. The height of the product layer in the cell can be different from 10 to 30 mm. The heat flow sensor fits snugly to the product through a layer of thermal paste for accurate heat flow measurement. Unit images in the presented Figures 2 and 3.

The thermal conductivity coefficient of the product sample was measured using the following formula:

$$\lambda_c = \frac{Q}{t_{c1}-t_{c2}}\Phi, \tag{1}$$

where Q – heat flow in stationary mode, W;

Φ – coefficient of the studied product shape;

tc1 and tc2 – temperatures on the sample isothermal sides, °C.

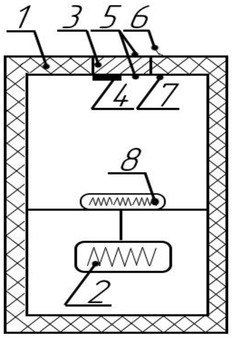

Figure 1. Plant diagram for measuring thermal conductivity
1 – body; 2 – main heating element; 3 – product sample mounting hole; 4 – heat low probe; 5 – thermocouples that measure the sample temperature difference; 6,7 – thermocouples that measure the outdoor and indoor air temperature; 8 – compensation heater

Figure 2: Installation side view

Figure 3: Installation top view

In this case the shape coefficient takes into account the sample geometric shape and it is determined by the following formula for a flat sample:

$$\Phi = \frac{\delta_c}{F}, \tag{2}$$

where δc – the flat layer thickness, m;

F – surface area to which the heat flow is applied, m2.

The product layer thickness was 20 mm. The layer thickness was measured with a caliper. Fruits were cut on specially constructed devices with parallel blades arranged for this purpose. By means of this it was possible to maintain the correct linear dimensions.

The thermal conductivity was determined in fresh and frozen form. In the first case the temperature inside the plant was maintained at 55±1°C. In the second case the temperature inside the plant was maintained at 10±1°C. The sample was taken at a temperature of minus 25±1°C. At a higher heating temperature the sample approaches the cryoscopic point in temperature and begins to melt. In order to reach a negative temperature on the cooled product surface the plant was placed in the freezing chamber.

The heat capacity was calculated using the following formula:

$$\mathrm{C} = 1{,}424 m_{\mathrm{y}} + 1{,}549 m_{\mathrm{b}} + 1{,}675 m_{\mathrm{g}} + 0{,}837 m_{\mathrm{z}} + 4{,}187 m_{\mathrm{v}} \tag{3}$$

where: m_y, m_b, m_g, m_z, m_v – mass fractions of carbohydrates, proteins, fats, ash and moisture, respectively.

When calculating the frozen fruits heat capacity the heat capacity of ice at a temperature of minus 5°C was also taken into account.

The product was peeled off the skin in order to determine the cryoscopic temperature. Then the thermocouples were installed in its geometric center on the surface and at the thermocouples calculated point. The temperature in the freezing chamber was kept at -15...-20°C. The experimental data was recorded every 30 seconds followed by computer processing and plotting.

The thermal conductivity coefficient was determined by calculation and experiment using the following formula:

$$\alpha = \frac{\lambda}{\rho \cdot C} \tag{4}$$

where:

α – thermal conductivity, m2/s;

λ - the substance thermal conductivity coefficient, W/(m·K);

ρ – the test substance density, kg/m3;

C – specific heat capacity, kJ/(kg·K).

The hydrostatic weighing method was used to determine the density. The sample was weighed using an electronic scale with an accuracy of 0.001 g. The material density according to the results of hydrostatic weighing was calculated by the formula:

$$\rho = \frac{P_1 \rho_g - P_2 \rho_v}{P_1 - P_2} \tag{5}$$

where:

P1 – the sample weight in the air, N;

P2 – the sample weight in liquid, N;

ρ_g – liquid density, kg/m3;

ρ_v – air density, kg/m3

The sugar content was determined according to GOST 15113.6-77 by the refractometric method.

The moisture content was determined according to GOST 15113.4-77 by drying to a constant mass.

The frozen moisture amount was determined by the following formula:

$$\omega = 1 - \frac{t_{kp}}{t} \tag{6}$$

where: t, t_{kp} –the values of the frozen product final average volume temperature and the cryoscopic temperature, taken by the absolute value accordingly.

ω – frozen moisture percentage (at cryoscopic temperature $\omega = 0$, at eutectic temperature-$\omega = 1$ or 100%)

This characteristic was calculated for products whose thermal conductivity was measured in frozen form, the data were taken from experiments.

3. RESULTS

Moisture content, density, and sugar content are important characteristics that affect thermophysical properties. Moisture content is the amount of water that is not chemically bound to the product, that is free moisture, which is represented in the form of water and aqueous solutions of sugars, salts and other juice components of fruit and vegetable products. Since water has a known thermal conductivity of 0.59 W / m·K it follows that the more moisture in the product the closer its thermal conductivity coefficient is to the thermal conductivity coefficient of water.

Density is a characteristic that is responsible for the location of the product molecules and its structure. The more gas inclusions, the lower the density is. The density also depends on the organic product composition. The higher the density, the higher the thermal conductivity is and vice versa.

Sugar content is an important product composition characteristic. It affects the thermal conductivity especially of frozen food, because sugar forms a sugar solution with water, which lowers the freezing point of the water in the product, the content of frozen moisture and thermal conductivity.

Data according to the research of the above characteristics are given in Table 1.

Table 1. Tropical fruits physical and chemical characteristics

Name	Moisture, %	Density, kg/m3	Sugar, %	Dry substances, %
Kiwi	83,87	1065	13	16,13
Avocado	77,42	928	-	22,58
Papaya	86,32	1049	11,5	13,68
Fig	80,65	754	16	19,35

The highest moisture content is observed in papaya fruits, and the highest density in kiwis. Figs predominate among all the studied products in terms of the sugars amount.

Figure 4 shows the thermogram which is obtained during the experimental determination of the papaya thermal conductivity coefficient. Figure 5 shows a graph of changes in the heat flow density.

The heat flow change can be divided into three stages. At the first stage during the first 15 minutes the plant enters the mode. The air temperature inside the plant increases from 22 to 56°C. At the second stage the heat flow density decreases. This stage is explained by the fact that the air is no longer heated and the surface of the product is heated. Therefore the temperature difference between them decreases and the heat flow decreases accordingly. Hereafter the chamber temperature is kept at 55°C. Stationary mode (3 stages) occurred after approximately 120 minutes. The temperature of the product heated and cooled surface was accordingly 39 and 31°C.

According to the research results the thermal conductivity coefficient was for papaya 0.37 W / m·K, for kiwi-0.56 W/m·K, for avocado-0.4 W/m·K, for figs-0.63 W/m·K.

Kiwi as a fruit is of particular interest for thermal conductivity research. The coefficient shown in this table is given for green kiwi pulp. The heat flow was directed parallel to the fruit fibers. It was revealed that the temperature field in the fruit is located unevenly. The thermal conductivity coefficient of the fruit white middle is less and is 0.42 W/m2. And the thermal conductivity coefficient at a heat flow which is directed perpendicular to the fibers is 0.49 W/m2. That’s why it’s possible to conclude that as a result of its structure, kiwi does not obey the law of additivity. Generally the kiwi thermal conductivity coefficient is closer to the water thermal conductivity due to the high moisture content.

The thermal conductivity coefficient of papaya in fresh form is similar to the apple thermal conductivity coefficient. This is due to its structure which is similar to the pumpkin and apple structure. The kiwi structure may contain gas inclusions that significantly reduce the thermal conductivity.

The avocado relatively low thermal conductivity is also explained by its structure. This is also caused by the relatively low moisture content and high fat content.

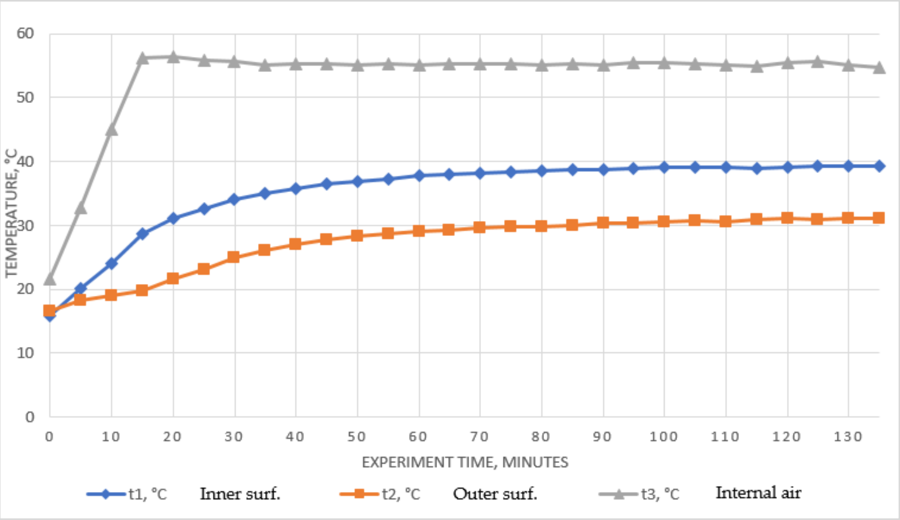

Figure 4. Thermogram of the papaya thermal conductivity determining process: t1 – the sample heated surface temperature; t2 – the sample cooled surface temperature; t3 – air temperature inside the plant

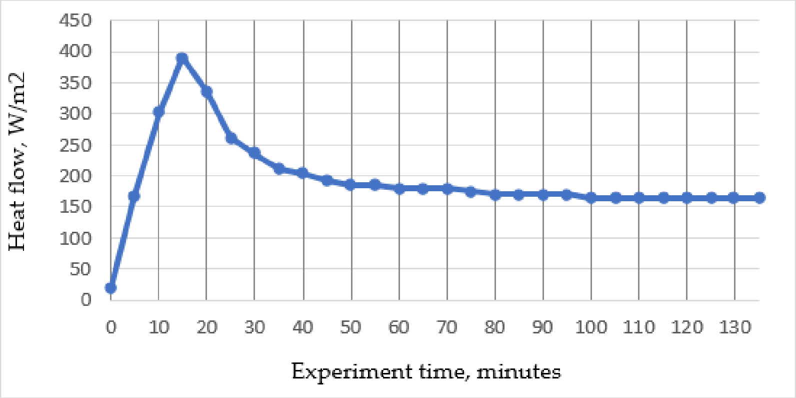

Figure 5. Diagram of the heat flow density in determining the papaya thermal conductivity coefficient

Figs have a higher thermal conductivity than water. This is due to the fact that the water which is contained in figs has a lot of dissolved sugars. In addition to the figs structure does not contain gas inclusions.
Then we conducted similar researches for frozen products.

The process thermogram in the frozen fruits research differs from the thermogram of the fresh fruits processing. The Figure 6 shows a thermogram for measuring the frozen kiwi thermal conductivity.
At first there is a decrease in the temperature on the inner and outer surface of the product. This is explained by the fact that the heat flow through the product is initially absent or insignificant. In this case the energy is intensively removed from the sample cooled surface. This is especially noticeable on the curve of the sample outer surface.

Further there is an increase in the temperature difference between the surfaces, that is, the gradient increases inside the sample. It can be explained by the effect of the "temperatures jump" on the separation of the product-air medium. The regular regime stage can be observed after the stage of the temperature jump on the surface. At the same time the product temperature gradient is unchanged and the temperature increase occurs at the same rate.

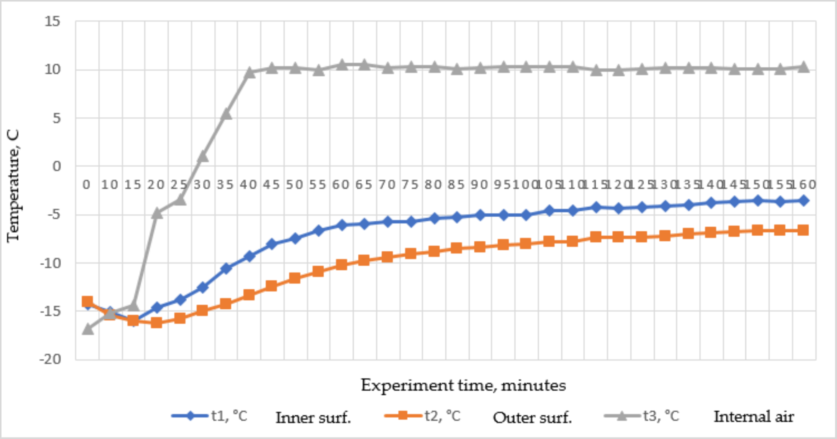

Figure 6. The process thermogram of frozen kiwi thermal conductivity determining

The stationary mode occurs approximately from the 150th minute. The temperatures in the sample form a time-invariable gradient and two isothermal surfaces. The temperature difference in the frozen product is less than in the experiment with a fresh product. It is due to the greater thermal conductivity of the frozen product owing to the transition of water to ice.

The thermal conductivity coefficients of the remaining studied frozen tropical fruits are shown in Table 2.

Table 2. The research results of the frozen tropical fruits thermal conductivity coefficient

Name	Thermal conductivity coefficient, W/m·K
Kiwi	1,13
Papaya	1,65
Avocado	0,97
Figs	2,06

In comparison with the fresh product the frozen avocado has a slightly increased thermal conductivity coefficient which is explained by its lower moisture content, according to the literature data. The figs thermal conductivity coefficient is significantly increased in 3.3 times. Figs have the highest thermal conductivity among the studied both fresh and frozen fruits (0.63 and 2.06 W / m·k accordingly). The kiwi thermal conductivity coefficient increased only in 2 times. This is probably due to the lower freezing point and therefore less frozen moisture. The papaya thermal conductivity coefficient is significantly increased in 4.2 times.

It should be noted that the products significantly change their thermophysical characteristics with the loss of moisture (shrinkage). The shrinkage expectancy is quite high during a two or three hour experiment. A possible way to prevent shrinkage is to use a food film. The corresponding experiments were conducted in order to verify this fact. A thin food film with a thickness of 8 microns was used for carrying out the experiment. The material is polyethylene. Two experiments were conducted with kiwis one is a control and the second is with using a film. The results are summarized in Table 3.

Table 3. The research results of the film influence on the thermal conductivity determination

Experiment parameters	Experiment	
	Control	With film
Duration, minutes	160	160
Layer height, m	0,0194	0,0194
Heating temperature, °C	55,3	50,2
Cooling temperature, °C	27,3	25
ΔT heating and cooling, °C	28	25,2
The heated surface final temperature, °C	39,8	41,6
The cooled surface final temperature, °C	33,9	36,3
ΔT isothermal surfaces, °C	5,8	5,3
Steady heat flow, W/m2	175	100
The obtained thermal conductivity coefficient, W/m-K	0,56	0,37

The experiments duration was the same and the samples thickness was the same. If the assumption about the positive film effect on the experiment was correct, there would be a smaller temperature gradient in the product and at the same time a greater heat flow. However according to the experiment results the heat flow on the contrary decreased and at the same time almost in 2 times.

The thermal conductivity coefficient of a sample with a film differs significantly from that of a sample without a film. The obtained thermal conductivity coefficient is close to pear and apple, quince, as a result of the porosity and the gas component in their structure, as a result of their lower density and wateriness. Kiwi is a fairly dense fruit, contains a lot of moisture and does not contain gas inclusions.

Thus the assumption was not justified the film creates the effect of a "thermos" but due to the additional thermal resistance although it reduces shrinkage, it does not allow heat to pass freely through the product which is delaying the heat flow. It negatively affects the experimental determination of the thermal conductivity coefficient.

The experiments were also conducted to analyze the influence of the fruit maturity degree on the thermophysical properties as part of the research. Two papaya fruits of different ripeness degrees were used for this purpose. One was purchased in the autumn (in October) and the second was purchased in the summer (in June). The first fruit was green-skinned, tasteless, with a lighter pulp. The second one has a yellow skin, a pronounced flavor and taste, softer and more watery. The experiment results are shown in Table 4. The results indicate that the fruit ripeness has some effect on the thermal conductivity coefficient, in the ripe fruit it turned out to be 0.02 W/m·K and it is higher than in unripe.

Table 4. The repeated experiment results with a more ripe papaya in fresh form

Experiment parameters	Experiment	
	Ripe	Not ripe
Duration, minutes	150	135
Layer height, m	0,0202	0,0193
Heating temperature, °C	55,2	55,2
Cooling temperature, °C	32,5	24,5
ΔT heating and cooling, °C	22,7	30,7
The heated surface final temperature, °C	44	39,2
The cooled surface final temperature, °C	36,3	31
ΔT isothermal surfaces, °C	7,7	8,2

Steady heat flow, W/m2	141	165
The obtained thermal conductivity coefficient, W/m-K	0,37	0,39

Such characteristics as heat capacity, cryoscopic temperature, thermal conductivity and the frozen moisture amount were also studied in addition to thermal conductivity.

The heat capacity was calculated based on the chemical composition data from the reference literature. The thermal conductivity obtained values are listed Table 5 according to the formula (3). The heat capacity was calculated for fresh fruits. The results of determining the remaining thermophysical characteristics are also summarized in Table 5.

Table 5. Some thermophysical characteristics values for tropical fruits

Name	Heat capacity C, kJ/(kg·K)		T_{kp}, °C	Thermal conductivity α, m^2/s		Frozen moisture quantity, %
	Ripe	Frozen		Ripe	Frozen	
Kiwi	3,64	2,46	-1,8	$14,6\times10^{-5}$	$41,2\times10^{-5}$	65,05
Avocado	3,34	2,13	-1,1	$12,9\times10^{-5}$	$48,9\times10^{-5}$	78,43
Papaya	3,83	2,67	-2,7	$9,2\times10^{-5}$	$58,7\times10^{-5}$	60,29
Fig	3,56	2,57	-2,9	$23,3\times10^{-5}$	$100,6\times10^{-5}$	57,66

The highest heat capacity is observed in papaya, which is due to the highest moisture content, the highest freezing point is in figs, which is due to the high sugar content in its composition; in terms of the frozen moisture amount avocado is at the first place, this is due to the reduced total moisture content and increased fat content

4. CONCLUSION

As a result of the carried out work the physical and chemical parameters of the kiwi, avocado, papaya and figs were determined. The tropical fresh and frozen fruits thermal conductivity coefficient was studied experimentally. The thermal conductivity increases after freezing the products. The film presence and the product ripeness on the thermal conductivity coefficient influence is analyzed. It is established that the film presence negatively affects the thermophysical properties analysis. The other tropical fruits thermophysical properties such as heat capacity, cryoscopic temperature, thermal conductivity, and the amount of frozen moisture are calculated by calculation.

The obtained values of the characteristics can be used in new products, to determine the modes of refrigeration and heat treatment, to develop technologies for enriching dairy, bakery and other industries with exotic fruits.

The tests of the installation made it possible to reveal its advantages:

- installation of a mains voltage rectifier, allows the compensating load heater without power fluctuations, and, therefore, provides a more stable stationary flow.

- organizing the correction of thermocouple readings on a computer, reducing the amount of manual work during the recording of the experiment;

- the developed method for studying the heat capacity thanks to this installation allows one to obtain experimentally only the value of the thermal conductivity coefficient, but also the heat capacity of the product;

The analysis showed the possibility of adding Peltier elements to the system, connected through a transformer and a voltage regulator, equipped with fans, which will make it possible to do without a chest freezer, but will somewhat complicate the operation and the design of the installation itself.

The developed installation can be successfully applied for:

- studies of thermal conductivity of heat-insulating materials, wood, rubber and materials from rubber, plastics;

- studies of the thermal conductivity of mushy products (subject to slight modernization): chopped berries, such as: sea buckthorn, cranberries, currants and any others;

- studies of thermal conductivity of livestock products, as well as mushrooms.

- the data obtained can be used to build mathematical models

- received new experimental data on the kinetics of temperature changes in thermal characteristics under conditions of phase transformations.

- the theoretical and practical results of this work can be useful in the design of similar heat measuring installations for studying the thermal properties of moisture-containing materials; in the automation of thermophysical devices and installations.

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