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DINVESTIGATION OF CONTACT HEATING OF FRUIT AND VEGETABLES WITH SATURATED WATER STEAM

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Abstract. The purpose of this research was to study the modes of heating different types of plant raw materials in model technological environments that imitate the blanching of raw materials under factory conditions. The research aimed at expanding the range of canned products made from fruit and vegetables. To this end, new methods were searched for, in addition to the existing ones, allowing heating various plant raw materials and increasing the energy efficiency of canned fruit and vegetables production. Saturated water steam was selected as the treatment medium. The experimental studies included determining the volume-average temperature of the fruit layer in the container. A pulse method of supplying the heating media has also been investigated. It allows using the inertial properties of raw materials and significantly reducing the expenditure of the heating media. The objects selected for study were various species of pomes and drupes, in particular, apples, plums, cherries, sweet cherries, as well as a vegetable crop of the gourd family, or *Cucurbitaceae*. The following characteristics have been studied: the dynamics of heating individual fruit and vegetables in the saturated water steam environment at atmospheric pressure; the dependence of the heating and cooling rates of individual fruit and vegetables on the geometric index; the dependence of the heating rate of individual fruit and vegetables on the value of the characteristic dimension; the dependences of changes in the volume-average temperature of the fruit layer on the duration of treatment with saturated water steam. It has been established that the volume-average temperature in the centre of a fruit is also influenced by the shape of the fruit itself. To characterise the anomalous shapes of plant raw materials, the geometric index G has been calculated. This index characterises the elliptical shape of a fruit, and allows determining parameters in two mutually perpendicular planes. Also, to compare fruit of the elliptical and the spherical shapes, a special concept of characteristic dimension was used, which is applicable to fruit of different shapes. The experimental data on the change in the dependences of the heating and cooling rates of individual elliptical fruit have been analysed. The analysis has shown that the size of a fruit significantly affects the volume-average temperature in the fruit layer. It has been suggested to use pulsed heating of the fruit layer with saturated water steam, which will appreciably increase the energy efficiency of production due to a significant reduction in heating media consumption.

Keywords: fruit, vegetables, saturated water steam, heating, pulse mode, energy efficiency.

Introduction. Formulation of the problem

The canning industry plays a special part in providing people with high quality food regardless of the geographical location and season. Using resource-efficient and environmentally-friendly methods and technologies to reduce the cost and improve the quality of canned products, thus making them competitive enough to saturate the food market is one of the most important problems in the canning industry.

To assess the efficiency of thermal processes when preserving juicy plant materials (fruit and vegetables), it is necessary to know the volume-average temperature that develops in the layer of raw materials which have been exposed to a heating or cooling medium (liquid, steam, air). This volume-average temperature not only results from the thermophysical properties [1] of the heated raw material and the duration of its treatment, but also from the specific features of the heating and cooling medium, as well as from the mode of treatment of fruit and vegetable raw materials.

Of all types of heating media, water steam is of particular interest [2], since when it is used, not only the raw material is heated [3], but also condensate forms on the surface, which liquefies the liquid phase of the product and reduces the mass fraction of soluble solids in it.

Analysis of recent research and publications

Development and implementation of new energy-saving technologies and creation of highly efficient processes and devices is one of the main tasks the food industry must solve to make canned products more competitive. It is necessary to search for new ways of intensifying the process of heat sterilisation of canned food and devices for this purpose, as it is one of the most energy-intensive and time-consuming processes in canned food production. The traditional technology has a number of significant disadvantages, the main of which are:

– long duration of heat treatment of the product resulting in a significant decrease in the quality of raw materials;

– uneven heat treatment of the product in cans;

– high consumption of heat and water.

Now, it is known that the time heat needs to penetrate deep into the product depends on a number of factors: the initial temperature before sterilisation of the products to be canned, the heating medium temperature, the use of rotation of cans during heat treatment [2,3]. It should be noted that an increase in the initial volume-average temperature of the product has a positive effect not only on the thermophysical, but also on the microbiological aspect of sterilisation: the higher the temperature of the product at the beginning of sterilisation, the fewer microorganisms will remain there, so the sterilising effect will increase. Taking into account the above-mentioned, it has been studied whether it is possible to improve the technology of manufacturing canned pear compote drink, when the fruit are pre-heated in cans in the electromagnetic field of super high frequency (microwave EMF) and high-temperature rotational heating in a hot air stream at 150-160°C is used.

Fruit, vegetables, and products of processing them, are indispensable sources of vitamins, organic acids, minerals necessary for people’s full-quality life. Since supplies of these raw materials are but season-dependent and their storage periods are short, it is necessary to develop and implement processing methods that will ensure more complete preservation of the raw material composition in the finished product [4-6].

Heat treatment is the most reliable and most common way to preserve food for long-term storage [7-9].

However, the existing and widely practised traditional methods of thermal sterilisation require a lot of cumbersome equipment, are energy-intensive and time-consuming.

All these circumstances give prominence to such a direction in scientific research as developing new, highly efficient and resource-saving technologies of processing plant raw materials, so as to ensure the competitiveness and high quality of finished products.

It is known from the literature that the most effective way to improve heat treatment is increasing the initial temperature of canned products before sterilisation using various thermal and physical processes [5,6,10-13].

A number of scientists have experimented to develop the parameters and modes of canned food sterilisation that involves increasing the initial temperature of the product. These studies have shown that a high initial temperature in a can when it is sealed leads to a certain decrease in the level of pressure that develops in cans during their heat sterilisation. This, in turn, allows performing heat treatment at lower values of back pressure in a heat sterilisation apparatus (autoclave). Besides, in this apparatus, it becomes possible to carry out the cooling process in two stages until the cooling water temperature is 50–55°C [2,3,9-13].

This allows significantly intensifying the further sterilisation: the duration of heat treatment decreases, and the product in different points of the can is heated more uniformly.

Intensification of heat treatment of products is a relatively new and rapidly developing area in food engineering [14-16]. Process intensification as a concept, when introduced, was defined as any engineering development resulting in a substantially cleaner, less space-consuming, safer, and more energy-efficient technology [17]. According to this strategy, developing a new process [18] aimed at effective heat treatment when producing canned food is a useful engineering approach as long as it orientates the process towards the desired result – obtaining high-quality canned food. This is contrary to the approach when the physicochemical features in the product manufactured are adapted to the processing procedure.

So far, it is not widely developed practice to heat plant raw materials (fruit, berries, vegetables) by the steam-contact method after they are placed into retail packages to be further filled with a liquid phase (syrup, marinade) and sealed. At present, this method is only used for a small range of products made from a limited number of raw materials (for example, dietary compote drink from dried plums). That is why there are no data on the heatability of fresh plant materials when the thermal process is intensifying by this method.

The purpose of the research is to study the innovative method of canned food production from fruit and vegetables, and to expand the existing range of canned products by suggesting new modes of heating various plant raw materials with saturated water steam and by increasing the energy efficiency of manufacturing canned fruit and vegetables.

For this purpose, it is necessary to achieve the following **objectives**:

– to study the dynamics of temperature changes in individual fruit and vegetables in the saturated water steam medium at atmospheric pressure;

– to study how the heating and cooling rates of individual fruit and vegetables depend on the geometric index;

– to establish how the heating rate of individual fruit and vegetables depends on the characteristic dimension;

– to establish how changes in the volume-average temperature of the fruit layer depends on the duration of treatment with saturated water steam;

– to study whether pulsed heating with saturated water steam can be applied to the fruit layer in order to increase the energy efficiency of the process;

– to investigate how the degree of heating the fruit layer with saturated water steam at atmospheric pressure is determined by different pulsed heating coefficients.

Research materials and methods

For the research, a test installation was specially prepared, in which the temperature of the raw materials was measured using various methods of supplying water steam.

The objects selected for study were various species of pomes and drupes, in particular, apples, plums, cherries, sweet cherries, as well as a vegetable crop of the gourd family, or *Cucurbitaceae*.

The test installation was a closed cube-shaped container made of a heat-insulating material. A steam pipe was connected to the inner volume of the cube. The water steam in the pipe was generated by an electric laboratory autoclave VK-75. The steam pressure was registered with a standard autoclave manometer. The temperature of the steam as it exited from the steam line corresponded to the temperature of saturated water steam at atmospheric pressure (100°C). Individual fruit and a fruit layer were placed inside a glass jar 1-82-500, into which steam was directed injected on exiting the steam line. The duration of treatment was registered with a stopwatch.

The experiments were carried out both for single fruit and for the layer of fruits.

In accordance with the current technological regulations, the number of fruit in a container is:

– for plums of the varieties *Renklod* and *Vengerka* (or *Uhorka*) – 0.673kg.

– for sweet cherry fruit – 0.716kg.

– for cherry fruit – 0.693kg.

The fruit were processed both once (for a fixed period of 5 minutes) and in pulses (in portions treated for 20 seconds each, with 20-second intervals) to establish whether this heating method led to reducing energy consumption without losing the efficiency of heating the raw material.

The temperature of the fruit was measured with sensors placed inside a fruit in its least heated point. This made it possible to obtain the most objective temperature values for various heating methods. The temperature sensors were installed in such a way as to prevent the heating steam from penetration into the thickness of the fruit and, thus, to avoid obtaining erroneous data on how they were heated. Since it was not possible to install a protective device against penetration of heating steam onto the fruit, this protection was provided by their special placement in the layer. The fruit that had the temperature sensors inside were placed in such a way that the orientation of the orifices through which the sensors were inserted was parallel to the direction of the heating steam flow, but on the side opposite to where the steam moved from. Thus, the heating steam touched the intact part of the surface of the sensor-containing fruit, and the condensate that formed on it trickled down into their lower part where the fruit surface had been damaged by the introduction of a sensor. Under the influence of gravity, the condensate continued to move downward and did not get inside the fruits with sensors. Thus, the thermal state of the inner volume of the fruit was not disturbed.

This way of placing fruit with temperature sensors inside made it possible to solve several problems important for the experiment:

– ensuring that there was no influence of the heating steam;

– orderly orientation of the temperature sensors in the volume of the product;

– obtaining good (not less than 95–97%) convergence of parallel experiments regardless of the heating steam consumption.

The heating steam was supplied to the test installation in such a way that it did not only enter the volume where the fruit were contained, but could also flow round the container from outside. This was especially important when studying how the layer of fruit was heated in retail containers made of glass: when heated, these containers could be damaged due to the excessive temperature difference between their inner and outer surfaces. Possible thermal shock breakage requires creating conditions when the temperatures of the outer and the inner surfaces will be practically equal. This was provided by a special device for supplying heating steam.

The experiments were carried out in at least three replicates for each type of raw material. The reliability of the results was 95%.

The results obtained after studying the heatability of single fruit in the saturated water steam medium have allowed developing a technology of heat treatment of heterogeneous products with a pH of not more than 4.0: compote drinks, marinades, canned and pickled fruit. This technology can be implemented in the form of continuous pasteurisation.

Results of the research and their discussion

The dynamics of heating individual fruit and vegetables in a saturated water steam medium at atmospheric pressure is shown in Fig. 1.

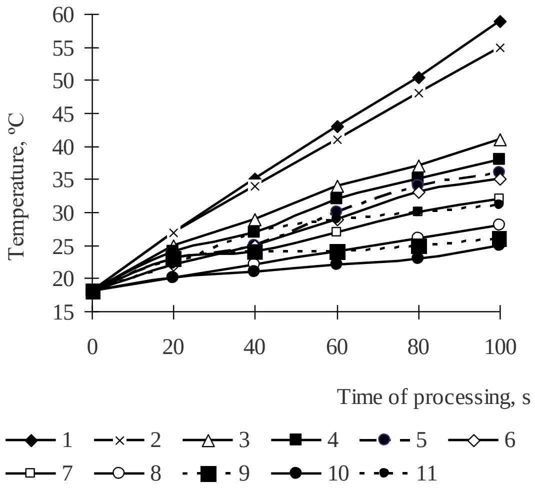


Fig. 1. Heating individual fruit with saturated water steam at atmospheric pressure: *1, 2, 3, 4, 5, 6 – plums of the variety Vengerka (dimensions in two mutually perpendicular planes, mm, respectively; 36x32; 28x23; 35x25; 32x27; 31x22; 37x26); 7, 8, 10 – plums of the variety Renklod (diameter, mm, respectively; 27; 34; 35); 9, 11 – cucumbers (dimensions in two mutually perpendicular planes, mm, respectively, 92.5x43; 105.2x45)*

Analysis of the data obtained (Fig. 1) allows characterising how the intensity of steam-contact heating of plums of various geometrical sizes at atmospheric pressure depends on their variety. The curves plotted according to the values obtained in the course of the experiments reflect the regular character of heating. They include the initial section, the shape of which is determined by the thermophysical characteristics of the raw material, and the section of regular heating where the temperature increases in proportion to the time of the process.

In the course of the experiments, a 0.2 mm temperature sensor was introduced into the studied samples in such a way that it was located either in the geometric centre of a fruit or a vegetable or immediately at the stone.

Analysis of the experimental data obtained indicates that the tendencies of temperature changes in the samples under study are similar and correlate with the findings of other researchers: V. Ochirova, A. Demirova, B. Flaumenbaum, A. W. Westerberg, etc. [1-3, 5, 9, 12, 18, 20].

Differences in the heating rate of the samples are explained by different species and size-mass characteristics. Table 1 shows the size and mass characteristics of the *Renklod* plum stones.

Table 1 – Size of the stones of *Renklod* plums

Diameter of the fruit of *Renklod* plums, mm	Size of a stone, mm			
27.0	13.0×19.0	15.0×19.0	12.5×17.0	14.0×19.0
32.0	12.5×18.0	13.0×17.0	14.0×19.0	15.0×18.0
34.0	11.6×19.0	12,19×19.0	13.0×18.0	13.0×17.0

As follows from these values of the size-mass characteristics of the *Renklod* plums, the deviation of the temperature sensor from the geometric centre of a fruit ranged 5.5mm to 9.5mm.

Most fruit and vegetables are abnormal-shaped bodies – ellipsoids of revolution, for which the value of the geometric index G is calculated according to the following relationship:

$$G = 0,625 + 0,375 \cdot \left(\frac{d}{1}\right) \quad (1)$$

where *d* and *l* are the dimensions of the ellipsoid in two mutually perpendicular planes.

Fig. 2 shows how the rates of heating and cooling the anomalous-shaped plums *Vengerka* and the cucumbers depend on their geometric index.

The obtained experimental data on the rates of heating and cooling the anomalous-shaped fruit have been analysed. The results have shown that for such fruit, the curves of the heating rate and of the cooling rate have a shape close to parabolic (Fig. 2).

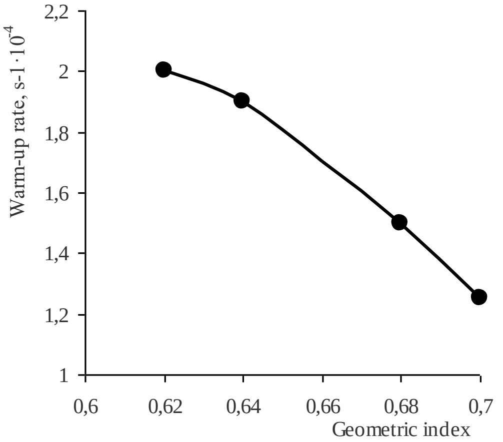
The analysis of the experimental data obtained explicitly shows that the rates of heating and cooling the fruit depend on the value of their geometric index. However, it does not reveal the influence of the true geometric dimensions of the fruit, and does not allow us to compare the heatability of ellipsoidal and of spherical fruit (the latter include plums *Renklod*, cherries, sweet cherries), since in this case, the geometric index G is 1.

To make this comparison possible, it was decided to apply the concept of characteristic dimension, a parameter, which can be applied to fruit of regular and irregular geometric shape.

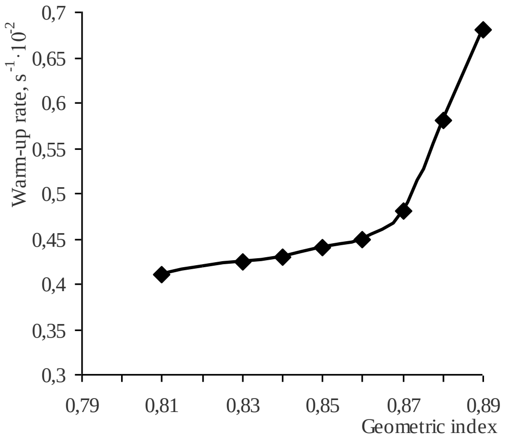
Fig. 3 shows how the rate of heating the fruit depends on the value of their characteristic dimension.

The correlation equations for the curves shown in Fig. 3 are given in Table 2. As it can be seen from the analysis of the data obtained, there is a dependence of the rate of heating individual fruit on their characteristic dimension. However, the geometry of these curves is practically the same. It is a direct relationship: its angle of inclination to the abscissa is wider, the larger the characteristic dimension of a heated fruit is.

Using the dependences obtained, the values of the thermal diffusivity of the fruit under study have been determined. They are given in Table 3.



a)



b)

Fig. 2. Dependence of the heating rate and cooling rate of individual ellipsoid-shaped fruit on the geometric index:
a – cucumbers, b – plums of the variety Vengerka

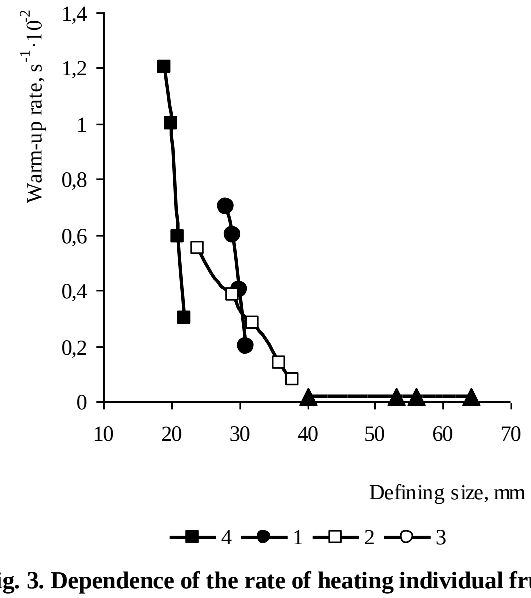


Fig. 3. Dependence of the rate of heating individual fruit on the characteristic dimension:
1 – plums *Renklod*, 2 – plums *Vengerka*,
3 – cucumbers, 4 – cherries

Table 2 – Dependence of the rate of heating individual fruit on the characteristic dimension

Name of fruit	Type of correlation
Plums *Vengerka*	m=0.03790-0.114D
Plums *Renklod*	m=0.00778-0.150D
Cucumbers	m=0.00047-0.006D
Cherries, sweet cherries	m=0.06250-2.640D

Table 3 – Thermal diffusivity coefficients of the fruit

Name of fruit	Characteristic dimension, mm	Thermal diffusivity coefficient, $10^6 m^2/s$
Sweet cherries	20.3	0.093
Cherries	18.8	0.115
Plums *Renklod*	34.4	0.079
Plums *Vengerka*	27.9	0.139
Cucumbers	51.6	0.162

Fig. 4 shows the findings on how the volume-average temperature of the layer of fruit (plums *Renklod*, plums *Vengerka*, sweet cherries, cherries) placed in glass cans 1-82-1000 changes depending on the duration of treatment with saturated steam.

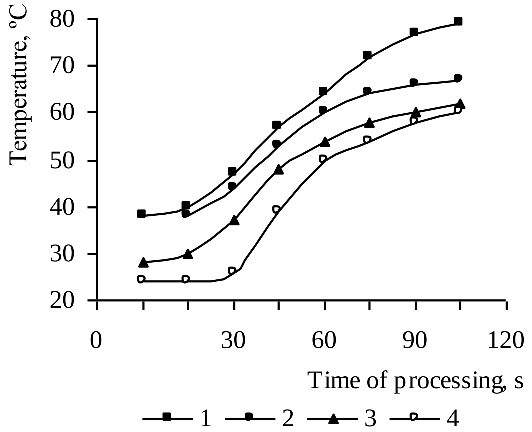


Fig. 4. Heating the fruit layer in a saturated water steam medium at atmospheric pressure:
1 – cherries; 2 – plums *Vengerka*; 3 – plums *Renklod*;
4 – sweet cherries

Analysing the experimental data, it can be noted that all fruit under study showed a significant increase in the volume-average temperature of the fruit layer. This parameter increased by 2.61–3.26 times, with the duration of steam treatment 90 s. Regardless of the type of fruit, the effect of steam can be observed as early as on the 10th second of the treatment.

In this regard, the possibility of pulsed heating of the fruit layer with saturated water steam has been investigated. It allowed significantly reducing the heating steam consumption, since it alternated periods of active energy supply with periods of heating the fruit layer due to thermal inertia.

Fig. 5 shows the results of this study at different values of the heating impulse coefficient φ̇. For continuous heating of the fruit with saturated water steam at atmospheric pressure, the value φ̇ = 1.

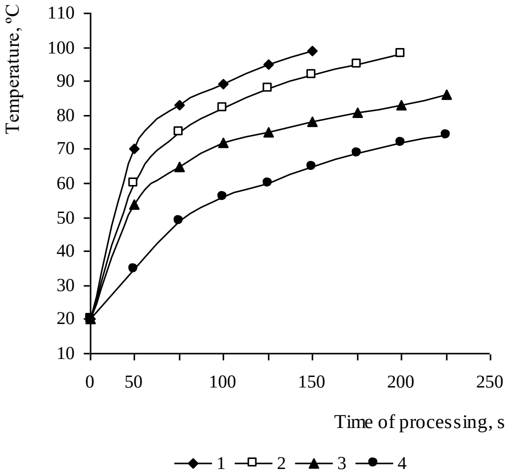


Fig. 5. Heating the fruit layer with saturated water steam at atmospheric pressure at different coefficients of the heating impulse:
1 - φ̇ = 1.0; 2 - φ̇ = 0.67; 3 - φ̇ = 0.50; 4 - φ̇ = 0.4

Analysing the dependences obtained, it can be noted that to achieve a predetermined value of the volume-average temperature of the fruit layer, there is a certain range of variation of the heating impulse magnitude φ̇. When its value is within this range, the fruit layer can be actively heated with saturated water steam at atmospheric pressure for a shorter time than it is required for continuous steam-contact heating.

Conclusion

This research has allowed expanding the existing range of canned products by suggesting new modes of heating various plant raw materials with saturated water steam. The use of the modes developed will significantly increase the energy efficiency of manufacturing canned fruit and vegetables.

The dynamics of temperature changes of individual fruit and vegetables in the saturated water steam medium at atmospheric pressure has been studied. The curves of the changes include the initial section, the shape of which is determined by the thermophysical characteristics of the raw materials, and the section of regular heating where the temperature increases in proportion to the time of the process. The tendencies of the temperature changes in the samples studied are similar.

It has been studied how the heating and cooling rates of individual fruit and vegetables depend on the geometric index.

It has been researched how the heating rate of individual fruit and vegetables depends on the characteristic dimension.

It has been studied how the volume-average temperature of the layer of fruit (plums *Renklod*, plums *Vengerka*, cherries, sweet cherries) placed in glass containerss 1-82-1000 changes depending on the duration of treatment with saturated water steam. This parameter has been shown to increase by 2.61–3.26 times, with the duration of steam treatment 90 s. Regardless of the type of fruit, the effect of steam can be observed as early as on the 10^{th} second of the treatment.

It has been studied whether the pulse mode of heating with saturated water steam can be applied to the fruit layer in order to increase the energy efficiency of the process, and it has been established how heating the fruit layer with saturated water steam at atmospheric pressure is determined by different pulse heating coefficients.

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ДОСЛІДЖЕННЯ КОНТАКТНОГО НАГРІВУ ПЛОДІВ ТА ОВОЧІВ НАСИЧЕНОЮ ВОДЯНОЮ ПАРОЮ

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Анотація. У статті наведено результати досліджень з визначення режимів прогрівання різних видів рослинної сировини в модельних технологічних середовищах, що імітують процеси бланшування сировини у виробничих умовах. Дослідження проводили з метою розширення асортименту консервованої продукції з плодів та овочів шляхом доповнення існуючих режимів прогрівання різних видів рослинної сировини та підвищення енергоефективності процесів виробництва плодоовочевих консервів. В якості середовища обробки обрано насичену водяну пару. У ході проведення експериментальних досліджень визначали середньооб’ємну температуру шару плодів в тарі. Також досліджено імпульсний спосіб підведення теплоносія, який дозволяє використовувати інерційні властивості сировини і значно економити витрати теплоносія. В якості об’єктів досліджень обрано різні види кісточкових і насіннєвих, зокрема яблука, сливи, вишні, черешні, а також овочеву культуру родини гарбузових – Cucurbitaceae. Досліджено динаміку прогріваємості одиничних плодів та овочів у середовищі насиченої водяної пари при атмосферному тиску, залежність швидкості прогріву та охолодження одиничних плодів та овочів від геометричного індексу, залежність швидкості прогріву одиничних плодів та овочів від величини визначального розміру; залежності змін середньоб’ємної температури шару плодів в залежності від тривалості обробки насиченою водяною парою. Встановлено, що на середньооб’ємну температуру в центрі плоду впливає також форма самого плоду. Як характеристику аномальної форми рослинної сировини обчислено геометричний індекс G, який характеризує еліпсоподібну форму плода, і дозволяє визначати дані в двох взаємно перпендикулярних площинах. Також в якості порівняння плодів еліпсоподібної і сферичної форми було застосовано спеціальне поняття «визначний розмір», яке застосовується для плодів різної форми. Аналіз експериментальних даних щодо зміни залежності швидкості прогріву і швидкості охолодження одиночних еліпсоподібних плодів показав, що розмір плода значно впливає на середньооб’ємну температуру в шарі плодів. Запропоновано застосування імпульсного нагріву шару плодів насиченою водяною парою, що дозволить істотно підвищити енергоефективність виробництва за рахунок суттєвої економії витрат середовища, що гріє.

Ключові слова: плоди, овочі, насичена водяна пара, нагрів, імпульсний режим, енергоефективність.

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