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DEVELOPMENT OF THE JUICE EXTRACTION EQUIPMENT: PHYSICO-MATHEMATICAL MODEL OF THE PROCESSES

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Multifruit juicers are designed, constructed and improved to be able to process pineapples, oranges and watermelons efficiently. Little juice manufacturers need both a small and efficient device for juice extraction for being economically concurrent compared to big corporations. The authors of the represented paper aim to present the experimental device for juice extraction, its effectiveness, and functional. This device was created using the compressive and compressive shear forces conveyed by an auger conveyor system as a working power. The juicer consists of a hopper, a screw conveyor shaft, a filter screen, a juice outlet, gearbox housing, and a motor. The analysis of the component design enabled the authors to use the data in order to identify the sizes, manufacture and assemble the machine. The authors have made a lot of tests to detect the efficiency and functionality of the presented device. Tests of the device productivity were carried out using watermelons loaded into the device both peeled and unpeeled. Percentage of juice yield, juice extraction efficiency and extraction losses were used as performance indicators. Productivity analysis results revealed that a fruit type and peel condition reliably influenced productivity indicators at the value of 1 %. The percentage of juice yield from peeled and unpeeled watermelons constituted 89.5 % and 89.7 %, respectively. Extraction efficiency constituted 96.6 % for peeled watermelons and 97.1 % for unpeeled ones. Extraction losses amounted to 2.9 % and 2.6 % correspondingly. The proposed device is easy to use and maintain, therefore, it will perfectly suit the needs of small fruit juice manufacturers and can help to get economic efficiency to the small manufacture

Keywords: watermelon, extractor, juice yield, extraction efficiency, extraction losses, juice constant

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1. Introduction

Nowadays there are many types of research in the juice extraction process in different ways: using biotechnology processes, physical processes, and with different created devices. For example, high-pressure homogenization is better for use in apple juice production. Researchers are looking to make more efficient local manufactures to use local food resources and to get independent from the products that have been imported in the region [1–3].

A fruit is a ripened ovary of a plant containing seeds. The inner part of a fruit or a berry is valuable, for the most part, due to its edible pulpy component, which serves as protection and a source of nutrition for a seed. The pulpy component contains a sufficient amount of water, sugar, vitamins (A and C, in particular), and fiber, cellulose. Its pulp and juice are used in the food industry as a supplement to a diet lacking basic food items.

The crop capacity of specimens is affected by periodical climate changes and natural soil fertility. Thus, depending on the season, fruit can be available in a limited amount, which necessitates creating high-quality alternatives with sufficient content of all vital components. Juice can serve as such an alternative.

Fruit juice is a liquid contained in the cells and tissues of a fruit. Not without justice, fruit juice is believed to be the second best product after unprocessed fruit. Juice is a product that helps to consume nutrition components of fruits and vegetables. Rough and indigestible, or poorly assimilated, fiber, lignin, and other substances go to waste. But vitamins, sugar, organic acids, mineral salts remain in the product [4, 5].

The juice production process has several manufacturing problems like fast sedimentation, enzymatic browning, and flavor losses. So, there are data about a small percentage of the quality natural juice from the modern big manufacturing companies. So, it becomes actual to form little local manufactures for producing natural juice [1, 5].

Agricultural engineering is used to get juice, pulp, and candied fruits. And watermelon peel can be used as feed for animals [6]. So juice extraction from watermelon can be waste-free manufacture.

2. Literature review and problem statement

In order to obtain juice from fruit, traditional methods are employed. They include maceration of a fruit by hand or peeling, chopping, breakage and pressing of the fruit. These methods are not only energy- and labor-consuming, but also underproductive (they are characterized by a little juice yield) as well as unsanitary. Thus, this traditional method of juicing can be used neither in small nor in medium productions to satisfy local commercial needs. Hence, in order to meet the growing demand for such food products, there emerged a necessity to design a medium-sized mechanic device able to extract juice from a range of tropical fruit cultures [7]. A small juice extractor for a whole pineapple was designed and constructed. The device consisted of blades of a beater and a shaft connected to a screw press drive. The machine successfully processed 12 kg of ripe pineapple fruit into 8 l of pineapple juice [8].

Banana juice extractor operation through beating and friction occurring as a mixer acts on the banana mixture of grass and rough walls of the extraction chamber was developed, and juice extraction efficiency of 47 % was achieved [9].

In India, a small-size motorized multifruit juicer was designed. A lot of tests to identify juice yield from oranges, grapes, tangerines, watermelons, and pineapples have been made. Extraction efficiency was not less than 81.3 %.

Some researchers developed a system of extraction and distribution of fresh fruit. The system worked through cutting, beating, pressing with a knife and a brush, and also through peeling, extracting, and filtering. The cost of one system unit amounts to 1,500 $, which is not affordable for small entrepreneurs. Thus, the research was conducted so as to develop, manufacture, and evaluate the productivity of the juicer for several fruits, particularly, for watermelons, using a physical and mathematical model [10].

An experiment conducted with a physical impact on a fruit requires taking all its physic-mathematical properties. It is worthwhile to generalize the properties creating a fruit model. This will allow representing the features crucial for the result: elasticity, viscosity, and plasticity. The model of melons and gourds can be identified by the structure of a fruit peel. It consists of a hard "skeleton" filled with semi-fluid, fluid, or gas matter.

A more realistic model contains significantly more than three simple elements. But it has been discovered through practice that using more than 3–4 elements in a model can drastically complicate visual observation of the behavior of the bodies under simultaneous change of that number of its properties [11].

Theory of similarity makes it possible to determine the relation between the criteria of similarity and derive a dimensionless equation, without using differential equations. This will explain the running processes with maximum precision [12].

Derivation of such equations does not require any additional simplifications, which are usually necessary to find analytical solutions of differential equations, when some more complicated phenomenon is described.

Information about the physical properties of the fruits under research is needed in order to project and optimize their whole processing [13]. It is known that there is a dependence of the physical properties of watermelon crops on soil condition (its physical and chemical characteristics). And it has been noted that crop yield and physical conditions are the effect, in most, of soil tillage [14].

Previously much work had been done over optimization of the food industry, development of new tools able to solve design problems, however, even now this issue remains open. Multi-purpose optimization embraces determining efficiency indicators, process modeling, gauging of compromises, and searching for optimum models of fruit processing [15]. It is very important to create not only efficient but also cheap manufacturing devices to get more goodness from the engineering progress. In most cases, the method adopted by the manufacturers depends on its cost-effectiveness [16]. And we would like to make a piece in resolving this problem.

3. The aim and objectives of the study

The aim of the study is to create a juice extraction device for different watermelon fruitage and to test its efficiency mathematically.

To achieve this aim, the following objectives are accomplished:

– to present the created juice extractor for watermelon fruitage;

– to consider the processes of watermelon pulp detachment from the crust and its grinding;

– to study the process of crust cutting;

– to make physical and mathematical experimental tests of the device for watermelon processing;

– to evaluate the test criteria and response surfaces.

4. Materials and methods

The paper presents the research conducted over watermelons of the Dishim variety. 60 watermelons of this variety had been selected for the experiment. All the berries were thoroughly examined for the absence of visual defects by hand. The average mass of watermelon equaled 8 kg and the circuit perimeter was 78–79.5 cm.

4. 1. Storing and tasting

During the experiment, the watermelons were kept in a laboratory with a temperature of 5±1 °C and relative humidity of 90±5 %. It was necessary to preserve their freshness and initial qualities. In order to determine the mechanical characteristics of different components of the fruit, 5 samples of the same size were subtracted from every fruit part under research.

4. 2. Determining the ultimate shear stress

This research was based on finding the shear stress with studying the following parameters: *Fres* – residual load force; h – penetration depth, m; δ – ultimate shear stress, Pa (1).

$$\delta = Cc \cdot \mathrm{Fres}/h2, \quad (1)$$

where Cc – cone coefficient (1.11 according to the technical passport of the device); $Fres$ – residual force of a load on the "cone" indentor, N, is identified by a graph as a constant value of a load force after mechanical stress relaxation; h – penetration depth, m, corresponds to the value of the set residual load force.

The arithmetic mean of three result values can be considered a final result [17].

4. 3. Method of determining load force

The method is based on determining the parameter of load force (Fl). The arithmetic means of three result values were accepted as an ultimate result. The studies of load force changes on the indentor depending on the depth of its penetration into the studied fruit were carried out.

The fruit was evenly cut, then equal 10 mm wide parts were taken from it. They were placed on an apparatus table close to the indentor and, thus, the apparatus studied the parts of the fruit and constructed graphs, which elicited the parameter of load force.

4. 5. Studying strength properties of fruits of Dishim watermelons

Further research required determining the strength properties of watermelon and its constituent parts (Fig. 1). Winter varieties were chosen for the experiments. They are characterized by a thick peel and a darker coloring of a cuticle. A CT-2 structure meter was used for recording data.

In this case, watermelon was cut into pieces with their width not exceeding 1 mm. The pieces were taken from different parts of watermelon, which had been previously cut into 2 cm wide slices. Among the prepared slices, the ones having identical and parallel parts of the cut were singled out.

Then breakout force was determined, and afterwards another three pieces were identically prepared and tested for oscillation. The results of the analysis were processed and presented as a graph and as a table.

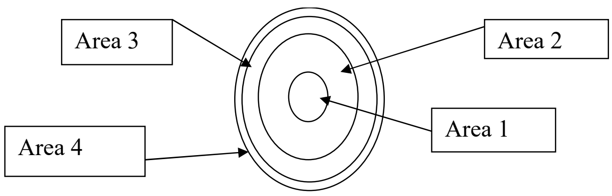


Fig. 1. Sampling areas, watermelon in section: Area 1 – the core of watermelon, approximately 5 cm in diameter; Area 2 – fleshy parenchyma, the main part where seeds are located, approximately 15–20 cm; Area 3 – mechanical shell, pre-rind zone, 23 cm and more in diameter; Area 4 – the rind (epidermises+cuticle)

In the first stage of the research, we studied the maximum strength of the fruit with a rotational viscosimeter (Table 1).

We have carried an experiment [18] to obtain the data needed to calculate and design a device, which would:

– peel the cuticle from watermelons;

– cut and extract the flesh;

– evenly chop the peeled rind for the production of candied peel.

In Table 2, presented below, you can get to know the results of the conducted experiments.

Table 1

Maximum shear stress in different areas of the watermelon section

Areas of watermelon	Maximum strength under shear (N)	Maximum shear stress (N/mm^2)
Area 1	4±0.2	0.048±0.009
Area 2	5.5±0.1	0.069±0.002
Area 3	10±0.2	0.0139±0.003
Area 4	50±0.2	0.070±0.007

Table 2

Strength properties of watermelon

Studied area of the fruit	Crush force, N	Puncture force, N	Hardness, kg/mm^2	Force of cut with a flat knife N/cm	
				lengthwise	crosswise
Watermelon rind					
Pedicel	470.4–472.7	129.3–133.1	0.81–1.1	28.2–28.9	36.6–37.6
Equator	428.6–444	1088.9–109.6		36.01–37.0	36.1–37.3
Receptacle	432.3–445.4	103.5–108.95		26.00–27.01	38.6–39.7
Watermelon flesh					
Pedicel	173.6–180.5	–	–	12.7–13.2	10.4–10.8
Equator	102.1–103.9	–	–	12.26–12.62	11.9–12.22
Receptacle	165.2–170.9	–	–	9.08–9.38	8.54–8.9

The elasticity coefficient of watermelon constituted 9.79×100 Pa for vertical compression and 8.92×100 Pa for horizontal compression.

At that, the juice extraction efficiency and losses were calculated with the following formulas (2)–(4):

– juice yield (JY)

$$JY,\% = \frac{Wje \cdot 100}{Wje + Wrw} = 31.6 \pm 0.23; \tag{2}$$

– extraction efficiency (EE, %)

$$EE,\% = \frac{100 \cdot Wje}{Wfs \cdot x} = 38.3 \pm 1.4; \tag{3}$$

– extraction loss (EL, %)

$$EL,\% = \frac{100 \cdot \left(Wfs - \left(Wje + Wrw\right)\right)}{Wfs} = 6.4 \pm 1.2. \tag{4}$$

We are going to extract juice from flesh only (in the case of watermelon – from mesocarp), therefore the rind will be peeled. Thus, we can calculate how much of the extracted flesh we will be able to use for juice (5):

$$\begin{cases} v_p = \dfrac{dT}{F \cdot d\tau}. \\ A = 2H_F \int \mathrm{d}F. \end{cases} \tag{5}$$

Or, otherwise (6), (7):

$$dT = v_p \cdot Fd\tau, \tag{6}$$

where v_p is the speed of the cutting process; dT – elementary cutting force when separating the pulp from the inner surface of watermelon; F – cutting area; H_F – a constant for a given material, characterizing its surface-active properties or otherwise specific work (energy) spent on the formation of a unit area of the cut material, J/m^2:

$$dA = H_F \cdot 2dF. \tag{7}$$

In order to extract the juice, we need to deform or break the watermelon flesh, turning it into juice. The most appropriate is to break the flesh by compression (mainly) and cutting. Thinking similarly, we get the following mathematical sequence (8):

$$dA = dA_1 + dA_2 + dA_3. \tag{8}$$

We are throwing away only the dA_3 value (9)

$$dA = dA_1 + dA_2. \tag{9}$$

Elementary work dA_1 (10) spent on volume deformation can be described as follows:

$$dA_1 = \frac{\sigma^2 \cdot dV}{2E}, \tag{10}$$

σ is the breaking stress due to blades creating pressure, Pa; dV is the elementary volumetric gain occurring during deformation, m^3; E is the shear modulus characterizing strength properties of this material (flesh of the product), Pa.

This formula allows acquiring total energy (work) spent on volume deformation (11):

$$A_1 = \frac{\sigma^2}{2E}\int \mathrm{d}V. \tag{11}$$

And total energy (work) spent on the section is calculated as follows (12):

$$A_2 = 2H_F \int \mathrm{d}F. \tag{12}$$

The velocity of the process can only be calculated by joint action of crush and cutting deformations. We have used the following formula (13):

$$v_p = \frac{dR}{F \cdot d\tau}, \tag{13}$$

dR=dR_1+dR_2 is the elementary crush and cutting force; F is the area of processing.

Therefore, the mathematical model of the flesh breaking process can be introduced as these combined formulas (14), (15):

$$v_p = \frac{dR}{F \cdot d\tau},$$

$$A_1 = \frac{\sigma^2}{2E}\int \mathrm{d}V,$$

$$A_2 = 2H_F \int \mathrm{d}F. \tag{14}$$

Or otherwise:

$$v_p = \frac{dR}{F \cdot d\tau},$$

$$dA_1 = \frac{\sigma^2 \cdot dV}{2E},$$

$$dA_2 = 2H_F \cdot dF. \tag{15}$$

Using these simple formulae, we can see all the profitability of using a flesh breaking tool.

4. 6. Stirring the pulp inside the cavity

The process of stirring fluid is characterized by a complex distribution of velocities in its volume. It depends on the shape and size of the reservoir and the stirrer as well as on the speed the stirrer blades are rotating [19].

According to Stokes theorem, vector circulation ā in a closed contour (as by stirring (Fig. 2)) will be expressed as follows (16):

$$S_c = \oint_c \vec{a} \cdot \delta\vec{r}, \tag{16}$$

c is the closed contour, $\vec{a}$ is the circulation vector (velocity of rotation); S_c is the $\vec{a}$ vector circulation along the closed contour c (particularly, its motion in a circle during stirring); $\delta\vec{r}$ is the elementary move (elementary path).

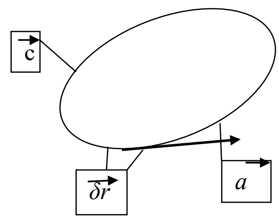


Fig. 2. Scheme of stirring in a closed contour

Juice or puree can be stirred so in a vessel. At that, the work (A_c) of closed contour motion force can be represented in the equation (17):

$$A_c = \oint_c \vec{R} \cdot \delta\vec{r}, \tag{17}$$

$\vec{R}$ is the force overcoming the resistance of fluid layers, N.

Thus, having obtained the work (A_c) of closed contour motion force, we can compute the power spent on stirring in a transient mode. Work per one time unit conducted in a closed contour constitutes the power, which can be calculated by the formula (18):

$$N = \oint_c \frac{\mathrm{d}A}{\tau}. \tag{18}$$

Afterwards, we carried out a computation of the angular velocity vector. According to the Helmholtz's first theorem, the angular velocity vector (19) is determined as follows:

$$\vec{\omega} = \frac{1}{2} \cdot rot\vec{V}, \tag{19}$$

$rot\vec{V}$ is the rotor of circumferential velocity defining the intensity of circumferential motion and is equal to a doubled angular velocity (20), (21):

$$rot\vec{V} = \vec{\Omega}, \tag{20}$$

$$\Omega = rot\vec{V} = 2 \cdot \vec{\omega}. \tag{21}$$

A rotor is a spatial derivative of velocity. The rotor is vorticity equal to a doubled angular velocity. Provided that the circulation is $G_F>0$, there is vorticity in the fluid. Thus, separate layers of the fluid and the fluid in general are stirred. Such stirring occurs more efficiently.

In order to obtain the final result, we need to find a few more values. During the stirring process, the kinetic energy in E is being conveyed (22), (23):

$$dE = \frac{\rho \cdot (\omega_0 \cdot x)^2}{2} \cdot h \cdot \omega_0 \cdot xdx, \tag{22}$$

dE is the elementary kinetic energy conveyed by the stirrer blades; ρ is the density of a fluid system, kg/m^3; ω_0 is the constant angular velocity of stirrer rotation, s^{-1}; x is the distance from the rotation axis (axis of the rotor), m; h is the height of the blade, m; dx is the elementary length of the blade, m;

$$E = \frac{\rho \cdot \omega_0{}^3 \cdot h}{2} \int_{r_1}^{r_2} x^3 \cdot \mathrm{d}x = \frac{\rho \cdot \omega_0{}^3 \cdot h}{8} \cdot \left(r_1{}^4 - r_2{}^4\right), \tag{23}$$

r_1 is the radius of the inner blade tip, m; r_2 is the radius of the outer blade tip, m.

Elementary friction force (dP) acting on a blade is represented in compliance with Newton's law (24):

$$dP = \frac{\xi \cdot \rho \cdot (\omega \cdot r_0)^2}{8} dF. \tag{24}$$

And total friction force (P) N (hydrodynamic resistance) is defined (25):

$$P = \frac{\xi \cdot F \cdot \rho \cdot (\omega \cdot r_0)^2}{8}, \tag{25}$$

F is the area of the blade, m^2; ξ is the head drag coefficient of the blade, which depends on its shape and mode of fluid movement; r_0 is the radius of the blades, m; ω is the working angular velocity of stirrer rotation, s^{-1}.

Simultaneously, a moment of friction (M_f) can be represented with the equation (26):

$$M_f = \frac{\xi \cdot F \cdot \rho \cdot \omega^2 \cdot r_0{}^2}{8}. \tag{26}$$

And a torsional moment (M_t) in the working mode (27), (28):

$$M_t = \frac{h \cdot p \cdot \omega^2 \cdot \left(r_2^4 - r_1^4\right)}{8}, \tag{27}$$

$$M_t = \frac{h \cdot \rho \cdot \omega^2 \cdot \left(r_2{}^4 - r_1{}^4\right)}{8}, \tag{28}$$

μ is the dynamic coefficient of viscosity of the fluid system, Pa·s;

Operating power (N, W) on the shaft or stirrer conforms to the equation (29), (30):

$$N = M_t \cdot \omega, \tag{29}$$

$$N = \frac{h \cdot \rho \cdot \omega^3 \cdot \left(r_2{}^4 - r_1{}^4\right)}{8}. \tag{30}$$

With the rotational speed of stirrer blades n in c/s, the angular velocity will amount to $\omega=2\pi n$, where d is the diameter of stirrer blades, and $r=d/2$.

Having completed all the calculations described above, we can make certain conclusions and determine how much energy is spent and how profitable this device is.

4. 7. Derivation of a dimensionless equation of the relative velocity of pulp stirring

After the motor of the stirrer is launched, it stabilizes quite quickly and the stirring mode becomes steady. Now we will determine a torsion torque on the stirrer shaft and blades (31), (32).

$$M_{to} = \frac{p \cdot h \cdot \omega_1^2}{8_\mu} \cdot \left(r_2^4 - r_1^4\right), \tag{31}$$

$$M_{to} = \frac{\rho \cdot h \cdot \omega_1{}^2}{8\mu} \cdot \left(r_2{}^4 - r_1{}^4\right), \tag{32}$$

M_{to} is the torsion torque on the stirrer shaft, N·m; ρ is the average density of the fluid system, kg/m^3; ω_1 is the steady angular velocity, s^{-1}; μ is the dynamic coefficient of fluid viscosity, Pa·s; r_1 and r_2 are the inner and outer radii of stirrer blades, m.

At that, the friction force is also considered. Thus, the moment of friction force of the blades relative to fluid and stirrer walls (inner cavity of watermelon) is determined as follows (33):

$$M_f = \frac{\xi \cdot F \cdot p \cdot \omega^2 \cdot r_o^3}{8} \cdot \frac{\xi \cdot F \cdot p \cdot (\omega_o \cdot \omega_1) \cdot r_o^3}{8}, \tag{33}$$

M_f is the moment of friction force, N·m; F is the friction force area, m^2; ξ is the hydraulic resistance coefficient; ω is the initial angular velocity, s^{-1}; ω_0 is the maximum operating angular velocity, gained by the blades immediately after launching, s^{-1}; $\omega_1=\omega_0-\omega$.

All the torsion torque energy transfers into the energy against friction force. Therefore, $M_{to}=M_f$ torsion torque energy, in its turn, is calculated (34), (35):

$$M_{to} = \frac{\rho \cdot h \cdot \omega_1{}^2}{8\mu} \cdot \left(r_2{}^4 - r_1{}^4\right) = \frac{\xi \cdot F \cdot \rho \cdot (\omega_0 - \omega_1)^2 \cdot r_0{}^3}{8}, \tag{34}$$

$$M_f = \frac{\xi \cdot F \cdot p \cdot \omega^2 \cdot r_o^3}{8} \cdot \frac{\xi \cdot F \cdot p \cdot (\omega_o \cdot \omega_1) \cdot r_o^3}{8}. \tag{35}$$

After rearranging, we receive a dimensionless equation (36):

$$\left(\frac{\omega_0 - \omega_1}{\omega_1}\right)^2 = \frac{h}{\xi \cdot F} \cdot \frac{r_2{}^4 - r_1{}^4}{r_0{}^3}. \tag{36}$$

The left-hand side of the equation is a dimensionless group, which is a square of similarity parameters of angular velocities during stirring. This is a criterion of the relative rate (Sd) (37), (38).

$$Sd = \frac{\omega_0 - \omega_1}{\omega_1}, \tag{37}$$

$$Sd^2 = \left(\frac{\omega_0 - \omega_1}{\omega_1}\right)^2. \tag{38}$$

Considering all the above mentioned, we acquire a dimensionless equation of the relative angular velocity during stirring (39).

$$Sd^2 = \frac{h}{\xi \cdot F} \cdot \frac{r_2^4 - r_1^4}{r_0^3}. \tag{39}$$

The criterion of relative rate (Sd) is an important component, since it remains a defining one in providing stirring of high quality (40).

$$F = 2\pi r0 \cdot H, \tag{40}$$

H is the height of the blending tank (average vertical height of the inner cavity of watermelon).

It is worth mentioning that during stirring there occur two simultaneous processes:

– macroprocess – blending of separate parts and components of the fluid system;

– microprocess – certain separation of blended components.

It was determined that optimal blending at high angular velocities is characteristic of propeller and impeller stirrers. Dimensionless groups – simplexes – were determined in the following way (41)–(43):

$$\frac{r_2^4 - r_1^4}{r_0^4} = S_r, \tag{41}$$

$$\frac{h}{H} = S_M, \tag{42}$$

$$\frac{1}{2\pi\xi} = \phi(\mathrm{Re}). \tag{43}$$

The result was a dimensionless equation of relative rate (44):

$$Sd^2 = \frac{1}{2\pi\xi} \cdot S_M \cdot S_r. \tag{44}$$

The following dimensionless equation for calculating the optimal value of Reynolds number (Re_m) was empirically proved to suit the stirrer (45):

$$\mathrm{Re}_m = 0.105 \cdot \mathrm{Ga}^{0.6} \cdot S_\rho^{0.8} \cdot S_r^{0.4} \cdot S_d^{1.9}. \tag{45}$$

Ga is Galileum number (46).

$$\mathrm{Ga} = \frac{d_m^3 \cdot g}{\upsilon^2}. \tag{46}$$

A physical simplex of particle number and environmental density can be calculated by the following equation (47):

$$S_\rho = \frac{\rho_c}{\rho_f}. \tag{47}$$

And the geometrical simplex of particle and stirrer sizes (48):

$$S_p = \frac{d_p}{d_s}. \tag{48}$$

Also we determined the geometrical simplex of the stirrer (49):

$$S_d = \frac{D}{d_s}. \tag{49}$$

The value of the minimum energy consumption corresponding to the optimal operating mode for impeller stirrers was determined empirically and constitutes (50):

$$(n\tau)_{\min} = 85 - 120, \tag{50}$$

τ is the optimal stirring time [20].

5. Results of the study

5. 1. Structure of the juice extractor for watermelon fruitage

The device for the extraction of juice from watermelon crops was created by our research group (Fig. 3).

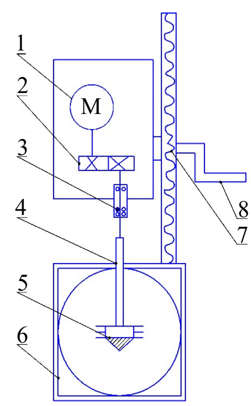


Fig. 3. Scheme of the experimental juice extractor: 1 – electric motor; 2 – gear transmission; 3 – bearing; 4 – shaft; 5 – drill; 6 – building; 7 – lifting and lowering mechanism; 8 – handle of the lifting and lowering mechanism

The presented device build by us consists of two main parts:

– extraction chamber;

– machine frame.

The extraction chamber from stainless steel consists of a turning handle (ϕ24.5×400 mm), a screw shaft (ϕ32×620 mm), a vise (ϕ100 mm), perforated inner cylinder (ϕ115×180 mm), nonperforated outer cylinder (ϕ120×180 mm) and a branch tube [21].

The machine frame (350×415×60 mm) is made from low-carbon steel with channel iron.

The apparatus mostly operates according to the principle of compressive force transfer. Loaded fruits inside the perforated inner cylinder of the compression chamber perceive the compression force applied by an operator through the turning handle and the screw shaft [22].

The juice will be extracted from fruits and collected through a juice outlet when fruit cells, which are naturally integral in fruit, will not be able to bear the applied force.

5. 1. 1. Calculations. Screw shaft (shaft)

The structure of the juicer shaft particularly takes into account the analysis of durability and rigidity. The torsion load for the solid shaft can be obtained from the ASME equation [23].

This equation (51) represents the formula for this solid shaft:

$$T = F_x, \tag{51}$$

T is the torsion torque (121.50 N·m), F is the force (675 N) (required for a human), and the distance at which the fruit will be compressed and extracted (0.18 m).

The following equation (52) was used to calculate the diameter of the shaft for the juicer:

$$D^3 = \frac{16T}{S}, \tag{52}$$

S is the permissible strain (55 MPa for a shaft without a keyway); D is the shaft diameter (32 mm); T is the torsion torque (121.50 N·m).

The operative rigidity of the shaft was considered from the permissible twist angle and for a circular shaft. The equations (3)–(5) represent the formula (53) of the twist angle and polar moment of inertia [24]:

$$\varnothing = \frac{TL}{GJ}, \tag{53}$$

Ø is the twist angle (3°); T is the torsion torque (121.50 N·m); L is the shaft diameter permissible for a torsion bend (25 mm); G is the modulus of rigidity of shaft material (80 GN/m^2); J is the polar moment of inertia for a shaft section, introduced in the equation (54) as:

$$J = \frac{\pi D^4}{32}. \tag{54}$$

Inserting D into the equations (55):

$$D^4 = \frac{32TL}{\pi G \varnothing}. \tag{55}$$

From the calculations, in order to consider stress and twisting, the construction is equipped with a shaft with a diameter of 32 mm. The equation (56) represents the formula for the pressure required for compression and breakage of the fruit based on the maximum permissible load [25]:

$$P = \frac{F}{A}, \tag{56}$$

P is the pressure conveyed for fruit breakage (1866.232 N/m^2); F is the required force (675 N); A is the area of a crosswise section of the inner perforated cylinder of the extraction chamber (0.362 m^2) [26].

5. 1. 2. Construction and operation principle

In the process of loading and extraction, there will occur pressure in the inner cylinder, which will provoke more efficient juice compression. The equation (57) was used to calculate the maximum pressure during compression [27].

$$\gamma = \frac{P_r}{4_t}, \tag{57}$$

γ is the maximum transverse strain, which the cylinder will undergo due to destruction caused by fluidity (liquid limit with a margin of safety for steel equals 70 MN/m^2); P is the inner pressure of the cylinder (35 MN/m^2); r is the inner radius of the cylinder (0.0575 m), and t is the thickness of the cylinder (13 mm) [28].

5. 2. Watermelon pulp detachment from the crust and its grinding

It should be mentioned that with the aim to extract juice, fruits can be cut arbitrarily: after being cut the pieces easily move away from the knife and do not change their shapes.

There is a concept of constrained cutting, when the cut pieces do not move and are deformed in the process of cutting. This puts additional pressure on the knife. In our experience, the flesh was cut in constrained conditions and its stirring was carried out inside the fruit.

Rotation velocity is undoubtedly important for qualitative and efficient work. But rotation velocity is of supreme influence on an operating element, since during the work process it is acted upon by two main forces:

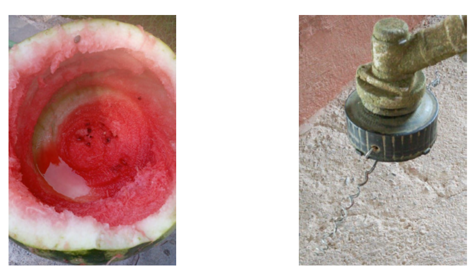
– centrifugal, which is trying to keep it in the radial position. It depends on the rotation velocity of the operating mechanism;

– force of environmental resistance resulting in a bend of the operating element. The bend depends on the environmental resistance and durability of the operating element [29].

Accurate selection of these parameters will allow cutting flesh neatly leaving the inner part of the watermelon rind untouched.

A device with a circular section would not have suited our experiment. Its flexural resistance is equal at all the axes, which allows it to bend up- and downwards while operating and find a zone of the least resistance. That is why it moves in the already cut zone, ignoring the adjacent flesh. In order to avoid it, one needs to choose another shape of an operating element, for example, rectangular. Or one needs to fix a few same-height elements with circular sections right up to each other.

We had chosen a puck-shaped operative device with two strings fixed opposite to each other. When the pucks rotate they cut the flesh of watermelon (Fig. 4) [30].



a *b*

Fig. 4. Results of breaking flesh inside a fruit conducted with the designed device: *a* — cleaned watermelon rind; *b* — operating element of the apparatus

The research of flesh properties of these watermelons concluded that the deformation of fruit under pressure increases until it reaches a certain extreme value. After that, the flesh is immediately broken.

The analysis also revealed that flesh at different points of fruit has different durability, but the compression process conforms to Hooke law.

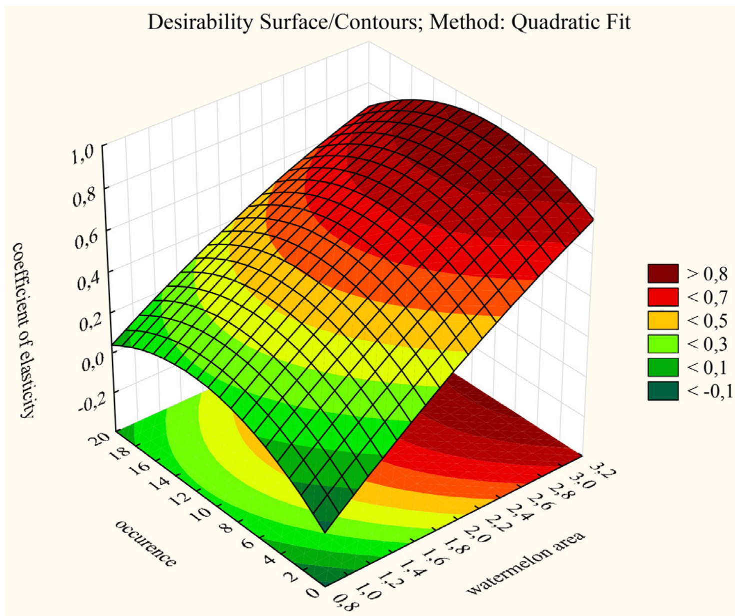
The coefficient of elasticity of flesh from a watermelon fruit is less close to the equator and higher at the pedicle. And Table 3 and Fig. 5 demonstrate that the average value of the coefficient of elasticity for the flesh of Dishim watermelon constitutes: near the pedicle – 1.56 MPa, in the equator area – 0.99 MPa, in the receptacle area – 1.32 MPa.

Table 3

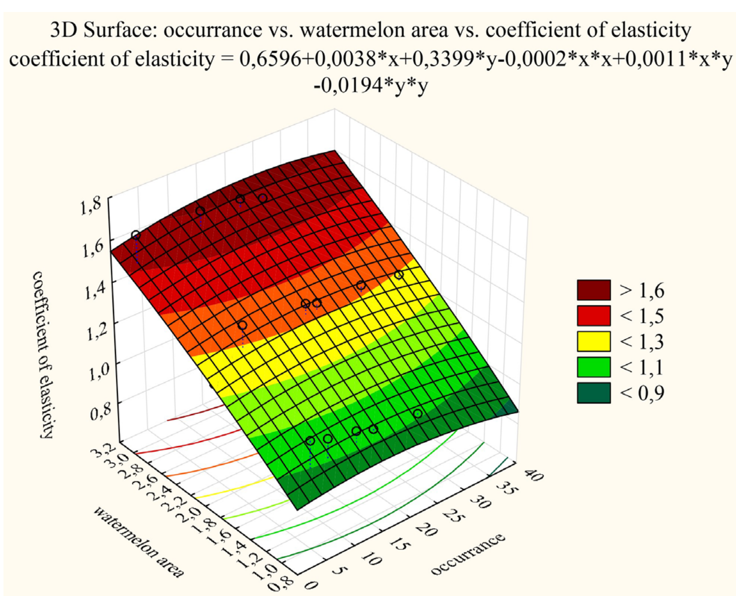
Characteristic of the elasticity coefficient of Dishim variety watermelon

Characteristic of fruits	Dishim watermelon		
	x_{max}	$\underline{x}$	x_{min}
Coefficient of elasticity in the pedicle area, MPa	1.66	1.56	1.45
	$\underline{x}$=1.56; s=0.418; V=2.17 %; m=0.034; A=0.03; E=−0.31; X=$\underline{x}$±m=1.56±0.067		
Coefficient of elasticity in the equator area, MPa	1.14	0.98	0.84
	$\underline{x}$=0.98; s=0.058; V=5.84 %; m=$4.7\cdot10^{-3}$; A=0.31; E=−0.28; X=$\underline{x}$±$t\cdot m$=0.98±$9.2\cdot10^{-3}$		
Coefficient of elasticity in the receptacle area, MPa	1.42	1.32	1.17
	$\underline{x}$=1.32; s=0.042; V=3.21 %; m=$3.5\cdot10^{-3}$; A=−0.24; E=0.41; X=$\underline{x}$±$t\cdot m$=1.32±$6.8\cdot10^{-3}$		

*Note: *s – standard deviation, V – coefficient of variation, t – Student's test, M – mean error. A and E are complementary quantities used for calculating statistical characteristic*[S]



a



b

Fig. 5. Desirability function and graph of elasticity coefficient response depending on the watermelon area: *a* — the first cut plane; *b* — the second cut plane

Analysis of the research results reveals that the force of cut at the velocity of 10...15 m/s is higher than at the speed of cutting being 0.5 m/s, but the difference between the values does not exceed 12 %.

5. 3. Determining the force of cutting watermelon flesh with a flat knife

The force of cut is necessary when evaluating the durability and capacity of knives needed for actuators of the operating elements of the device [31]. The force of cut for the flesh of melons and gourds with a flat knife was determined using a measurement system. And the results of our experiments are presented in Table 4.

Table 4

Results of studying the force of cut for flesh

No	Characteristic of fruits	Dishim		
		x_{max}	$\underline{x}$	x_{min}
1	Force of cutting flesh with a flat knife along the pedicle area, N/cm	17.47	12.96	9.52
		$\underline{x}$=12.96; s=1.37; V=10.58 %; m=0.11; A=0.05; E=0.78; X=$\underline{x}$±t·m=12.96±0.22		
2	Force of cutting flesh with a flat knife along the equator area, N/cm	14.92	12.44	9.49
		$\underline{x}$ =12.44; s=1.10; V=8.87 %; m=0.09; A=−0.36; E=0.05; X=$\underline{x}$±t·m=12.44±0.18		
3	Force of cutting flesh with a flat knife along the receptacle area, N/cm	12.24	9.23	6.93
		$\underline{x}$=9.23; s=0.91; V=9.89 %; m=0.07; A=0.05; E=0.8; X=$\underline{x}$±t·m=9.23±0.15		
4	Force of cutting flesh with a flat knife crosswise the pedicle area, N/cm	13.08	10.61	7.66
		$\underline{x}$=10.61; s=1.1; V=10.39 %; m=0.09; A=−0.36; E=0.05; X=$\underline{x}$±t·m=10.61±0.18		
5	Force of cutting flesh with a flat knife crosswise the equator area, N/cm	14.32	12.06	9.34
		$\underline{x}$=12.06; s=1.00; V=8.41 %; m=0.08; A=−0.3; E=0.03; X=$\underline{x}$±t·m=12.06±0.16		
6	Force of cutting flesh with a flat knife crosswise the receptacle area, N/cm	11.18	8.72	5.76
		$\underline{x}$=8.72; s=1.01; V=12.66 %; m=0.09; A=−0.4; E=0.04; X=$\underline{x}$±t·m=8.72±0.18		
7	Force of cutting flesh with a grinder-knife in the receptacle area at the speed of 0.5, m/s, N	111.81	84.03	62.86
		$\underline{x}$=84.03; s=8.43; V=10.03 %; m=0.69; A=0.05; E= 0.79; X=$\underline{x}$±t·m=84.03±1.35		
8	Force of cutting flesh with a grinder-knife in the equator area at the speed of 0.5, m/s, N	64.89	49.67	38.07
		$\underline{x}$=49.67; s=4.62; V=9.29 %; m=0.38; A=0.04; E=0.70; X=$\underline{x}$±t·m=49.67±0.74		
9	Force of cutting flesh with a grinder-knife in the receptacle area at the speed of 0.5, m/s, N	86.91	71.73	53.54
		$\underline{x}$=71.73; s=6.79; V=9.46 %; m=0.55; A=−0.36; E=0.05; X=$\underline{x}$±t·m=71.73±1.09		
10	Force of cutting flesh with a grinder-knife in the pedicle area at the speed of 10...15 m/s, N	103.90	91.20	75.90
		$\underline{x}$=91.20; s=5.58; V=6.11 %; m=0.46; A=−0.17; E=0.08; X=$\underline{x}$±t·m=91.20±0.89		
11	Force of cutting flesh with a grinder-knife in the equator area at the speed of 10...15 m/s, N	63.00	53.77	45.07
		$\underline{x}$=53.77; s=3.77; V=7.02 %; m=0.31; A=−0.03; E=−0.51; X=$\underline{x}$±t·m=53.77±0.60		
12	Force of cutting flesh with a grinder-knife in the receptacle area at the speed of 10...15 m/s, N	91.85	79.88	69.02
		$\underline{x}$=79.88; s=3.98; V=4.98 %; m=0.32; A=0.25; E=0.28; X=$\underline{x}$±t·m=79.88±0.64		

The average value of the force of cutting the flesh of Dishim watermelon crosswise constituted: in the pedicle area – 10.61 N/cm, in the equator area – 12.06 N/cm, in the receptacle area – 8.72 N/cm. So, the desirability function for the force of cut acts in conformance with a linear equation and directly depends on the watermelon area: green color marks the equator, red – the pedicle. Consequently, the least resistance is observed in the receptacle area [32].

The average value of the force of cut with a grinder-knife at the speed of 10...15 m/s for the flesh of Dishim watermelon equaled: in the pedicle area – 91.20 N, in the equator area – 53.77 N, in the receptacle area – 79.88 N.

5. 4. Capacity requirements

It was assumed that an adult with the average capacity of 0.075 kW is must be able to use a manual juicer. The equation introduces a formula (59) for the capacity required for the compression process:

$$P = 2\pi NT, \tag{59}$$

P is the required capacity; N – velocity (45 c/min); T – torsion torque (121.50 N m).

The result of performance evaluation (juice yield, extraction efficiency, juice content, extraction losses and extraction capacity) is presented. If we compare the results of the researchers worldwide, the literary data claims that pineapple shows the highest juice yield and extraction efficiency 68.74 % and 82.99 %, which are followed by watermelon with 63.35 % and 76.46 %, respectively. In the Citrinae group, sweet orange had the highest juice yield 51.28 %, grapes, lemons and limes had different values of juice yield – 31.54 %, 42.58 % and 22.53 %, respectively [33, 34].

6. Discussion of experimental results

There are data about watermelon juice's effect on the human body. So, it can be effective for weight loss. Several epidemiological studies showed watermelon juice has phytochemicals that can reduce the risk of Cardio Vascular Disease and contain the great antioxidant lycopene [35]. So, watermelon juice can be consumed in health feeding and preventive nutrition therapy systems.

Manufacture, especially for rural regions, needs cheep, using locally-available construction materials, and effective juice extraction machines. Many advantages are working in this direction in the world [27]. The world researches data show that extraction losses for a manual multi-purpose juicer were higher for fruits with a higher juice yield, especially for watermelon and pineapple, which constituted 5.12 % and 3.35 %, correspondingly [36]. Low juice content was observed in lime – 22.02 %, and the highest one, again, was obtained for pineapples – 66.40 %.

Discovers from all over the world are looking for universal juice extractor machines, and mainly tests are carried out in apples, watermelon, pineapples, and oranges. We had a goal to create both efficient and economic rational device. There are data that a liquid limit of juice is 45 and 46.5, 55.3 % for orange, pineapple, and watermelon, respectively. These values were lower than those obtained from oranges, pineapples, and watermelons with a machine designed in this research [37, 38].

Cutting of fruit and vegetable flesh has not been studied enough. Such aspects as loss of product quality due to long exposure, quality of the cut slices, chemical properties of a product, etc. have not been considered.

The reason for these observations can be linked to the physiology of fruits, varieties, ripening stage, natural moisture content at the time of harvesting, storing and treatment prior to juice extraction and the season when the fruits were received. Evaluation of motorized fruit juicer performance was designed and conducted. The values of 96.9 %, 94.3 % and 96.6 %, which represented extraction efficiency for peeled pineapples, oranges, and watermelons, respectively, were obtained [39, 40]. Additional researches were conducted whose results showed 83.86 % and 85.38 % extraction efficiency for orange and pineapple, correspondingly, while the manual juicer showed the average extraction efficiency of 85.38 % [18, 41]. It is possible that the size, the capacity of the machine and the level of the operator's technical knowledge resulted in better performance (of both manual and mechanical machines).

Moreover, according to the results, extraction loss when using the portable motorized extractor for pineapple juice amounted to 12.50 %. Pineapple and lime had the highest and the lowest extraction capacity – 92.85 and 29.81 (g/min), respectively. Where extraction capacities for pineapples and oranges constituted 1.32 kg/h and 1.29 kg/h, accordingly, compared to the manual juicer [41]. The multi-purpose manual juicer developed at the moment has a higher extraction capacity for pineapple (92.85 g/min) and sweet orange (79.25 g/min). Possible reasons can be associated with the initial juice content in the fruit and characteristics of the fruits, such as size and sort [42].

We carried out a performance evaluation in order to elicit the abilities of the extractor to extract juice from selected fruits. Our discoveries showed that the machine is effective for extracting juice from watermelon fruits. But it has to be studied more to understand the efficiency of the represented mechanism in different watermelon varieties in case of different physical proprieties of the watermelon crops.

7. Concl usions

1. We as constructors and testers of the juice extractor for the watermelon fruitage present the created device. The presented device operates according to the principle of compressive force transfer. And it has been noted that our juice extractor machine has several advantages. Materials used for the construction of the device are available and cheap.

2. The extractor was designed for juice extraction and was based on the compression and shift principle occurring due to the action of the conveyor frame and the screw conveyor. And the processes of pulp breakage cutting and stirring have been also studied. Dimensionless equations of these processes considering watermelon flesh and rind were derived. Because of the chosen puck-shaped operative device (with two strings fixed opposite to each other), watermelon pulp is destructed rotary. And the pulp destruction has been carried by the Hooke law (in the pulp compression process).

3. The data we have got showed crust cutting is in the function of the desirability of the cutting force acting according to a linear equation. It directly depends on the density of the watermelon area. The highest cutting force was detected in the equator area (12.06 N/cm). For the pedicle area, this parameter was 10.61 N/cm, and in the receptacle area – 8.72 N/cm.

4. We have made physical and mathematical experimental tests of the device for watermelon processing. The obtained dimensional equations can be used for determining technological parameters of the machines, which require breaking a fruit with minimum consumption.

5. The values of the given quantities depend on cinematic parameters of dynamic interaction as well as on physical-mathematical and rheological properties of melon and gourd fruits. The fruit density of different areas of watermelon crops is various. So, the destruction of the watermelon pulp in different areas is not the same. But this parameter is needed to be more studied to detect this in different watermelon varieties.

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