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Energy-efficient technologies for thermal treatment and drying of food products

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ABSTRACT

A study of the process of heat treatment, concentration, and drying of food products in a thermomechanical unit with a rotary thermosiphon was conducted. Analysis of experimental data revealed that, compared to convective drying, the dryers with a rotary thermosiphon (RTS) spend most of the energy (69.4%) on moisture evaporation. When drying dispersed products (peas, wheat), energy consumption is lower compared to the energy consumption of existing convective dryers. Energy consumption approaches the minimum when drying at the RTS condenser temperature of T_s = 142.9 °C for different rotation frequencies. In the conducted series of experiments at a rotation frequency of 28 rotations per minute (RPM) and a surface temperature of 142.9 °C, the energy consumption for the process is minimal and reaches 3.2 MJ/kg. Energy consumption is reduced by 832.9 kJ/kg of product when drying cereals that do not require boiling with the use of a thermomechanical aggregate (TMA) with RTS. The total energy consumption of the line is reduced by 30% when using TMA with RTS as a dryer and softener. When using TMA with RTS in the tomato paste production line, fuel consumption can be reduced from 46.5 kg to 30.2 kg. It is also possible to reduce specific energy consumption from 3.9 MJ/kg to 2.6 MJ/kg to intensify the thermomechanical processing of tomato mass by 1.4 times or decrease the processing time from 4,090 s to 2,900 s.

Keywords: drying, energy consumption, food product, rotary thermosiphon, thermal treatment

INTRODUCTION

Analysis of the food market shows that drying and concentration technologies are energy-intensive, limiting their use and reducing the assortment's volume. Expanding the assortment of dry and concentrated products and developing modern energy-efficient technologies is urgent and relevant (Bezbah et al., 2023; Bandura et al., 2023; Bandura et al., 2018; Bulgakov et al., 2018; Burdo et al., 2019; Kumar et al., 2024; Ihoume et al., 2023).

Dryers' designs differ in several features, including the method of supplying heat, used heat carrier used, the mutual direction of the material and drying agent movement, the condition of the material being dried, etc. Convective drying with hot air or flue gases is most common in food production. The process occurs due to heating the product with hot air or flue gases (Ononogbo et al., 2023). Air or gases move due to forced convection, so dryers of this type are called convective.

The energy efficiency indicator of dryers is the specific energy consumption, which is defined as the ratio of energy consumed to the amount of moisture removed, MJ/kg (of removed moisture). The specific moisture extraction rate (SMER) is also used, which is defined as the amount of moisture removed per unit of power, as stated in (Mustaffa et al., 2018). Essentially, this is the inverse of the specific energy consumption. For a convective dryer, this indicator is 0.08 kg/MJ, which corresponds to 11.9 MJ/kg (of removed moisture), for a screw dryer based on ring heating pipes – 0.57 kg/MJ, which corresponds to 1.7 MJ/kg (of removed moisture). The highest indicators are for sublimation drying – 45 MJ/kg (of removed moisture), the lowest, for dryers with a heat pump – 0.4 MJ/kg (of removed moisture).

Convective mine dryers are used in grain processing enterprises. For European industrial plants, the most typical productivity is 2-10 t/h. The convective drying method has significant disadvantages, which involve the irrational use of the dryer's energy. The physical energy required to convert 1 kg of water into steam is 2.5 MJ, but drying technologies consume 2.5-3 times more. Considering the useful energy spent on moisture evaporation, the efficiency of convective dryers is only 40% (Mondal and Sarker, 2024). Energy consumption of convective dryers used at enterprises reaches 8 MJ/kg of moisture removed. Energy consumption is practically maximal for dryers of this type (Mustaffar et al., 2018). In addition, the content of impurities in the drying agent (and, hence, in the product) of such dryers is not controlled.

Conductive drying is used in grain and flour mills for heating grain and drying cereals (Menon et al., 2020). Steam dryers are used for conductive drying. Heat is transferred to the grain from heated steam pipes, and air is used to remove moisture. The heat transfer surface of such dryers can be stationary or rotating. Dryers with a movable heating surface have a heat transfer coefficient almost 2 times higher than dryers with a fixed heat exchange surface. Dryers with a rotating surface are used for processing a wide range of products. However, these dryers have some disadvantages. Thus, their energy consumption reaches 7-8 MJ/kg of moisture removed. Energy consumption is almost at its maximum for dryers of this type (Mustaffar et al., 2018). They have high pressure of heating steam (0.39-0.88 MPa). They may form condensate plugs and have a low degree of mixing of the dispersed flow, as well as complex technical implementation of the process (Romdhana et al., 2015).

On the market, there is a wide range of products obtained using thermal methods of concentration, namely evaporation. The process is one of the important, but energy-consuming, technological processes. Energy consumption for evaporation is 2.8×10^9 - 0.85×10^8 kJ/kg (Burdo et al., 2020). The disadvantage is a change in the product quality depending on the duration of the heat treatment, intensive scale formation, and lack of effective ways of utilizing the energy of the secondary steam. The problem is urgent and of great importance for the food industry.

Infrared radiation (IR), ultrahigh frequencies (UHF), ultrasound, membrane technologies, contact dryers based on heat pipes (HP), and thermosiphons (TS) are used for drying and concentration.

According to Aboud et al. (2023), IR technology differs in high energy efficiency and environmental friendliness compared to traditional technologies. The process is characterised by uniformity, short duration of heating, high heat transfer rate, low energy consumption, and improved product quality.

The problem is the scaling of UHF and IR technologies. Drying, heating, and concentration installations have high productivity. For dryers and evaporation installations, it ranges from 0.3 to 16.7 kg/s or even higher. In such cases, high-power UHF generators or a large number of generators are required. As the power of the installation increases, more electricity is needed, which is technically challenging. The use of IR for heating large volumes of products is difficult because the radiation only affects the surface layer.

When combining microwaves and ultrasound, it is possible to achieve a more complex and effective product processing (Zhou et al., 2024). Ultrasound helps microwaves penetrate the product more effectively, improving the effect of microwave heating. Such technologies in the food industry require sufficiently powerful magnetrons and ultrasound generators. However, it complicates the implementation of technology.

Ononogbo et al. (2023) considered the use of various heat exchangers of recuperators. The heat exchanger-recuperator with HP in a ceramic furnace was tested. Heat recovery in the range of 76-103 kW was achieved. The use of HP heat exchangers in food technology is limited, which may be due to the specifics of food products.

Tubular heat exchangers are used to obtain a clean drying agent and to solve the problems of the penetration of carcinogens into the product. Exhaust gases are used as heat carriers (Ononogbo et al., 2020). The heat carrier moves in the tubes of the heat exchanger, and the drying air flows out. The paper examines a tray-type dryer with periodic action. The disadvantage is that such a dryer can only be used for small batches of grain. According to Alit et al. (2021), rice husk combustion gases are used as heat carriers. The device shows high thermal efficiency. The disadvantage is the need for additional fans for pumping the heat carrier.

Mustaffar et al. (2018) presented the design of a screw dryer based on an annular heat pipe. Used for drying ceramic sludge. The overall heat transfer coefficient was 35% higher than that of a conventional dryer with a steam jacket. The designed dryer is compact and saves energy during the drying process. The disadvantage is that the use of screw devices during the drying process leads to grain injury.

Bezbah et al. (2022) designed an energy-efficient grain dryer based on thermosyphons, with the energy consumption of 3.5-6.8 MJ/kg of moisture removed, depending on the surface temperature and air consumption. Design features of the dryer allow the drying process to be carried out without direct contact of combustion gases and the product. The disadvantage of the dryer is that it can only be used for drying dispersed products.

Liquid food products are concentrated by traditional methods, e.g. multi-stage vacuum evaporation. However, this method often leads to color deterioration, loss of taste and undesirable "overcooked" taste due to the thermal process, burning of the product on the heating surface.

Preservation of nutritional components and taste properties of a food product during the concentration process is a difficult task. To solve this problem, membrane separation technology appears to be a promising one. Membrane processes have several advantages, including minimal thermal damage to the product, lower equipment costs, lower energy consumption and improved retention of aromatic compounds. However, low productivity and membrane contamination remain a significant drawback of these processes (Zhun et al., 2024).

Solving these problems is possible due to the use of thermomechanical aggregates (TMA) in the food industry.

TMA's main elements are a container, a stirrer, and a heating-cooling system. In practice, the most widespread ones are capacitive aggregates of periodic action, in which the heating and cooling system is located in the body in the form of a jacket or a coil. According to the main feature, TMA's are divided into capacitive ones of intermittent and continuous action. The difference between the devices is also observed in the design of the heating and cooling system. One of the most effective is circulating and autonomous heat transfer systems. These are devices with a highly developed surface; their shape ensures efficient heat exchange, so another heating and cooling system, usually located in the wall of the case, is not needed. TMA with a rotary thermosyphon (RTS) is referred to as an autonomous one (Balanuţă et al., 2009).

The use of TMA in the food industry ensures the implementation of the following ways of reducing energy consumption:

- reduction of the energy transformation chain;
- a combination of several technological processes in the device;
- intensification of the heat and mass exchange process;
- effective delivery of energy to the product.

The use of TMA in the food industry makes it possible to achieve a significant effect in the treatment of viscous and dispersed media. In the canning and dairy industries, aggregates are used to heat milk, cream (Creamatic HDS devices), and tomato mass (KÖLLEMANN screw heat exchangers). In winemaking, aggregates of this class are used for preliminary heating of pulp (Balanuţă et al., 2009). In the sugar industry, TMAs are used when crystallizing solutions. Industries where TMAs are applied, and TMA specifications are shown in Table 1.

The efficiency of the TMA, especially when processing viscous solutions, lies in the fact that the thermal boundary layer is destroyed directly at the heating surface. This allows for higher heat transfer coefficients (Table 1) compared to conventional heat exchangers, thereby reducing energy consumption. A decisive advantage is the greater power that can be transferred to the product, compared to energy transfer through the shaft pipe or casing.

The use of a scheme with circulating TMA significantly intensifies the process, and the use of TMA with RTS, in addition to the process intensification, reduces the chain of energy thermotransformation.

The purpose of the research was to investigate the process of heat treatment, concentration, and drying of food products in TMA with RTS, to evaluate the energy efficiency of applying the developed design.

The research objectives are as follows:

- to determine the specific energy consumption when processing dispersed products;
- to evaluate the energy efficiency of TMA with RTS when drying dispersed products;
- to evaluate the energy efficiency of TMA from RTS in the line for the production of groats that do not require boiling;
- to evaluate the energy efficiency of TMA with RTS in the tomato paste production line.

MATERIALS AND METHODS

The stands for the study of heat and mass exchange processes in TMA with RTS

An experimental installation was developed to study the processes of heat and mass transfer in TMA with RTS (Figure 1).

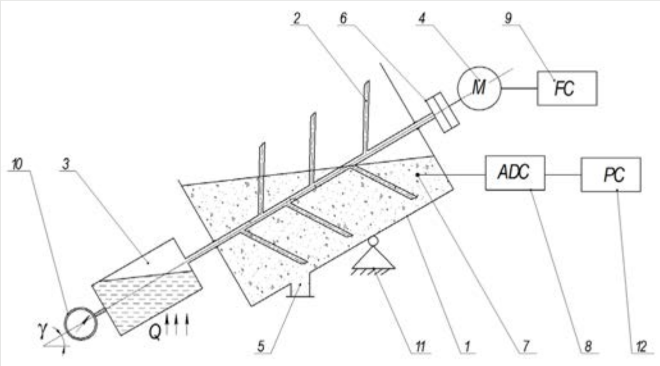


Figure 1. Scheme of the experimental installation with RTS: 1 – housing, 2 - condenser RTS, 3 – evaporator RTS, 4 – electric motor, 5 – nozzle, 6 – coupling, 7 – thermocouple, 8 – analogue-digital converter, 9 – frequency converter, 10 – manovacuometer, 11 – hinge, 12 – computer

The installation consists of a housing (1), a RTS condenser (2), a RTS evaporator (3), an electric motor (4), a nozzle (5), a coupling (6), a thermocouple (7), an analog-to-digital converter (8), a frequency converter (9), a manovacuometer (10), and a hinge (11). The RTS condenser is a branched tube mixer connected to the evaporator. The system is closed and operates under

Table 1. Fields of TMA application

Industry	Process	Product	Heat transfer coefficient, W/m^2 °C
Canning, Dairy, Winemaking	Heating, evaporation	Tomato paste, milk, pulp	950-1,000
Dairy Sugar	Cooling, crystallisation	Cream, sugar solution	900-1,000
Food concentrate	Drying	Groats, flour	250

vacuum. The evaporator is partially filled with a heat carrier. When heat is supplied to the evaporator, the heat carrier begins to boil. The steam formed is directed to the condenser, where it condenses on the walls. Thus, the heat of phase transition is transferred to the product. The steam moves due to the pressure difference between the evaporator and the condenser. The condensate moves into the evaporator under the influence of gravitational forces. The RTS implements a closed evaporative-condensation cycle, which allows for transferring large heat fluxes with a small temperature difference. The pressure inside the RTS was monitored using a vibration-resistant manovacuometer DM 063.5 (Ukraine). The RTS is connected to the motor via a coupling. The rotation speed was regulated using an ATV12 frequency converter (Schneider Electric). The K-type thermocouples (chromel-alumel) were placed in the product and connected to the analog-to-digital converter (ADAM-4018+, USA). This is an analog input module that supports the connection of eight thermocouples of different types. Upon request from the computer, the module sends data to the host through the standard RS-485 interface. The rotation speed of the RTS was controlled using a contact tachometer PCE-T 230 (PCE Instruments, Germany). The tilt angle of the RTS was measured using an electronic digital protractor TL454-200 (Taiwan). To measure the parameters of air (ambient and exhaust), a thermohygrometer with internal and external temperature sensors, PCE-HT 50 (PCE Instruments, Germany), was used. Based on the temperature and relative humidity values, the moisture content and enthalpy of the air were determined. These values were included in the heat balance equation of the dryer and influence the energy consumption of the dryer. The removal of humid air from the installation was performed by a centrifugal fan directly from the product surface (the fan is not shown in the diagram). The air capacity ranged from 0.009 m^3/s to 0.04 m^3/s.

For each type of product, the same batch sizes were used. Research was carried out according to a periodic scheme, the product was loaded into the case, dried, treated with heat, and then unloaded. The mode parameters varied: RTS inclination angle (γ); RTS rotation frequency (n); pressure in the RTS condenser (P); power supplied (Table 2).

The content of dry matter for tomato mass varied in the range of 5-25%, for apple puree, 5-20%.

The dry matter content for tomato paste ranged from 5% to 25%, while for apple puree it ranged from 5% to 20%.

For processing the experimental data, analysis of variance was used. The homogeneity of variances was tested using Cochran's criterion. The hypothesis of homogeneity of variances was accepted when the tabular value of Cochran's criterion was greater than the calculated value. The evaluation of variance differences was performed using Fisher's criterion at a 5% significance level. If the tabular value of Fisher's criterion exceeded the calculated value, it indicated that the effect of operational parameters on the drying kinetics surpassed the level of experimental data error.

Table 2. The range of measured values

Grain product	Slope of RTS, γ	RTS's rotation frequency, n	Pressure in the RTS's condenser, P	Power supplied	Initial moisture of products, ω_i
	degrees	min^{-1}	MPa	kW	%
Wheat					20
Boiled peas		14-28			25
Amaranth	30-45		0.05-0.15	0.8-1.5	20
Apple puree		2-28			95
Tomato mass					

Methodology for determining specific energy consumption when drying dispersed products

Determination of energy efficiency of the drying process in TMA with RTS was carried out by evaluating the specific energy consumption when processing the results of measurement.

The amount of moisture released during drying *W* was determined in kilograms by the formula:

$$W = G_i - G_f \quad (1)$$

where,

G_i, G_f are the masses of the initial and final material (kg), respectively.

Air consumption for the drying process, *L* in kilograms, was determined by the formula:

$$L = W / (x_2 - x_0) \quad (2)$$

where,

x_0, x_2 are the moisture content of fresh and exhausted air (kg of moisture)/kg of dry air, respectively, determined according to the I-x diagram.

Heat consumption for air heating during drying, *Q* (in Joules), was determined by the formula:

$$Q = L\,(I_1 - I_0) \quad (3)$$

where,

I_0, I_1 are air enthalpy, J/kg.

The total consumption of thermal energy for drying, Q_t (in Joules), was determined by the formula:

$$Q_t = G_{mf} \times Q_H^p \quad (4)$$

where,

G_{mf} is the mass of fuel, kg;

Q_H^p is lower heat of fuel combustion, J/kg.

Energy losses with exhaust air Q_{exh} (in Joules) were determined by the formula:

$$Q_{exh} = L \times C_h \times (t_2 - t_0) \quad (5)$$

where,

L is the air consumption for the drying process, kg;

t_0 is ambient air temperature, °C;

t_2 is air temperature after the drying chamber, °C;

C_h is the heat capacity of the air after the drying chamber, J/kg K.

Environmental losses of thermal energy from the surface of the drying chamber Q_{exh} in Joules were determined by the formula:

$$Q_{exh} = \sum Q_{exhi} \quad (6)$$

where thermal energy losses from the i-surface:

$$Q_{exhi} = \alpha\, F\,(t_{si} - t_0)\,\tau \quad (7)$$

where,

F is the area of the drying chamber, m^2;

t_0 is the ambient air tempetature, °C;

t_{si} is the temperature of the i-surface of the drying chamber, °C;

τ is the total drying time, s;

α is the coefficient of heat transfer from a heated surface to the environment, W/m^2 K:

$$\alpha = 9.74 + 0.07\,(t_{si} - t_0) \quad (8)$$

The energy consumption for the evaporation of moisture from the material, Q_{ev} (in Joules), was determined by the formula:

$$Q_{ev} = W \times r \quad (9)$$

where,

r is the heat of vaporization, *r* = 2,258.2 10^3 J/kg;

W is the amount of extracted moisture, kg.

The specific energy consumption for the drying process, *q* (Joules per kilogram), was determined by the formula:

$$q = Q_{ev} / W \quad (10)$$

where,

Q_{ev} is energy consumption for moisture evaporation from the material, J;

W is the amount of extracted moisture, kg.

Heat balance equation for drying dispersed products in TMA with RTS is as follows:

$$Q_t = G_d\, C_c\,(t_i - t_f) + L\,(i_1 - i_0) + W\,(i - t_i C_w) + Q_s \quad (11)$$

where,

G_c is the dry product consumption, kg/s;

C_c is the heat capacity of the product, J/kg K;

t_i is the initial temperature of the product, °C;

t_f is the final temperature of the product, °C;

L is the consumption of dry air, kg/s;

i_0 is the initial enthalpy of dry air, J/kg;

i_1 is the final enthalpy of dry air, J/kg;

W is the consumption of extracted moisture, kg/s;

i is the enthalpy of extracted moisture, J/kg;

C_w is the heat capacity of water, J/kg K

The total amount of heat for the drying process, Q_t in Watts, is as follows:

$$Q_t = Q_h + Q_a + Q_e + Q_l \qquad (12)$$

where,

Q_h is the amount of heat for heating the product, W;

Q_a is the amount of heat for air heating, W;

Q_e is the amount of heat for moisture evaporation, W;

Q_l is the amount of heat loss, W.

RESULTS

Results of studies of heat and mass transfer processes in TMA based on RTS

Based on equation (10) and experimental data, the specific energy consumption for the drying process was obtained. The calculation was carried out for the drying process of boiled peas in a dryer based on RTS (Figure 2).

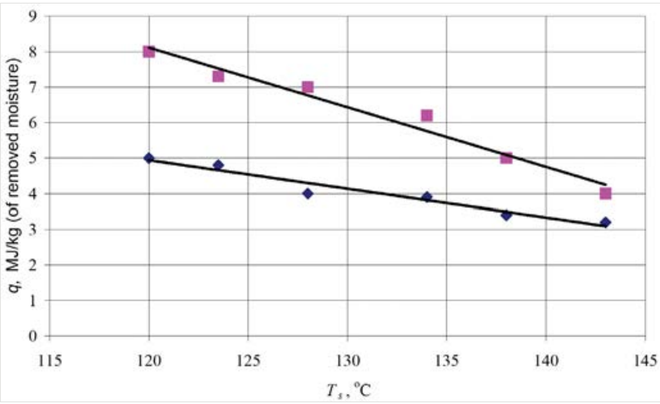


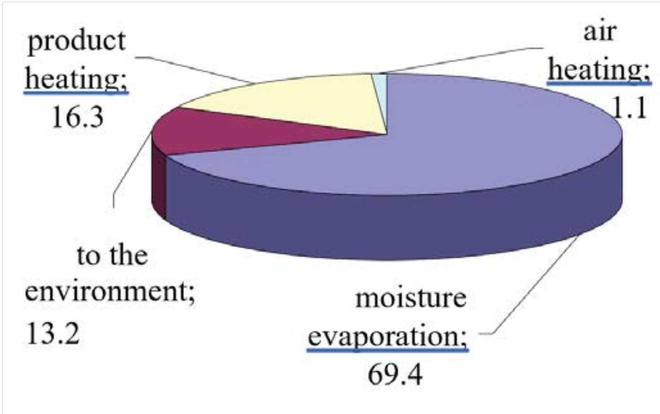
Figure 2. Dependence of specific energy consumption on the RTS surface temperature and rotation frequency when drying boiled peas: 1 – rotation frequency n = 28 rpm, 2 – rotation frequency n = 14 rpm

RTS condenser's surface temperature and the rotation frequency of the RTS affect the amount of energy consumption. An increase in surface temperature by 25 °C leads to a 2-fold decrease in energy consumption during the process. A 2-fold increase in the rotation frequency of the RTS decreases energy consumption by an average of 1.5 times.

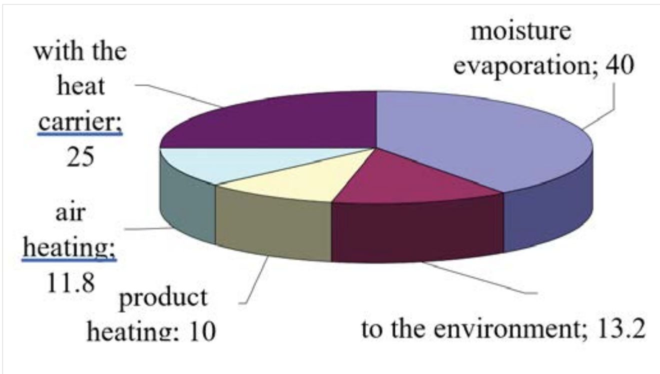
Evaluation of the energy and environmental efficiency of the proposed scheme

Based on equations (11 and 12), the energy efficiency of the proposed schemes was evaluated. As a result of the analysis, it was found that if we consider the useful energy that is spent on the evaporation of moisture in convective dryers, the efficiency coefficient is only 40%.

Analysis of experimental data shows that, compared to convective drying in RTS dryers, most of the energy (69.4%) is spent on moisture evaporation, 16.3% on product heating, 13.2% on environmental losses, and only about 1.1% on air heating (Figure 3).



(a)



(b)

Figure 3. Distribution of thermal energy in dryers: a) RTS drier, b) convective drier

The features of the RTS-based dryer allow the drying process to be carried out without the contact of combustion gases with the product. This solves the problem of the penetration of carcinogens into the product. In dryers based on HP, RTS, the air is used only as a moisture carrier. Unlike convective dryers, where air serves as both a heat and moisture carrier.

As a result, the amount of air used to remove moisture and released into the environment is several times smaller.

The enthalpy of the moist air at the outlet of the RTS dryer reaches I_2 = 200 kJ/kg, and the moisture content of the air is x_2 = 0.06 kg/kg. These parameters are nearly 3 times higher than those in the convective dryer DSP-10 (I_2 = 60 kJ/kg, x_2 = 0.024 kg/kg), which is used in grain processing enterprises. The high values of enthalpy and moisture content of the air allow it to be used as a heat carrier for preliminary grain heating. This process can be implemented in a tubular heat exchanger, where moist air passes through the inner tubes, and grain is passed around the tubes for preliminary heating. When the air temperature drops to the dew point, both moisture and dust present in the air will be removed.

Energy studies of the technological line for the production of cereals that do not require boiling

The project for the construction of TMA with RTS was developed for the current technological line for the production of cereals that do not require boiling, which is located at the production facilities of PJSC "Enni Foods" (Odesa).

The research was carried out on a line for cooking peas, which are used in the recipes of quick-cooking, briquetted soups.

For the production of instant soups, deep hydrothermal processing of raw materials (peas) and two-stage drying with intermediate flattening are used.

According to the technological scheme, raw materials are cleaned of extraneous impurities on a grain separator. After washing in a washing machine, the peas are sent to the cooking apparatus. Boiled peas are transferred to a belt dryer for drying to a moisture content of 25-27%. Dried peas are flattened on a flattening machine and dried to a moisture content of 9-9.5% in a belt dryer.

The technological scheme involves the installation of two belt dryers operating in series. Peas are flattened between drying. In production conditions, there is a problem of high energy consumption of dryers and low reliability in the operation of these devices.

An energy analysis of the industrial line for the production of dried peas was carried out. Table 3 shows the amount of electric and thermal energy consumed by the installations and the specific energy consumption for the production of a kilogram of products.

The efficiency of the apparatus or the entire line is determined by the amount of energy spent on the process to achieve the required technological effect.

The specific energy consumption for the production of products, E_{sp}, kJ/kg of products, was calculated according to the formula:

$$E_{sp} = (E + Q) / G \tag{13}$$

where,

E is the total consumption of electrical energy for technological processes,

Q is the total consumption of thermal energy in technological processes, kW,

G is line productivity, kg/s.

Having analyzed the data given in Table 3, it can be seen that the highest specific energy consumption corresponds to the technological process of drying, 2,824.8 kJ/kg of products.

A significant reduction in energy consumption can be achieved by modernizing an industrial production line for the production of cereals that do not require boiling, using the developed design of TMA with RTS instead of belt dryers. When drying the boiled product, the developed structure combines two technological processes – drying and flattening.

Table 3. Specific energy consumption in the line for the dried pea production

Name of the technological process	Electric energy, E (kW)	Thermal energy, Q (kW)	Specific energy consumption/ 1 kg of products, E_{sp} (kJ/kg)
Separation	0.6	–	0.1
Washing	1.5	–	3.8
Boiling	2.2	60.6	299.0
Drying	10.2	58.3	2,824.8
Flattening	18.5	–	44.0
Cooling	11.7	–	26.6

Figure 4 shows the specific energy consumption of the cereal production line that does not require boiling with the use of belt dryers (a), with the use of TMA with RTS as a dryer (b).

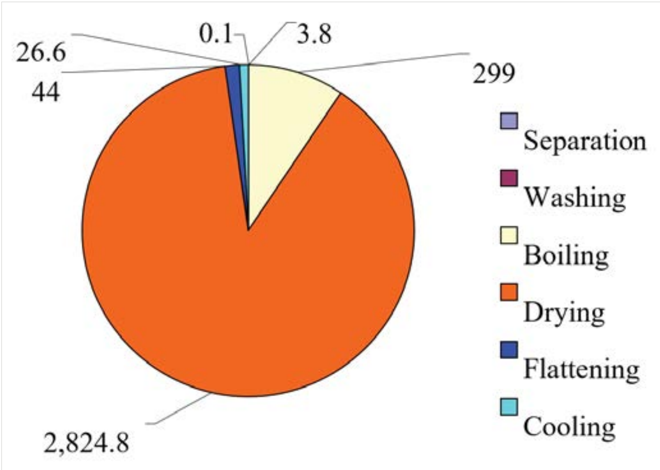
Energy consumption for the drying process in the production line of cereals that do not require boiling, with the use of TMA from RTS, is reduced by 832.9 kJ/kg of product.

The degree of crushing of peas and compliance of the granulometric composition of this product with the technological requirements were checked. The granulometric composition study was carried out by the method of sieve analysis, by mechanical separation of the material into fractions with particles of a certain size. Based on the results of the granulometric composition of dried peas after the RTS dryer, it can be concluded that the device works effectively as a softener.

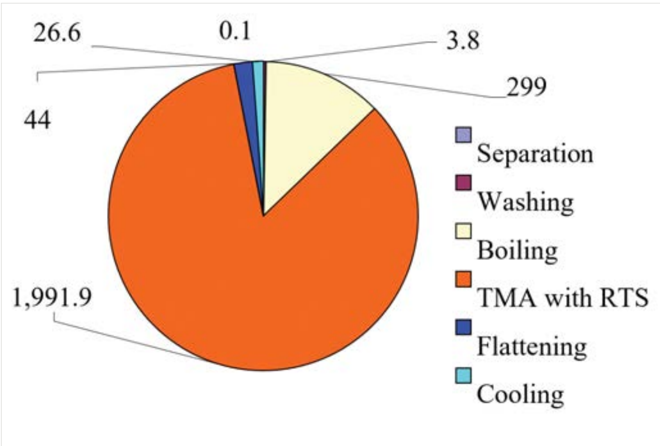
The total energy consumption in the line when using TMA with RTS as a dryer and softener is reduced by 30%.

Energy efficiency of TMA with RTS in canning production

The calculation of the apparatus for the tomato paste production line was carried out. The main technological operation in the production of tomato paste is the evaporation process. It is proposed to use RTS with the same heating surface as a heating system in the evaporation apparatus.



(a)



(b)

Figure 4. Specific energy consumption in the cereal production line that does not require boiling: a) using belt dryers, b) with the use of TMA with RTS as a dryer

The calculation is performed in two stages. The first one contains an assessment of the energy efficiency of the application of the RTS scheme in the tomato paste production line. The second is an assessment of the degree of intensification of the heat treatment process.

The causes of energy loss during its transformation, transportation and use can be established if a general principle of the study of losses' structure is developed. It is considered that such a principle can be a model of energy thermotransformation. The model of energy thermotransformation (Figure 5) shows the energy efficiency of applying a basic technological scheme with the evaporator and the scheme with RTS.

It is shown how fuel energy is transformed and enters the apparatus. The model takes into account possible energy losses. Fuel energy is transformed into water vapor energy. Steam is transported to the apparatus. At the same time, losses occur during the burning of fuel (Q_{l1} = 152 MJ), in the steam generator (Q_{l2} = 439.5 MJ), during transportation of steam to the installation (Q_{l3} = 270 MJ), from the walls of the device (Q^{l4} = 65.9 MJ), with condensate that is removed (Q_{l5} = 807.3 MJ) (Figure 5). Using the scheme with RTS, it is possible to avoid losses during the transportation of steam to the device and with condensate.

Based on the above assumptions, apparatus calculations for the tomato paste production line are performed. Boiling of tomato mass takes place in a vacuum-evaporating apparatus of periodic action (Table 5). The apparatus installed in the technological line has a cylindrical body with a spherical bottom and a cover, and a steam jacket heating chamber. An anchor-type stirrer is installed inside the device body. The working volume of the device is 750-1,000 L. The tomato mass enters the apparatus with a mass of *m* = 500 kg and an initial temperature of t_i = 90 ± 2 °C. The surface of heating of the evaporator is (3.7 m²).

Equipment specifications are compared in Table 6.

The use of the RTS scheme makes it possible to reduce energy consumption, fuel consumption, cycle time, and specific energy consumption.

The quality of tomato paste was studied in a line where the RTS was installed. Organoleptic indicators were determined: taste, smell, color, appearance, and consistency. The color of the paste is red, typical for

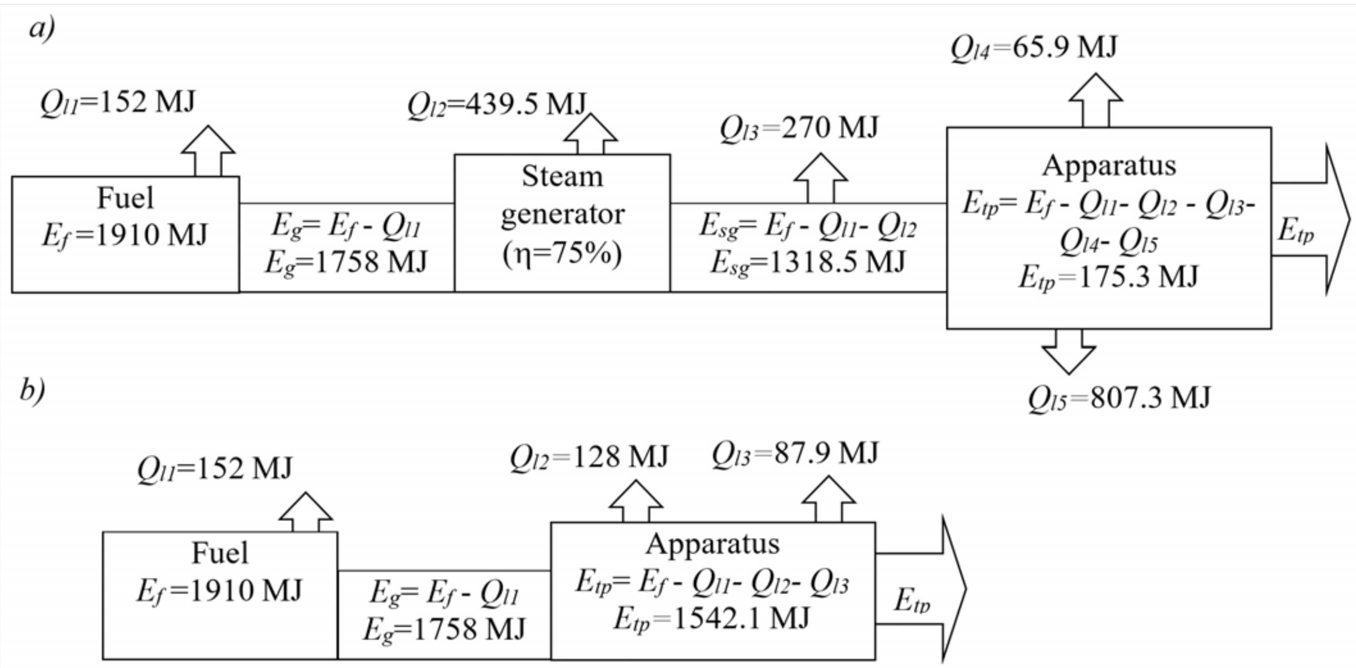


Figure 5. The model of transformation, transportation and energy loss: a) basic scheme; b) RTS scheme: E_f – Energy of fuel, Q_l – losses of energy, E_{tp} – energy transferred to the product, E_g– Energy of heat generator, E_{sg}– Energy of steam generator

Table 6. Comparison of specifications

Scheme	Unit loading, m	Energy consumption, E_f	Fuel consumption		Cycle time, τ	Specific energy consumption, E_y
	kg	MJ	kg	%	s	MJ/kg
Basic	500	1,910	46.5	100	4,090	3.9
RTS	500	1,200	30.2	63	2,900	2.6

tomato products made from ripe tomatoes, and uniform throughout the mass. The paste is homogeneous, without skin, seeds, or other defects. There is no foreign taste or odor. The dry matter content was determined using the refractometric method. The mass fraction of soluble dry substances is 25%. The quality parameters meet the standard.

DISCUSSION

The most important factors affecting energy consumption are the temperature of the heat carrier and the frequency of RTS rotation.

When the pressure of water vapor inside the RTS module increases, its surface temperature increases, the drying mode becomes more rigid, the drying speed increases, the drying time is shortened, and, as a result, energy consumption decreases.

The decrease in energy consumption with an increase in the frequency of RTS rotation (Figure 2) can be explained by the destruction of the boundary thermal layer directly by the surface of heat transfer, which leads to the process intensification.

A reduction in energy consumption is achieved due to the process intensification, the autonomy of the apparatus, and the shortening of the energy conversion chain (Figure 5).

A significant increase in the efficiency coefficient of TMA with RTS, compared with convective dryers (Figure 3), is achieved since energy is supplied to the dispersed product not due to the heated air, but due to the heated surface of the RTS with simultaneous mixing of the product.

CONCLUSIONS

When drying dispersed products (peas, wheat), energy consumption is lower compared with the energy consumption of existing convective dryers.

Based on the obtained experimental data, the specific energy consumption during the drying of dispersive products (peas, wheat) in the TMA with RTS was calculated (Figure 2). At a rotation speed of 28 rpm and a surface temperature of 142.9 °C, the energy consumption for the process is minimal, reaching 3.2 MJ/kg. When compared to dryers of other types, this value is 3.7 times lower than the energy consumption of convective dryers but 1.7 times higher than that of a screw dryer based on a ring heat pipe.

Analysis of the experimental data revealed that compared to convective drying in TMA with RTS, most of the energy (69.4%) is spent on moisture evaporation, 16.3% on product heating, 13.2% on environmental losses, and only about 1.1% on air heating (Figure 3).

Energy consumption for the drying process in the production line of cereals that do not require boiling, with the use of TMA from RTS, is reduced by 832.9 kJ/kg of product. The total energy consumption of the line when using TMA with RTS as a dryer and softener is reduced by 30%.

When using TMA with RTS in the tomato paste production line, it is possible to reduce fuel consumption from 46.5 kg to 30.2 kg and decrease specific energy consumption from 3.9 MJ/kg to 2.6 MJ/kg. It is possible to achieve an intensification of the thermomechanical processing of tomato mass by 1.4 times or reduce the processing time from 4,090 s to 2,900 s.

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