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# IMPROVING THE EFFICIENCY OF EVAPORATION PLANTS THAT PRODUCE CONDENSED MILK BY APPLYING LIQUID-VAPOR JET UNITS

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***This study's object is the evaporation unit that produces condensed milk.***

***The problem of low efficiency of evaporation units producing condensed milk has been solved by replacing steam jet ejectors with fundamentally new two-phase jet devices represented by liquid-vapor jet units. Their operational process is based on a jet thermocompression principle, which makes it possible to reduce the consumption of boiler steam, which is used in steam jet ejectors as a working jet of primary flow. In liquid-vapor jet devices, boiler steam is used only to heat the working fluid of the primary flow in a heat exchanger-heater. Given this, it is possible to reduce its consumption by 2.95 times and achieve the economic effect averaging USD 1,337.***

***Another advantage of liquid-vapor jet units is that the generation of working steam occurs in the supersonic part of the motive nozzle. As a result, it is possible to improve the degree of increase in the pressure of the secondary flow and abandon its multi-stage compression as is implemented in steam jet ejectors. This further increases the efficiency of installations based on such units by 25–30% compared to steam jet ejectors.***

***And, most importantly, the use of liquid-vapor jet devices makes it possible to simplify the design of the evaporation unit and switch from a two-case to a single-case scheme. This provides a reduction in the cost of a product unit by an average of USD 450 per ton.***

***This paper reports the thermodynamical, exergy, and thermoeconomic analyses. As a result of the study, it was found that the modernization of evaporation units that produce condensed milk by using liquid-vapor jet unit makes it possible to improve the efficiency of such systems by 2.1 times on average***

***Keywords: evaporation unit, liquid-vapor jet unit, condensed milk, recompression, efficiency, thermal economics***

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## 1. Introduction

In the modern food industry, the task to improve the efficiency of existing installations and to design new energy-saving systems is quite relevant. Such systems include evaporation units that produce condensed milk. The issue of their energy efficiency is associated with the constant growth of prices for energy carriers, in particular for electricity used in these installations to drive auxiliary equipment, as well as for boiler steam, which is the working medium for steam jet ejectors [1, 2].

Modern evaporation units for the food industry are quite energy-intensive since they include inefficient steam jet ejectors [3]. Among their disadvantages, the most significant is the low degree of increase in the pressure of the secondary flow; therefore, as a result, they are multi-stage. This leads to a large amount of auxiliary equipment, such as interstage condensers and condensate pumps. The total efficiency of such steam jet units does not exceed 10%, which leads to a rapid decrease in the efficiency of the entire evaporation unit.

In recent years, there has been significant progress in the development of milk condensation technologies, which has made it possible to improve the efficiency of evaporation units. That became possible through the introduction of thermocompression methods for utilizing secondary steam, as well as the design of more economical structures for such systems.

However, the use of steam jet ejectors and multi-body evaporation units still hinder the development and improvement of plants that produce condensed milk [4, 5]. In this regard, a relevant issue is to replace inefficient and energy-intensive equipment and simplify the design of evaporation units.

## 2. Literature review and problem statement

Modern evaporation units used in the food industry, in particular for the production of powdered milk, have been known since the second half of the 20th century but, over this time, their structure has not been significantly improved. They typically operate on the basis of steam jet ejectors and are multi-body, which significantly reduces their efficiency.

The results of studies on steam jet ejectors that create a vacuum in the working cavities of evaporation units are reported in [6, 7]. It was found by the authors that their efficiency directly depends on the operating parameters of the primary and secondary flows that participate in the working process of the steam jet ejector. However, in those papers, the issue of reducing the number of compression stages of the secondary flow in these units and, as a result, simplifying the design of the entire installation remained unresolved. In [8, 9], simplification of the structure was proposed by introducing a two-stage unit based on a steam jet ejector, which is capable of providing the parameters necessary for the process of condensed milk production. However, such a circuit solution does not significantly improve the efficiency of the entire installation.

In [10], the results of theoretical studies on evaporation units for the food industry are reported, in which recompression of secondary steam formed in the working cavities of the evaporators is used. This makes it possible to increase their efficiency; however, steam jet ejectors are still used in them.

In [7, 11], research on improving the working process of steam jet ejectors toward reducing the consumption of boiler steam, which is necessary as a working jet of the primary flow, was continued. However, the authors note that reducing the consumption of boiler steam leads to a transition to lower values of the primary flow pressures and requires the creation of a deeper vacuum for the secondary flow.

The above research results show that changing the structure of the installation and switching to other operating ranges only partially resolve the issue of energy efficiency of evaporation units for the food industry. The main problem associated with the imperfection of the working process of steam jet ejectors is still unresolved.

A possible solution may be the use of two-phase jet units, which can significantly improve the efficiency of such systems. However, the main factor hindering their implementation in various industries is the insufficient knowledge of the working process, which complicates their theoretical and experimental studies. The currently known results of research on such apparatuses indicate the prospects for their use because they are more energy-efficient and environmentally friendly [12, 13]. That is why, to improve the efficiency of evaporation units for the production of powdered milk, it is proposed to use liquid-vapor jet units (LVJUs), which operate on the principle of jet thermocompression. Due to the peculiarities of their working process, it is possible to switch from a multi-stage steam-jet unit to a single-stage one based on LVJU. Additionally, this will simplify the design of the entire evaporation unit due to the transition from a two-body to a single-body system.

To assess the feasibility of using LVJUs in evaporation units, it is necessary to perform an analysis of the efficiency of systems based on them. For this purpose, modern analytical methods can be used – exergy analysis combined with thermoeconomic analysis [14, 15]. Such a combination is advanced for assessing the efficiency of thermomechanical systems in which several types of energy are simultaneously converted and allows for fairly accurate calculation of the efficiency indicators of each component of the system, knowing only its initial and final parameters. This makes it possible to accurately determine the exergy efficiency of each element in the system, which subsequently enables defining specific ways to improve the efficiency of both a specific component and the system as a whole. As a result of such an analysis, it is possible to obtain the exergy values of the product and fuel flow and determine how appropriate the application of the proposed schemes is compared to conventional ones. That also makes it possible to determine the tariff per unit of output at which it could be supplied to the consumer, which would provide an opportunity to compare this tariff with existing analogs and choose the optimal option [16, 17]. Examples of the application of such analysis are given in [18, 19], the results of which allow us to assert the prospects of such an approach for the analysis of other thermomechanical systems, including evaporation units that produce condensed milk.

Therefore, the use of liquid-vapor jet devices will simplify the design and improve the efficiency of evaporators that produce condensed milk. The application of exergy and thermoeconomic analyses makes it possible to assess the feasibility of their use and determine the achievable efficiency indicators from their implementation.

## 3. The study materials and methods

The purpose of our study is to assess the feasibility of using liquid-vapor jet devices to improve the efficiency of existing evaporation units used in the production of condensed milk and to design new energy-efficient systems based on them. This will make it possible to simplify their structure by switching from two-body to one-body plants, as well as reduce the consumption of boiler steam required for the operation of steam jet ejectors in the basic scheme.

To achieve the goal, the following tasks were set:

– to describe the basic and proposed schemes of evaporation units that produce condensed milk, indicating specific design simplifications that occur when using liquid-vapor jet devices;

– to perform a thermodynamic analysis of the basic and proposed schemes to determine flow rates, loads, and power consumption of the devices, as well as to calculate the thermodynamic efficiency of a typical evaporation unit and a plant based on LVJU;

– to perform an exergy analysis of the basic and proposed schemes to determine the exergy of fuel and product flows, as well as the exergy efficiency of a typical evaporation unit and a plant based on LVJU as a whole. It is also necessary to take into account the degree of steam overproduction in the alternative scheme;

– to perform a thermoeconomic analysis of the basic and proposed schemes to determine the total cost of fuel and the specific cost of a unit of product in a typical evaporation unit and an LVJU-based plant. It is also necessary to take into account the degree of steam overproduction in the alternative scheme.

## 4. The study materials and methods

The object of our study is an evaporation unit that produces condensed milk.

The principal hypothesis of the study assumes the possibility of determining ways to improve the efficiency of an evaporation unit that produces condensed milk. A possible way to achieve it may involve using a liquid-vapor jet unit.

The work assumes that the system under consideration is limited only to the evaporation unit, and the mass flow rates of the main flows in the basic and proposed schemes are the same. The simplifications adopted in our study are that the complete removal of condensate occurs by pumps after the evaporators and the condenser, so none of it enters the liquid-ring vacuum pump and does not cause additional condensation in it.

This work considers a modernized evaporation unit that produces condensed milk based on a liquid-vapor jet unit, which is more energy-efficient. In this installation, LVJU is used as a forevacuum unit in combination with a liquid ring vacuum pump (LRVP). That is why our work is aimed at improving the evaporation unit that produces condensed milk by using LVJU in its structure. Studies on the influence of steam overproduction degree on the efficiency of the proposed scheme and determining the optimal operating parameters for an LVJU working process were carried out in combination with LRVP.

The working medium of the installation is water vapor. The parameters of the working medium at the inlet to the motive nozzle of LVJU are as follows: $t_{p1}$ = 103°C, $p_{p1} = 1.2 \cdot 10^5$ Pa, the pressure at the outlet of LVJU is different and depends on the suction pressure in LRVP; the pressure of the secondary flow at the inlet to LVJU is $p_{s1} = 0.331 \cdot 10^5$ Pa.

In the proposed scheme, as in the basic one, secondary steam is taken after the evaporator for its recompression in order to reduce the load on the condenser and the circulating water supply system. The task of optimizing the operating parameters in order to achieve maximum efficiency of LVJU is to ensure the maximum injection coefficient to achieve the required increase in the thermodynamic parameters of the secondary steam.

During LVJU operation, steam is overproduced, which is a consequence of the relaxation vaporization process. Therefore, it is necessary to calculate and analyze the following functional dependence

$$u = f\left(\frac{p_3}{p_{w1}}, \psi_4\right), \quad (1)$$

where $p_3$ is the pressure of the mixing flow, which provides the required parameters in the heating chamber of the first housing;

$p_{w1}$ is the pressure of the secondary steam in evaporator EA1 for the basic scheme and in evaporator EA for the alternative scheme.

The steam re-production rate [20] can be expressed in terms of the mass flow rates

$$\psi_4 = \frac{\dot{m}_4''}{\dot{m}_s}, \quad (2)$$

where $\dot{m}_4'' = \dot{m}_m + \dot{m}_{EE}$ is the mass flow rate of the vapor phase in the mixing flow (at the outlet of separator S1);

$\dot{m}_s$ – mass flow rate of the secondary flow at the inlet to the receiving chamber of LVJU

$$\psi_4 = \frac{\dot{m}_m + \dot{m}_{EE}}{\dot{m}_s}. \quad (3)$$

In turn, we can write

$$\dot{m}_s = \dot{m}_{v2} + \dot{m}_{R1}, \dot{m}_{v1} = \dot{m}_{R2} \cdot \frac{u_{v2}+1}{u_{v2}}. \quad (4)$$

Hence

$$\psi_4 = \frac{\dot{m}_m + \dot{m}_{EE}}{\dot{m}_{R1} + \dot{m}_{R2} \cdot \dfrac{u_{v2}+1}{u_{v2}}}, \quad (5)$$

or

$$\dot{m}_{R2} = \frac{\dot{m}_m + \dot{m}_{EE} - \psi_4 \cdot \dot{m}_{R1}}{\psi_4 \cdot \dfrac{u_{v2}+1}{u_{v2}}}. \quad (6)$$

Calculation of operating parameters of the evaporator that produces condensed milk assumes equality of mass flow rates, pressures, and temperatures of the main flows and secondary steam flows after the evaporator, which are sent for recompression. This is true for both the basic scheme and the alternative one.

After calculations using formulas (5) and (6), the influence of value $\psi_4$ on the efficiency of LVJU was investigated; the relationship between the operating parameters within the interval of optimal values for this evaporator was established (Fig. 1).

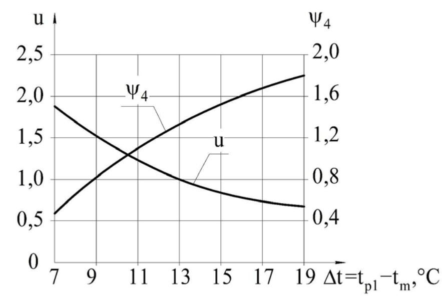


Fig. 1. Operating parameters of the liquid-vapor jet unit for conditions $p_{p1}$ = 1–1.2 bar, $t_{p1}$ = 92–104°C, $p_s$ = 0.311 bar

To assess the feasibility of using LVJU in evaporation units that produce condensed milk, thermodynamic, exergy, and thermoeconomic analyses were used.

Thermodynamic analysis for assessing the energy efficiency of thermomechanical systems is based on the postulates set out in [21]. To conduct a thermodynamic analysis, it is necessary to determine the boundaries of the system and identify the main flows participating in the energy conversion processes. Then, it is necessary to write the heat balance equation for each device of the system and for the system as a whole, which would allow us to determine their thermodynamic efficiency. As a result of thermodynamic analysis, the loads and power consumption of devices in the installation are determined, as well as the conversion coefficient (COP), which serves as an indicator of the system efficiency.

The purpose of exergy analysis is to determine the degree of exergy perfection of thermomechanical systems as a whole and each component separately [22–25]. This makes it possible to identify possible ways to improve the component with the lowest efficiency, which would allow us to improve the efficiency of the system as a whole. To obtain reliable results from exergy analysis, it is necessary to correctly determine the product and fuel flows involved in the energy conversion process in the system under consideration. As a result of exergy analysis, the exergy of product and fuel flows, the destruction of the system, and the exergy efficiency of each component and the system as a whole are determined.

Thermoeconomic analysis makes it possible to determine a change in the cost of exergy of product and fuel flows obtained as a result of performing exergy analysis [26–28]. As a result of performing thermoeconomic analysis, one can compare different types of fuel on which a thermomechanical system can operate, which would allow us to choose the cheapest and most economical one, owing to which the efficiency of the system under consideration will be the highest.

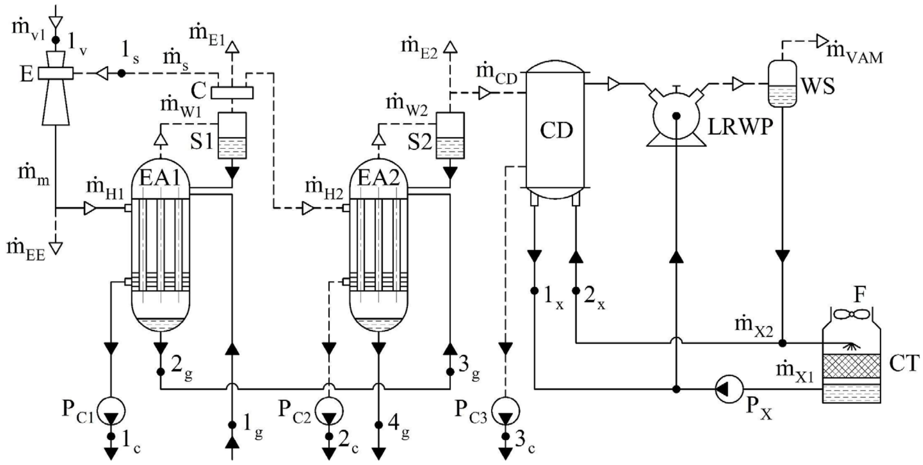


Fig. 2. Basic diagram of a two-case evaporation unit with secondary steam recompression in the first case, Wiegand 4000: E – steam jet ejector; EA1, EA2 – evaporators; S1, S2 – separators; C – collector; $P_{C1}$, $P_{C2}$, $P_{C3}$ – condensate pumps; CD – condenser; LRWP – liquid ring vacuum pump; WS – separator; $P_X$ – coolant pump; CT – cooling tower; F – fan

## 5. Results of research into the effectiveness of using liquid-vapor jet devices in evaporation units that produce condensed milk

### 5. 1. Description of circuit solutions

As a basic installation, a two-body circuit of an evaporation unit based on a Wiegand-4000 type system (manufacturer RUDISLEBEN, Germany) was considered, which is used to produce condensed milk (Fig. 2).

To achieve the required parameters in the EA1 and EA2 evaporators secondary steam recompression is used in the first stage of the two-stage steam jet ejector E. After recompression, the working mixture in separator S1 is divided into two components: extra steam for the second stage of the steam jet unit E and the main flow for the EA1 and EA2 evaporators. The temperature of the working steam at the inlet to the tank is 70°C.

In the EA1 evaporator, the process of evaporation of the milk solution to the primary (initial) concentration, which is 5–8% of the dry matter content, takes place. The secondary flow, which is physically formed in the first housing of the EA1 evaporator after passing through the S1 separator, is divided into three components. Among them are the secondary flow for the steam jet ejector E with mass flow rate $\dot{m}_S$, extra steam with mass flow rate $\dot{m}_{E2}$, and a heating flow at rate $\dot{m}_{H2}$. The latter is sent to the second housing of the EA2 evaporator to evaporate the solution to the final (required) concentration, which is 20–30% of the dry matter content.

The secondary flow, which is physically formed in the EA2 evaporator after passing through the S2 separator, is divided into two components. Namely, the heating flow with mass flow rate $m_{CD}$, which is sent to the CD condenser to heat the solution, and the extra steam with mass flow rate  The CD condenser is necessary to maintain the required vacuum value in the evaporation unit and to condense the steam that enters into heat exchange with the cooling water coming from the CT cooling tower.

As an alternative scheme, a scheme based on a liquid-vapor jet unit for recompression of secondary steam is proposed (Fig. 3). Its use makes it possible to offer an alternative, more economical option for implementing the technological process of condensed milk production in the form of a single-body installation. This additionally allows for increased economic efficiency and simplified design.

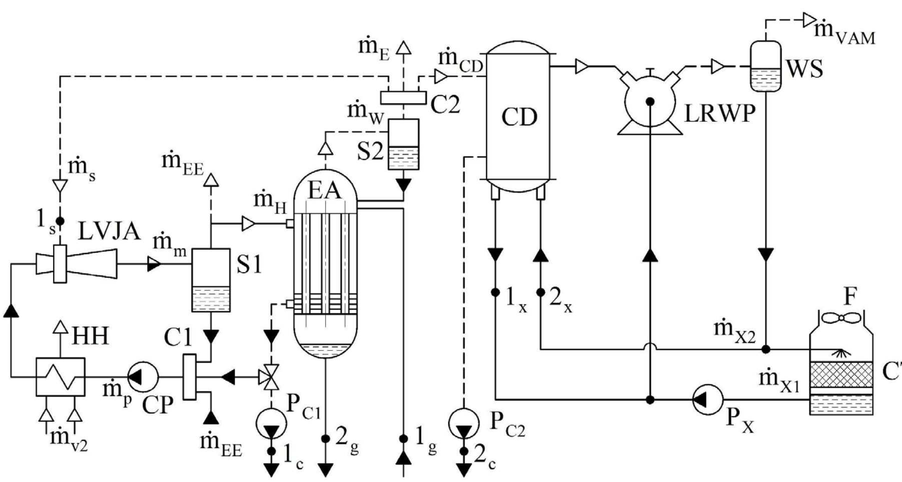


Fig. 3. Energy-saving scheme of a single-case evaporation unit based on a liquid-vapor jet unit: LVJU – liquid-vapor jet unit; EA – evaporator; S1, S2 – separators; C1, C2 – collectors; HH – heat exchanger-heater; CP – circulation pump; $P_{C1}$, $P_{C2}$ – condensate pumps; CD – condenser; LRWP – liquid-ring vacuum pump; WS – separator; $P_X$ – coolant pump; CT – cooling tower; F – fan

The use of LVJU in the technological scheme of secondary steam recompression is less energy-consuming than in the cases of using compressors of any type. The necessary parameters of the secondary steam after the evaporator are achieved due to the peculiarities of the LVJU working process. The working steam flow is formed inside the apparatus through the boiling of the working fluid in the supersonic part of the motive nozzle. This is the main difference from the basic scheme, in which the main flow is boiler steam, which is heated and supplied under pressure to the primary flow nozzle of the steam jet ejector. In the proposed scheme, boiler steam is used only for heating the working fluid of the primary flow in the heat exchanger-heater NN.

Due to the ability to generate in one stage of LVJU a larger vacuum value of the secondary flow at the entrance to the receiving chamber, it is possible to switch from a two-body evaporation unit to a one-body one. In it, the working flow, after passing through evaporator EA, will be divided into three components. Among them, the secondary flow for LVJU with mass flow rat $\dot{m}_S$, the heating flow with mass flow rate $m_{CD}$, which is sent to condenser CD to heat the solution, and the extra steam with mass flow rate $\dot{m}_E$. The temperature of the flow, which is the secondary flow for LVJU, has a temperature of 50°*C*.

In both schemes, condenser CD is cooled by water from cooling tower CT. In the steam cavity of the condenser, even when using all separators and vacuum units, when the condenser unit is operating under operating modes, there are gases that do not condense. That is why, to remove them, both in the basic and in the proposed schemes, a liquid ring vacuum pump LRWP is used. It is connected to the condenser steam line. For the operation of the LRWP pump itself, a cooling line is provided, coming from cooling tower CT. Pumps $P_{C1}$ and $P_{C2}$ are provided to remove condensate from heat exchangers and evaporators. The heat that can be obtained during additional cooling of the condensate can be used for heat recovery needs, in particular, for heating auxiliary production facilities.

The energy supply for both schemes of the evaporator unit includes the use of two types of energy: electric – to drive vacuum, hydraulic pumps, and fans, and thermal, which comes from the boiler room.

A feature of the working process of LVJU is that in its output section we obtain a two-phase vapor-drop flow, which is characterized by the degree of steam overproduction [20]. This means that a certain amount of working fluid must be constantly added to the cycle to ensure a material balance between the primary and secondary flow. This degree of steam overproduction directly affects the efficiency of both the LVJU and the unit based on it.

Our paper considers the influence of the degree of steam overproduction on the efficiency of the evaporation unit.

**5. 2. Results of thermodynamic analysis**

The calculation of the efficiency of implementing an evaporation unit that produces condensed milk based on a liquid-vapor jet unit was performed according to the methodology given in [21].

The drive power of condensate pumps is determined from the following formula

$$\sum P_C = \sum \frac{\dot{m} \cdot v' \cdot \Delta p}{\rho_w \cdot \eta_p \cdot \eta_{eng}}, \tag{7}$$

where $\Delta p$ is the change in pressure of the pumped medium in the pump;

$\rho_w$ is the density of the pumped medium in the pump;

$\eta_p$ is the pump efficiency;

$\eta_{eng}$ is the pump drive efficiency.

The pump drive power for pumping the coolant is determined from the following formula

$$P_X = \frac{\left(\dot{m}_{\delta} + \dot{m}_{LWRP}\right) \cdot v' \cdot \Delta p}{\rho_w \cdot \eta_p \cdot \eta_{eng}}. \tag{8}$$

In addition, when performing the thermodynamic analysis, the influence of the degree of steam overproduction for the alternative scheme was taken into account. The thermodynamic analysis resulted in determining the conversion coefficient of each scheme variant.

The results of the thermodynamic calculation are given in Table 1.

Table 1

Thermodynamic calculation results

| No. of entry | Parameter | Designation | Dimensionality | Basic EU | EU with LVJU | | |
|---|---|---|---|---|---|---|---|
| | | | | | $\psi_4 = 1.2$ | $\psi_4 = 1.4$ | $\psi_4 = 1.6$ |
| 1 | Power consumption of condensate pumps | $P_{C1}$ | kW | 0.25 | 0.18 | 0.182 | 0.185 |
| | | $P_{C2}$ | kW | 0.12 | 0.107 | 0.11 | 0.114 |
| | | $P_{C3}$ | kW | 0.10 | – | – | – |
| 2 | Boiler steam mass flow rate | $\dot{m}_v$ | kg/h | 1550 | 688.5 | 515 | 375.2 |
| 3 | Condenser heat load | $\dot{Q}_{CD}$ | kW | 676.3 | 676.3 | 676.3 | 676.3 |
| 4 | Condenser coolant mass flow rate | $\dot{m}_{X1}$ | kg/s | 54.13 | 54.13 | 54.13 | 54.13 |
| 5 | Vacuum pump volumetric efficiency under suction conditions | $\dot{V}_{LWRP}$ | m$^3$/min | 4.02 | 4.02 | 4.02 | 4.02 |
| 6 | Mass flow rate of refrigerant through vacuum pump | $\dot{m}_{X2}$ | kg/s | 0.2 | 0.2 | 0.2 | 0.2 |
| 7 | Power consumption of vacuum pump | $P_{LWRP}$ | kW | 7.25 | 6.83 | 6.83 | 6.83 |
| 8 | Volume flow rate of coolant through pump | $\dot{V}_{PX}$ | m$^3$/h | 195 | 190 | 190 | 190 |
| 9 | Coolant pump power consumption | $P_X$ | kW | 7.2 | 6.15 | 6.15 | 6.15 |
| 10 | Cooling tower fan volumetric efficiency | $\dot{V}_F$ | m$^3$/s | 95 | 85 | 85 | 85 |
| 11 | Cooling tower fan power consumption | $P_F$ | kW | 0.941 | 0.079 | 0.079 | 0.079 |
| 12 | Total equipment drive electrical power | $\sum P$ | kW | 15.391 | 13.059 | 13.059 | 13.059 |
| 13 | VA conversion coefficient | $COP_{BA}$ | – | 21.87 | 41.25 | 34.86 | 30.81 |

As a result of thermodynamic analysis, it can be stated that it is advisable to use liquid-vapor jet devices. Due to this, the mass flow rate of boiler steam is reduced by an average of 2.95 times, the power consumption of the installation is reduced by 18%, and the conversion coefficient of the evaporator increases by an average of 63%. The influence of the degree of steam overproduction in evaporation installations based on LVJU was also studied. With an increase in the degree of steam overproduction, their efficiency decreases. In the optimal range of the degree of steam overproduction [20], their efficiency is the highest.

### 5. 3. Results of exergy analysis

Exergy analysis was performed according to the methodology described in [22–25]. The diagram of exergy transformations in the basic and proposed schemes is shown in Fig. 4.

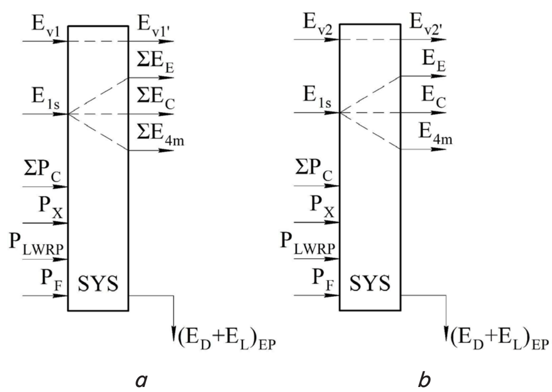


Fig. 4. Diagram of exergy transformations: *a* — in the basic scheme; *b* — in the alternative scheme

The ratio of exergy efficiencies of the compared plants can be written as

$$\frac{\varepsilon^{LVJA}}{\varepsilon^{BAS}}=\frac{E_P^{LVJA}/E_F^{LVJA}}{E_P^{BAS}/E_F^{BAS}}. \qquad (9)$$

Due to the fact that the exergy of the product flow of the installation is the same for both schemes, that is, $E_P^{LVJA}=E_P^{LVJA}$, we obtain the following expression

$$\frac{\varepsilon^{LVJA}}{\varepsilon^{BAS}}=\frac{E_F^{BAS}}{E_F^{LVJA}}, \qquad (10)$$

where $E_F^{BAS}$. $E_F^{LVJA}$ is the exergy of the fuel flow for the basic and alternative schemes, respectively.

In turn, after exergy transformations we have the following expressions for determining the exergy of the fuel flow:

– for the basic scheme

$$E_F^{BAS}=\left(\Delta E_v\right)_{VE}^{BAS}+\sum P_{C1}+P_X+P_{LWRP}+P_F; \qquad (11)$$

– for an alternative scheme

$$E_F^{LVJA}=\left(\Delta E_v\right)_{HH}+\sum P_{C2}+P_X+P_{LWRP}+P_F, \qquad (12)$$

where $\left(\Delta E_v\right)_{VE}^{BAS}$, $\left(\Delta E_v\right)_{\acute{I}\acute{I}}$ – change in boiler steam exergy in the steam jet unit of the basic scheme and in the heat exchanger-heater for the alternative scheme;

$\Sigma P_{C1}$, $\Sigma P_{C2}$ – total power of condensate pump drives for the basic and alternative schemes, respectively;

$P_X$ – power of the pump drive for pumping the coolant;

$P_{LWRP}$ – power of the vacuum pump drive;

$P_F$ – power of the cooling tower fan.

The change in boiler steam exergy is determined from the following formulas:

– for the basic scheme

$$\left(\Delta E_v\right)_{VE}^{BAS}=\dot{m}_{v1}\cdot\left[r\left(t_{v1}\right)-T_{env}\cdot\left(s''_{v1}-s'_{v1}\right)\right]=\dot{m}_{v1}\cdot\Delta e_{v1}; \qquad (13)$$

– for an alternative scheme

$$E_F^{LVJA}=\dot{m}_{v2}\cdot\Delta e_{v2}, \qquad (14)$$

where $\dot{m}_{v1}$, $\dot{m}_{v2}$ – mass flow rates of boiler steam for the basic and alternative schemes, respectively;

$r\left(t_{v1}\right)$ – heat of condensation of boiler steam at temperature $T_{bs}$;

$T_{env}$ – ambient temperature;

$s''_{v1}$, $s'_{v1}$ – specific entropy of boiler steam in the state of dry saturated steam and saturated liquid, respectively;

$\Delta e_{v1}=\Delta e_{v2}$ – change in specific exergy of boiler steam (for calculation, we assume the same conditions for boiler steam parameters for both schemes, namely $p_v = 8$ bar, $T_v = 172°C$).

The results of exergy analysis are given in Table 2.

As a result of exergy analysis, it was found that the use of liquid-vapor jet devices in evaporation units that produce condensed milk increases their efficiency by an average of 2.03 times. The degree of steam overproduction also affects the value of exergy efficiency of the evaporation unit based on LVJU. With an increase in the degree of steam overproduction from $\psi_4 = 1.2$ to $\psi_4 = 1.6$, the exergy efficiency of the plant decreases by 84%.

Table 2

Results of exergy analysis

| No. | Parameters | Designation | Dimensionality | Basic EU | EU with LVJU | | |
|---|---|---|---|---|---|---|---|
| | | | | | $\psi_4 = 1.2$ | $\psi_4 = 1.4$ | $\psi_4 = 1.6$ |
| 1 | Product flow exergy | $E_P$ | kW | 41.43 | 41.43 | 41.43 | 41.43 |
| 2 | Fuel flow exergy | $E_F$ | kW | 321.163 | 120.436 | 161.206 | 221.55 |
| 3 | Evaporation plant exergy efficiency | $\varepsilon$ | – | 0.129 | 0.344 | 0.257 | 0.187 |

### 5. 4. Results of thermoeconomic analysis

We performed thermoeconomic analysis according to the methodology described in [26–28]. Based on this methodology, the scheme of changes in the cost of exergy in the process is shown in Fig. 5.

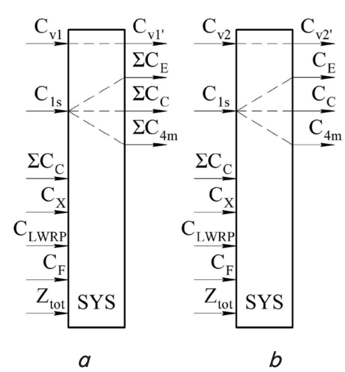


Fig. 5. Scheme of changes in the cost of exergy: *a* — in the basic scheme; *b* — in the alternative scheme

The system of equations for determining the change in the cost of exergy takes the following form:

– for the basic scheme

$$\begin{cases} c_{P,E}\cdot E_{P,E}=c_{F,E}\cdot E_{F,E}+Z_E, \\ c_{P,EA1}\cdot E_{P,EA1}=c_{F,EA1}\cdot E_{F,EA1}+Z_{EA1}, \\ c_{P,EA2}\cdot E_{P,EA2}=c_{F,EA2}\cdot E_{F,EA2}+Z_{EA2}, \\ c_{P,\Sigma P_C}\cdot E_{P,\Sigma P_C}=c_{F,\Sigma P_C}\cdot E_{F,\Sigma P_C}+Z_{\Sigma P_C}, \\ c_{P,P_X}\cdot E_{P,P_X}=c_{F,P_X}\cdot E_{F,P_X}+Z_{P_X}, \\ c_{P,P_{LWRP}}\cdot E_{P,P_{LWRP}}=c_{F,P_{LWRP}}\cdot E_{F,P_{LWRP}}+Z_{P_{LWRP}}, \\ c_{P,F}\cdot E_{P,F}=c_{F,F}\cdot E_{F,F}+Z_F; \end{cases} \tag{15}$$

– for an alternative scheme

$$\begin{cases} c_{P,LVJA}\cdot E_{P,LVJA}=c_{F,LVJA}\cdot E_{F,LVJA}+Z_E, \\ c_{P,EA}\cdot E_{P,EA}=c_{F,EA}\cdot E_{F,EA}+Z_{EA}, \\ c_{P,\Sigma P_C}\cdot E_{P,\Sigma P_C}=c_{F,\Sigma P_C}\cdot E_{F,\Sigma P_C}+Z_{\Sigma P_C}, \\ c_{P,P_X}\cdot E_{P,P_X}=c_{F,P_X}\cdot E_{F,P_X}+Z_{P_X}, \\ c_{P,P_{LWRP}}\cdot E_{P,P_{LWRP}}=c_{F,P_{LWRP}}\cdot E_{F,P_{LWRP}}+Z_{P_{LWRP}}, \\ c_{P,F}\cdot E_{P,F}=c_{F,F}\cdot E_{F,F}+Z_F, \end{cases} \tag{16}$$

where $c_{P,E}$, $c_{F,E}$ is the exergy cost of the product and fuel flow of the steam jet ejector for the basic scheme;

$Z_E$ – cost of capital costs of the steam jet ejector for the basic scheme;

$c_{P,LVJA}$, $c_{F,LVJA}$ – exergy cost of the product and fuel flow of LVJU for the alternative scheme;

$Z_{LVJA}$ – cost of capital costs of LVJU for the alternative scheme;

$c_{P,EA1}$, $c_{F,EA1}$, $c_{P,EA2}$, $c_{F,EA2}$ – exergy cost of the product and fuel flow of the first and second evaporator casings, respectively, for the basic scheme;

$Z_{EA1}$, $Z_{EA2}$ – cost of capital costs of the first and second evaporator casings, respectively, for the basic scheme;

$c_{P,\Sigma P_C}$, $c_{F,\Sigma P_C}$ – exergy cost of the product and fuel flows of the condensate pumps for the basic and alternative schemes;

$Z_{\Sigma P_C}$ – cost of capital costs of condensate pumps for the basic and alternative schemes;

$c_{P,P_X}$, $c_{F,P_X}$ – cost of exergy of the product flow and fuel of the coolant pump for the basic and alternative schemes;

$Z_{P_X}$ – cost of capital costs of the coolant pump for the basic and alternative schemes;

$c_{P,P_{LWRP}}$, $c_{F,P_{LWRP}}$ – cost of exergy of the product flow and fuel of the liquid ring vacuum pump for the basic and alternative schemes;

$Z_{P_{LWRP}}$ – cost of capital costs of the liquid ring vacuum pump for the basic and alternative schemes;

$c_{P,F}$, $c_{F,F}$ – cost of exergy of the product flow and fuel of the fan for the basic and alternative schemes;

$Z_F$ – cost of capital costs of the fan for the basic and alternative schemes.

The results of thermoeconomic analysis are given in Table 3.

Table 3

Results of thermoeconomic analysis

| No. | Parameter ID | Basic EU | EU with LVJU | | |
|---|---|---|---|---|---|
| | | | $\psi_4 = 1.2$ | $\psi_4 = 1.4$ | $\psi_4 = 1.6$ |
| 1 | Total cost of fuel, c. u. | 2,716.50 | 1,587.28 | 1,372.20 | 1,179.06 |
| 2 | Specific cost of product unit, c. u./t | 1.736 | 1.438 | 1.314 | 1.104 |

As a result of thermoeconomic analysis, we have results that confirm the feasibility of using liquid-vapor jet devices in evaporation units. This is evidenced by a reduction in the total cost of fuel, as well as the specific cost of a product unit by an average of 25.9%. Our analysis does not take into account the savings in materials associated with the simplification of the design and the transition to a single-body scheme of the evaporation unit. This could provide an additional economic effect from the introduction of new technology.

## 6. Discussing the feasibility of introducing liquid-vapor jet devices in evaporation units that produce condensed milk

Owing to the combination of secondary steam recompression and the introduction of liquid-vapor jet units, it has become possible to solve the issue of improving the efficiency of evaporation units that produce condensed milk. An additional solution was to simplify the design scheme of the plant by switching to single-body evaporation.

The proposed schematic solution (Fig. 3) is based on previous studies reported in [7, 11, 12], in which preliminary optimization of the existing evaporation unit was carried out by introducing the secondary steam recompression process. This improvement, even at the initial stage, makes it possible to improve the efficiency of the entire system without interfering with the working process in individual components of the scheme.

Our results of thermodynamic analysis make it possible to determine the conversion coefficient of the evaporator, which is key when studying the influence of the degree of steam overproduction, which is indicated in Table 1. Table 2 gives the values of exergy efficiency for each of the schemes taking into account the degree of steam overproduction. The optimal value of the degree of steam overproduction is the value in the range $\psi_4 = 1.1$–$1.25$ [20]. This is confirmed by the results of thermodynamic and exergy analyses. Table 3 gives the monetary expression of fuel cost savings for the alternative scheme, as well as the value of the specific cost of a unit of product depending on the degree of steam overproduction.

The use of liquid-vapor jet devices makes it possible to solve the task of improving the efficiency of vacuum evaporation units that produce condensed milk by introducing liquid-vapor jet devices into them. Due to this, their efficiency increased by an average of 2.03 times compared to the use of steam jet ejectors in basic schemes [6–8, 12, 13]. This is fully possible due to the transition from two-stage steam jet ejectors to a single-stage unit based on LVJU. The use of LVJU also makes it possible to simplify the structure of the evaporation unit due to the ability to achieve the required parameters in a single-body evaporator. The physical properties of the structural materials from which they are made can serve as the limits of the use of liquid-vapor jet devices. They determine the maximum possible value of the secondary flow vacuum that can be generated in the receiving chamber. Our results could be applied not only to evaporation units operating under a vacuum mode as this methodology allows calculations to be performed for similar systems operating under a compressor mode.

The disadvantages of the study include the simplifications and assumptions adopted when conducting a comparative analysis of the basic and alternative schemes. Among them are those related to the equality of mass flows of the main flows participating in the energy conversion process in the production of condensed milk. In reality, the mass flows will be somewhat different since the additional part of the water that must be returned to the LVJU cycle before the circulation pump changes the material balance of the flows by approximately 3–3.5%. However, this does not significantly affect the results obtained.

Another inaccuracy in the calculation is the fact that the transition to a plant with one evaporator will slightly change the operating parameters of the condensate that will be removed from this device. However, this inaccuracy only affects the result by 0.5%.

This study is the initial stage of investigating the feasibility of using liquid-vapor jet devices in the food industry, in particular in evaporation units that produce condensed milk. Its continuation can be an experimental study of LVJU under the operating modes listed in Table 1. Supplementing our theoretical study and comparative analysis with an experimental part would allow us to determine not only the operating and thermodynamic parameters of LVJU but also optimize the design and geometry of its flow part. The structure of LVJU should include its layout, that is, whether the device has a diffuser or not. Optimization of the geometric shape of the flow part involves determining the shape of the supersonic part of the primary flow nozzle and the shape of the confuser part in the mixing chamber.

## 7. Conclusions

1. We have described the basic and proposed schemes of evaporation units that produce condensed milk. In the proposed scheme, inefficient steam-jet ejectors were replaced with liquid-steam jet devices, which made it possible to simplify the design by switching to a single-body evaporation unit.

2. As a result of our thermodynamic analysis, it was determined that the use of liquid-steam jet devices in evaporation units that produce condensed milk makes it possible to reduce boiler steam consumption by 2.95 times. At the same time, the conversion coefficient of the evaporator in the alternative scheme increases by an average of 63%.

3. As a result of our exergy analysis, the exergy efficiency of the basic and proposed schemes was determined. The use of liquid-steam jet devices increases the efficiency of the alternative scheme by an average of 2.03 times.

4. As a result of our thermoeconomic analysis, it was determined that the specific cost of a unit of product decreases by an average of 25.9%. Savings in electricity and boiler steam would amount to an average of USD 1366.99 per month. The calculations were performed without taking into account the savings due to the transition to a single-casing scheme, which could provide an additional economic effect. Thus, the use of liquid-vapor jet devices in evaporation units that produce condensed milk is advisable, but it is necessary to enable such an operating mode that the degree of steam overproduction is at the level of $\psi_4 = 1.2$. In this case, the efficiency of LVJU operation will be the highest.

## Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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## Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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