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Original article

Electrotechnological Heat Treatment of Milk: Energy and Exergy Efficiency

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Abstract.
The dairy industry needs new and more energy-efficient technological procedure for milk pasteurization. This article introduces a comparative efficiency assessment of various milk pasteurization technologies and electrotechnological means.

The study featured milk, which was heated from 20 to 75°C with a capacity of 1000 kg/h at an estimated power of 58.95 kW. The treatment involved a steam-to-milk pasteurizer with electric indirect or direct heating, an induction pasteurizer, and a thermosiphon pasteurizer with direct or indirect electric heating. The study relied on the methods of energy and exergy analyses.

The system of steam-to-milk pasteurizer with electric indirect (elemental, induction) or direct (electrode) heating demonstrated the following indicators: exergy loss – 1.29 kW, power consumption – 71.29 kW, exergy efficiency – 0.99, energy efficiency – 0.827. The thermosiphon pasteurizer with direct or indirect electric heating demonstrated the following properties: exergy loss – 1.29 kW, power consumption – 60.92 kW, exergy efficiency – 0.99, energy efficiency – 0.9676. The induction pasteurizer had the least competitive parameters: exergy loss – 10.8 kW, power consumption – 70.43 kW, exergy efficiency – 0.867, energy efficiency – 0.837.

The thermosiphon pasteurizer with direct or indirect electric heating was able to increase the energy efficiency of milk pasteurization, while the induction pasteurizer proved to be a promising R&D direction.

Keywords. Pasteurization, dairy products, exergy efficiency, energy efficiency, electrotechnology, direct heating, indirect heating, induction heating, thermodynamic properties

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Энергетическая и эксергетическая оценка электротехнологических средств термической обработки молока

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Аннотация.
Поиск и обоснование перспективных направлений повышения энергоэффективности технологических процессов пастеризации молока является актуальной научно-технической проблемой. Целью настоящей работы являлось получение сравнительной оценки эффективности технологий и технических устройств пастеризации молока с использованием электротехнологических средств.

Объектом исследования являлся процесс нагрева молока от 20 до 75 °C производительностью 1000 кг/ч при расчетной мощности 58,95 кВт в разных устройствах термической обработки молока: пастеризатор «водяной пар – молоко» с использованием электротехнологических средств нагрева, пастеризатор индукционного типа и термосифонный пастеризатор с использованием прямого или косвенного электронагрева. Использовали методы энергетического и эксергетического анализа.

Система «пастеризатор молока “водяной пар – молоко” с использованием электрического косвенного (с помощью элементного, индукционного) или прямого (электродного) нагрева» характеризуется следующими показателями: потери эксергии – 1,29 кВт, потребляемая мощность – 71,29 кВт, эксергетический КПД – 0,99, энергетический КПД – 0,827. Для системы «термосифонный пастеризатор с использованием прямого или косвенного электронагрева» характерны: потери эксергии – 1,29 кВт, потребляемая мощность – 60,92 кВт, эксергетический КПД – 0,99, энергетический КПД – 0,9676. Наименее конкурентоспособными параметрами обладает пастеризатор индукционного типа: потери эксергии – 10,8 кВт, потребляемая мощность – 70,43 кВт, эксергетический КПД – 0,867, энергетический КПД – 0,837.

Для повышения энергоэффективности процесса пастеризации молока целесообразно использовать систему «пастеризатор термосифонного типа с использованием прямого или косвенного электронагрева». Перспективным направлением дальнейших исследований следует считать совершенствование системы типа «пастеризатор индукционного типа».

Ключевые слова. Пастеризация, молочные продукты, эксергетическая эффективность, энергетическая эффективность, электротехнология, прямой нагрев, косвенный нагрев, индукционный нагрев, термодинамические свойства

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Introduction

The current development trends are such that food enterprises are increasing in capacity but decreasing in number. As a result, it takes longer to ship dairy raw materials from farms to shops or processing facilities, and milk cooling technologies often fail to meet this new challenge.

The primary milk processing destroys pathogenic microorganisms, e.g., *Escherichia coli*, typhoid pathogens, tuberculosis, etc. It also destroys enzyme systems, e.g., phosphatase: the absence of phosphatase is a marker of sufficient disinfection [1]. A proper treatment also means that none of these pathogens is able to form spores in milk.

Pasteurizers with water or vapor of varying saturation degrees as an intermediate heat carrier is currently the most popular commercial type [2, 3]. Water heating and vaporization are non-specific processes that can be provided by such electrotechnological means as indirect (elemental, induction) or direct (electrode) heating.

The dairy industry knows other antibacterial milk treatment technologies that do not involve thermal methods, e.g., ultrasound treatment, infrared and ultraviolet irradiation, solar energy, microwave currents, hydrodynamic, etc. [4–13]. These technologies still remain R&D projects and have not entered commercial dairy production.

Therefore, thermal treatment remains the only technology that ensures the safety of dairy products in terms of pathogenic microorganisms and enzyme systems. In fact, heat treatment is a combination of temperature and exposure time that destroys pathogenic microorganisms and enzyme systems in milk. Heat treatment modes in dairy production differ in temperature modes and heating time. Of all the methods listed in [1], we used the so-called high-temperature short-term pasteurization. It presupposes a temperature of 72–75°C for 15–20 s.

Induction heating is a promising thermal processing technology in food production. Its energy efficiency is as high as 95–99%, but the objectivity of this method is yet to be confirmed [14–18].

A literature review showed that the number of existing and effective milk pasteurization technologies is quite large, but food producers still need objective methods for assessing their energy efficiency and improvement prospects.

Modern approaches to efficiency tests of technological processes and systems rely on the efficiency criterion, energy efficiency, and exergy efficiency [19].

Exergy efficiency is based on the second law of thermodynamics. The thermodynamic analysis involves a system of equations for the balance of mass, energy, entropy, and exergy [20]. This study concentrated on the energy and exergy balance equations.

Heating processes are irreversible. The first and second laws of thermodynamics for irreversible systems can be represented as four characteristic thermodynamic functions that are irreducible to each other. One of them is the Gibbs energy (isobaric-isothermal potential) calculated as $G = h - T \times S$, where G is the Gibbs energy, h is the enthalpy, T is the temperature, and S is entropy.

The Gibbs energy equation was used to calculate specific exergy ψ in [20, 21]:

$$\psi = \left(h - h_0\right) - T_0\left(S - S_0\right) \tag{1}$$

where h_0, S_0 are enthalpy and entropy of the initial state of substances (base for comparison) at initial temperature T_0 and initial pressure P_0.

According to [20], the system exergy is calculated as follows:

$$E_X = m \times \Psi = m \times \left[\left(h - h_0\right) - T_0\left(S - S_0\right)\right] \tag{2}$$

The overall balance of exergy is estimated as follows [20]:

$$\Delta E_X = \sum E_X^{IN} - \sum E_X^{OUT} \tag{3}$$

where $\sum E_X^{IN}$ is the sum of exergies at the input to the system elements; $\sum E_X^{OUT}$ is the sum of exergies at the output of the elements of the system or the total exergy production.

Exergy efficiency is the ratio of exergy output (total exergy production) to exergy input (total energy consumed). Therefore, the exergy efficiency, %, is calculated as follows:

$$\eta_{en} = \frac{\sum E_X^{OUT}}{\sum E_X^{IN}} \times 100 = \left(1 - \frac{\Delta E_X}{\sum E_X^{IN}}\right) \times 100 \tag{4}$$

A greater exergy efficiency η_{en} is the condition for increasing the efficiency of compared processes or systems.

Energy efficiency is based on the first law of thermodynamics. Efficiency factor η_{en} serves as the simplest and most common assessment of energy efficiency. It is calculated as the ratio of the required useful power for heating milk P_{use} to the power consumed by the electrotechnological installation P_{ETI}, %:

$$\eta_{en} = \frac{P_{use}}{P_{ETI}} \times 100 \tag{5}$$

Efficiency can be increased by exceeding energy efficiency η_{en} of the process or system in question.

The research objective was to develop an assessment method based on energy and exergy analysis to compare the effectiveness of technologies and electrotechnological devices.

Study objects and methods

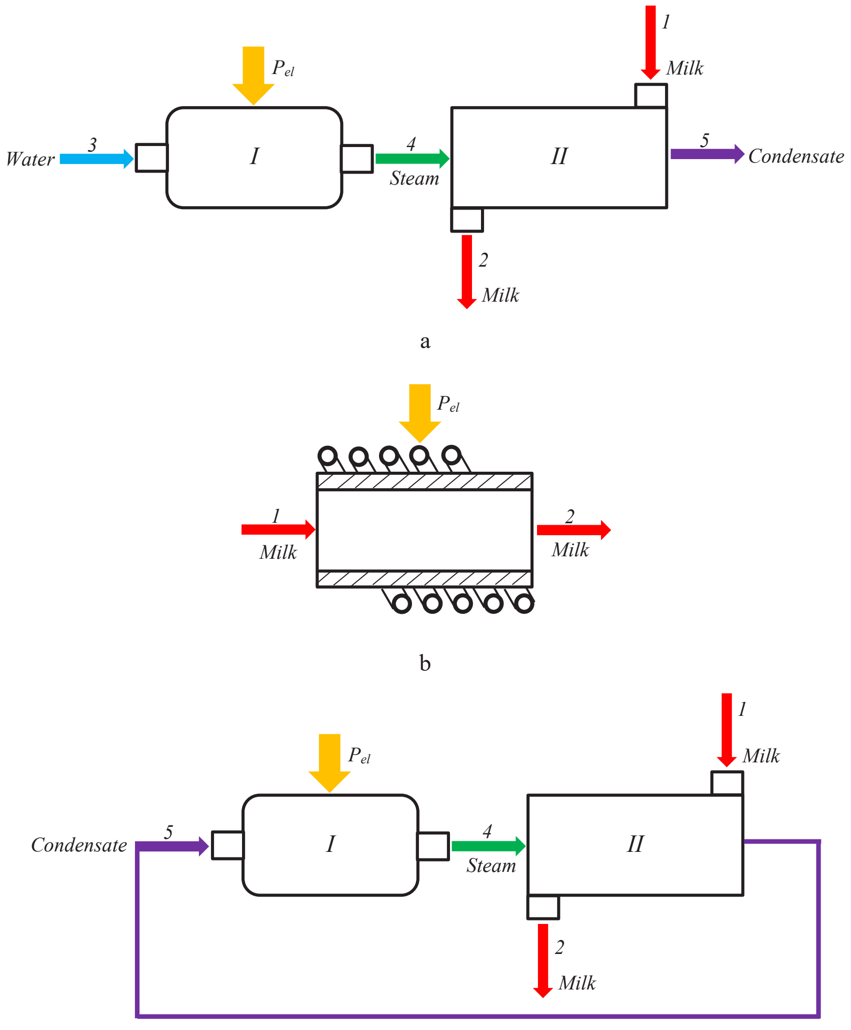
The research relied on the methods of energy and exergy analyses.

It involved exergy and energy processes based on the first and second laws of thermodynamics that occur in electrotechnologi cal devices used for the thermal treatment of liquid foods. The first device was a steam-to-milk pasteurizer with electrical indirect (with heating elements, induction) or direct (electrode) heating (Fig. 1a). The second device was an induction type pasteurizer (Fig. 1b). The third one was a thermosiphon pasteurizer with one of the above methods (Fig. 1c).

The analysis of the exergy and energy efficiency was correct due to the shared initial data reported in [22], which defined the hydro- and thermodynamic characteristics of heat exchangers for heating milk: milk production G = 1000 kg/h = 0.27 kg/s = 0.96 m^3/h, heating pipe wall temperature T_w = 100°C, milk input temperature T_{in} = 20°C, output milk temperature T_{out} = 75°C.

If the specific heat capacity of milk c is 3.97 kJ/(kg·deg), then the useful heat flow, kW, and the power of the electrothermal installation are:

$$P_{use} = Q = Gc \times \left(T_{out} - T_{in}\right) = 58.95 \tag{6}$$



a

b

c

I – a water steam-to-milk pasteurizer with electric direct or indirect heating; *II* – an induction pasteurizer; *III* – a thermosiphon pasteurizer with direct or indirect electric heating

Figure 1. Milk pasteurization systems: a – a steam-to-milk pasteurizer; b – an induction pasteurizer; c – a thermosiphon pasteurizer with direct/indirect electric heating

Рисунок 1. Схемы систем пастеризации молока: a – пастеризатор молока типа «водяной пар – молоко»; b – пастеризатор индукционного типа; c – пастеризатор термосифонного типа с использованием прямого или косвенного электронагрева

Wall temperature of the heat exchange surface $T_w = 100°C$ is limited by the requirements of thermal stability because raw milk must withstand heat treatment without protein coagulation (denaturation) [23]. It also depends on the presence of thermolabile proteins in milk.

We investigated the dependence of the coefficients of exergy and energy efficiency of electrotechnological milk-heating devices at given performance values for milk and heat exchanger geometry. The list of systems included a steam-to-milk pasteurizer with electric indirect or direct heating, an induction pasteurizer, and a thermosiphon pasteurizer with direct or indirect electric heating.

The research involved the following assumptions:

– We did not take into account the heat losses to the environment;

– The operation mode was considered to be in a steady state;

– We did not calculate the pressure drops in the heat exchangers and pipelines; and

– Kinetic, potential, and chemical energies were neglected.

Results and discussion

The thermodynamic properties of water and water vapor, i.e., enthalpy, entropy, specific heat of vaporization, etc., were known.

The enthalpy of substance h is the product of the specific heat capacity c and temperature T: $h = cT$.

Figure 1a shows the circuit for this type of the steam-to-milk pasteurizer with electrical indirect (using elemental, induction) or direct (electrode) heating. It is a steam generator with an electrode, elemental, or induction heater as energy source.

Steam temperature t_{st}, °C, at working pressure, MPa:

$$P_{st} = 0.13 - 0.15$$

$$t_{st}^{0.13} = 107.02$$

$$t_{st}^{0.15} = 120$$

Medium steam temperature t_m, °C:

$$t_m = \frac{t_{st}^{0.13} + t_{st}^{0.15}}{2} = 110 \qquad (7)$$

Heating steam consumption m_{st}, kg/s, given that (6):

$$m_{st} = \frac{Q}{\left(h_{st} - h_c\right)} = 0.0273 \qquad (8)$$

where Q is the useful heat flow and power of the electrothermal installation, kW; h_{st} is the steam enthalpy, h_{st} = 2117912 J/kg; h_c is the enthalpy of the condensate, h_c = 461696.1 J/kg.

According to the first law of thermodynamics, to ensure milk productivity G = 1000 kg/h = 0.27 kg/s when it is heated from T_{in} = 20°C at the input to T_{out} = 75°C at the output, the procedure requires steam flow m_{st} = 0.0273 kg/s.

The resulting water vapor condenses on the heat exchange surface of pipes or heat exchanger planes and transfers heat to the heated medium. Water enters the steam generator from an external source.

We calculated the exergy parameters using the thermodynamic parameters of water, steam, condensate, and milk according to formulae (1) and (2) (Table 1).

We calculated the electrical energy cost used to produce steam P_{el}, kW, according to Table 1:

$$P_{el} = m_{st} \times \left(h_5 - h_4\right) = 0.0273 \times \left(2693.3 - 83.93\right) = 71.29 \qquad (9)$$

The data in Table 1 made it possible to determine the sum of exergies at the input to the elements of the system E_X^{IN}, kW, in line with the diagram represented in Fig. 1a. The indices of the constituent exergies followed the order in Table 1:

$$E_X^{IN} = P_{el} + E_{X4} + E_{X5} + E_{X1} = 155.55 \qquad (10)$$

The sum of exergies at the output to the elements of the system $\sum E_X^{OUT}$, kW, looked as follows:

$$\sum E_X^{OUT} = E_{X5} + E_{X6} + E_{X2} = 154.26 \qquad (11)$$

According to (4), exergy loss ΔE_X, kW, was calculated as

$$\Delta E_X = \sum E_X^{IN} - \sum E_X^{OUT} = 1.29 \qquad (12)$$

Then, the exergy efficiency, %, took the form of

$$\eta_{ex} = \frac{\sum E_X^{OUT}}{\sum E_X^{IN}} \times 100 = \left(1 - \frac{\Delta E_X}{\sum E_X^{IN}}\right) \times 100 = 99 \qquad (13)$$

As a result, the equation for the energy efficiency looked like this, %:

$$\eta_{en} = \frac{P_{use}}{P_{ETI}} \times 100 = \frac{58.95}{71.29} \times 100 = 82.7 \qquad (14)$$

Figure 1b illustrates the scheme of the induction pasteurizer. Such factors as induction heating of ferromagnets, optimal electromagnetic field frequency, inductors, loading geometry, and heating time were known and had no direct relation to the induction heating of foodstuffs. Few publications [14–18] on induction heating in the food industry feature both advantages and disadvantages of the heating technology in question.

As in Table 1, the energy used to heat milk P_{el}, kW, was defined as follows:

Table 1. Thermodynamic properties of liquids and calculated exergy indicators in the steam-to-milk pasteurizer with electric indirect (tubular electric heaters, induction) or direct (electrode) heating

Таблица 1. Термодинамические свойства жидкостей и результаты расчета показателей эксергии в системе «пастеризатор молока типа “водяной пар – молоко” с использованием электрического косвенного (с помощью элементного, индукционного) или прямого (электродного) нагрева»

No.	Medium	$T, \frac{K}{°C}$	$h, \frac{kJ}{kg}$	$S, \frac{kJ}{kg \times K}$	$m, \frac{kg}{s}$	$\psi = h - h_0, \frac{kJ}{kg}$	$E_x = m \times \psi$, kW
0	Water	283/10	42.07	0.150	0.0273	–	–
0’	Milk	283/10	38.80	3.880	0.2700	–	–
1	Milk	293/20	78.80	3.940	0.2700	40.00	10.80
2	Milk	348/75	299.63	3.995	0.2700	260.85	70.43
4	Water	293/20	83.96	0.296	0.0273	41.89	1.14
5	Steam	383/110	2693.30	7.244	0.0273	2651.23	72.38
6	Condensate	383/110	461.69	1.419	0.0273	419.62	11.45

Table 2. Thermodynamic properties of liquids and calculated exergy indicators in the induction pasteurizer

Таблица 2. Термодинамические свойства жидкостей и результаты расчета показателей эксергии в системе «пастеризатор индукционного типа

No.	Medium	$T, \frac{K}{^\circ C}$	$h, \frac{kJ}{kg}$	$S, \frac{kJ}{kg \times K}$	$m, \frac{kg}{s}$	$\psi = h - h_0, \frac{kJ}{kg}$	$E_x = m \times \psi$, kW
0	Water	283/10	42.07	0.150	0.0273	–	–
0’	Milk	283/10	38.80	3.880	0.2700	–	–
1	Milk	293/20	78.80	3.940	0.2700	40.00	10.80
2	Milk	348/75	299.63	3.995	0.2700	260.85	70.43

Table 3. Thermodynamic properties of liquids and calculated exergy indicators in the thermosiphon pasteurizer with direct or indirect electric heating

Таблица 3. Термодинамические свойства жидкостей и результаты расчета показателей эксергии в системе «пастеризатор термосифонного типа с использованием прямого или косвенного электронагрева»

No.	Medium	$T, \frac{K}{^\circ C}$	$h, \frac{kJ}{kg}$	$S, \frac{kJ}{kg \times K}$	$m, \frac{kg}{s}$	$\psi = h - h_0, \frac{kJ}{kg}$	$E_x = m \times \psi$, kW
0	Water	283/10	42.07	0.150	0.0273	–	–
0’	Milk	283/10	38.80	3.880	0.2700	–	–
1	Milk	293/20	78.80	3.940	0.2700	40.00	10.80
2	Milk	348/75	299.63	3.995	0.2700	260.85	70.43
4	Water	293/20	83.96	0.296	0.0273	41.89	1.14
5	Steam	383/110	2693.30	7.244	0.0273	2651.23	72.38
6	Condensate	383/110	461.69	1.419	0.0273	419.62	11.45

$$P_{el} = G \times \left(h_2 - h_{0'}\right) = 0.0273 \times \left(299.65 - 38.8\right) = 70.43 \quad (15)$$

We obtained the following results for the sum of exergies at the input to the elements of the system E_X^{IN}, kW,

$$E_X^{IN} = P_{el} + E_{x1} = 81.23 \quad (16)$$

and for the sum at the output $\sum E_X^{OUT}$, kW:

$$\sum E_X^{OUT} = E_{X2} = 70.43 \quad (17)$$

The indices for the constituent exergies follow the order in Table 1 while Table 2 summarizes the calculation results.

As in (4), exergy loss ΔE_X, kW was calculated as:

$$\Delta E_X = \sum E_X^{IN} - \sum E_X^{OUT} = 10.8 \quad (18)$$

The equation for the exergy efficiency, %, looked as follows:

$$\eta_{ex} = \frac{\sum E_X^{OUT}}{\sum E_X^{IN}} \times 100 = \left(1 - \frac{\Delta E_X}{\sum E_X^{IN}}\right) \times 100 = 86.7 \quad (19)$$

The energy efficiency, %, was calculated based on the equation below:

$$\eta_{en} = \frac{P_{use}}{P_{ETI}} \times 100 = \frac{58.95}{70.43} \times 100 = 83.7 \quad (20)$$

Figure 1c visualizes a diagram for the thermosyphon pasteurizer with direct or indirect electrical heating. The thermosyphon consists of an evaporator filled with a certain amount of intermediate heat carrier, e.g., water, which undergoes a phase transformation into water vapor as a result of external thermal action, i.e., electrode, elemental, or induction heating. The vapor condenses on the heat exchange surface as a result of the heat transfer process through the heat transfer surface, thus transferring the thermal energy to the heated substance. The temperature of the condensate is the same as the temperature of the water vapor with a lower enthalpy. The thermosiphon has a highly effective thermal conductivity.

Using Table 1, we calculated the energy used to heat milk P_{el}, kW:

$$P_{el} = m_{st} \times \left(h_5 - h_6\right) = 0.0273 \times \left(2693.3 - 461.69\right) = 60.92 \quad (21)$$

The data summed up in Table 1 made it possible to use the scheme in Fig. 1a in order to determine the sum of exergies at the input to the elements of the system E_X^{IN}, kW:

$$E_X^{IN} = P_{el} + E_{X6} + E_{X5} + E_{X1} = 155.5 \quad (22)$$

The equation for $\sum E_X^{OUT}$, kW, looked as follows:

$$\sum E_X^{OUT} = E_{X5} + E_{X6} + E_{X2} = 154.2 \quad (23)$$

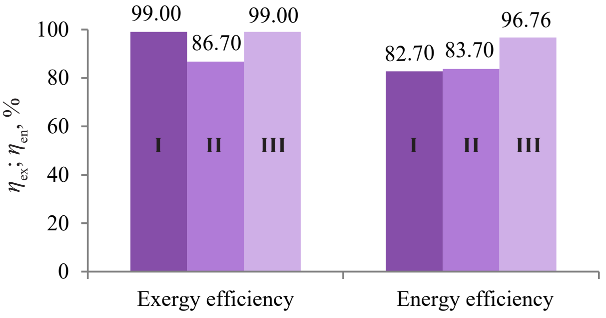
Table 4. Calculated exergy and energy characteristics of milk pasteurization systems

Таблица 4. Результаты расчета эксергетических и энергетических характеристик систем пастеризации молока

	E_X^{IN}, kW	E_X^{OUT}, kW	ΔE_X, kW	P_{use}, kW	η_{ex}	η_{en}
I	155.55	154.26	1.29	58.95	0.99	0.827
II	81.23	70.43	10.80	58.95	0.867	0.837
III	155.55	154.26	1.29	58.95	0.99	0.9676

I – a steam-to-milk pasteurizer with electric indirect (tubular electric heaters, induction) or direct (electrode) heating; II – an induction pasteurizer; III – a thermosiphon pasteurizer with direct or indirect electric heating.

I – пастеризатор молока типа «водяной пар – молоко» с использованием электрического косвенного (с помощью элементного, индукционного) или прямого (электродного) нагрева; II – пастеризатор индукционного типа; III – пастеризатор термосифонного типа с использованием прямого или косвенного электронагрева.



I – a water steam-to-milk pasteurizer with electric direct or indirect heating; II – an induction pasteurizer; III – a thermosiphon pasteurizer with direct or indirect electric heating

Figure 2. Exergy and energy efficiency, %

Рисунок 2. Эксергетическая и энергетическая эффективность, %

The indices of the constituent exergies follow the order in Table 1 while Table 3 sums up the calculations.

As in (4), exergy loss ΔE_X, kW, was calculated as follows:

$$\Delta E_X = \sum E_X^{IN} - \sum E_X^{OUT} = 1.29 \tag{24}$$

In the steady state, this heating technology does not waste the energy on heating water with a temperature of 20°C. Instead, it heats the condensate with a steam temperature of 110°C, which increases the energy efficiency of the process.

Therefore, the equation for exergy efficiency, %, looked like this:

$$\eta_{ex} = \frac{\sum E_X^{OUT}}{\sum E_X^{IN}} \times 100 = \left(1 - \frac{\Delta E_X}{\sum E_X^{IN}}\right) \times 100 = 99 \tag{25}$$

The equation for energy efficiency, %, took the following form:

$$\eta_{en} = \frac{P_{use}}{P_{ETI}} \times 100 = \frac{58.95}{60.92} \times 100 = 96.76 \tag{26}$$

Table 4 and Fig. 2 show the calculation results. It can be seen that the steam-to-milk pasteurizer (I) and the thermosiphon pasteurizer (III) had the same exergy efficiency whereas the induction pasteurizer (II) had a lower exergy efficiency.

The thermosyphon pasteurizer with direct or indirect electric heating (III) demonstrated the highest energy and exergy efficiency.

This heating technology revealed the following feature: in a steady state, the energy went not to heating the water with a temperature of 20°C to vaporize it but to the condensate with a steam temperature of 110°C. As a result, the process was more energy-efficient.

Conclusion

The steam-to-milk pasteurizer system with electrical indirect (elemental, induction) or direct (electrode) heating had the following indicators: exergy loss – 1.29 kW, power consumption – 71.29 kW, exergy efficiency – 0.99, energy efficiency – 0.827.

The thermosiphon pasteurizer with direct or indirect electric heating demonstrated the following results: exergy loss – 1.29 kW, power consumption – 60.92 kW, exergy efficiency – 0.99, energy efficiency – 0.9676.

The thermosiphon pasteurizer with direct or indirect electric heating had the highest energy efficiency in terms of energy and exergy analysis. It owed its advantage to the closed vaporization cycle, where the steam turned into condensate with the same temperature.

The induction pasteurizer had the least competitive parameters: exergy loss – 10.8 kW, power consumption – 70.43 kW, exergy efficiency – 0.867, energy efficiency – 0.837.

The steam-to-milk pasteurizer with electrical indirect (elemental, induction) or direct (electrode) heating and the thermosyphon pasteurizer with direct or indirect electric heating have almost exhausted their potential for further improvement. However, the induction pasteurizer still has good R&D prospects.

Contribution

A.A. Bagaev developed the research concept and methodology, set up the goal, formulated the conclusions and prospects, analyzed the data, provided scientific counselling, performed 2/3 of the analytical research, and proofread the manuscript. S.O. Bobrovskiy reviewed the literary sources, performed 1/3 of the analytical research, and proofread the article.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.

Критерии авторства

А. А. Багаев – разработал концепцию и предложил методику исследования, сформулировал цель, выводы и перспективы исследования, провел анализ аналитических данных, осуществлял научное руководство, участвовал в подготовке 2/3 аналитической части исследования, редактировал статью до ее подачи в редакцию. С. О. Бобровский – провел обзор литературных источников по исследуемой проблеме, участвовал в подготовке 1/3 аналитической части исследования, участвовал в редактировании статьи до ее подачи в редакцию.

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

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