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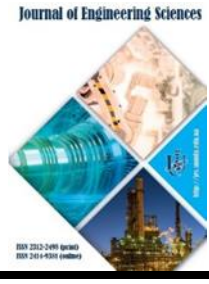

Energy-Saving Individual Heating Systems Based on Liquid-Vapor Ejector

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Abstract. The problem of increasing the efficiency of individual heating systems is solved by using heat pumps based on a liquid-vapor ejector with the working fluid R718 (water). The research object was the working process of the liquid-vapor ejector, based on the principle of jet thermal compression. It involves the generation of vapor in the nozzle of the motive flow of the liquid-vapor ejector and does not require its supply from an external source. Schemes and descriptions of the traditional system and the proposed scheme were given. Their difference from the traditional ones was indicated according to the schematic solution and working cycle. The article compared the proposed schemes' thermodynamic calculation with the working flow R718 and traditional heat pump systems with carried-out refrigerants R134a, R410a, and R32. As a result, the values of the thermodynamic parameters of all system components were obtained. The coefficients of performance (COP) for the traditional and proposed cycles were determined. Applying the new scheme made it possible to increase the COP by an average of 40 %. An exergy analysis assessed the expediency of implementing vacuum units based on liquid-vapor ejectors in individual heating systems. This made it possible to compare systems that use several types of energy (e.g., electrical, thermal) and to determine their efficiency with high accuracy. As a result of the exergy analysis, the value of the proposed scheme's exergy efficiency was obtained.

Keywords: heat pump installation, individual heating system, liquid-vapor ejector, energy efficiency, solar collector.

1 Introduction

One of the main problems faced by civilians during the russian-Ukrainian war concerns the autonomous and energy-efficient heating of residential buildings in the most cost-effective way. This issue requires solving bypassing the gas energy resource and the technology of centralized heating of apartment buildings, as there is a risk of destruction of critical infrastructure (gas pumping stations, highways, heating mains, and boiler houses). It is also necessary to consider the environmental aspect when designing new heat pump installations, which includes the problem of conserving non-renewable energy sources and the need to reduce harmful emissions into the atmosphere, which is, in particular, a fundamental factor in global warming.

The main direction of solving this problem is using energy-saving technologies based on heat pumps. Therefore, we propose a heat pump scheme using solar collectors of adsorption or vacuum type, using a liquid-vapor ejector (LVE). To compare the heating scheme, we took the model of a solar collector (SC) using a traditional vapor-compressor heat pump unit (VCHPU). The most common refrigerants in modern heat pumps are R134a, R410a, and R32. These refrigerants are more available on the market and are most commonly used in modern heat pump systems. The most common applications are air conditioning systems for residential buildings and public places, as well as climate control in motor vehicles. Therefore, they were taken for practical comparison.

Therefore, the issue of an affordable alternative to modern expensive heat pumps with refrigerants as water, a cheap working medium of the heat pump cycle with high efficiency, is quite relevant. Comparative analysis with existing analogs using modern and common refrigerants is necessary to assess the expected effect of the liquid-vapor ejectors' introduction into heat pump systems for individual heating.

2 Literature Review

The authors [1, 2] note the high efficiency of modern heat pumps, but it directly depends on the characteristics of the working media involved in the thermal conversion process. It depends on the temperature of the utilized low-potential environment. It is noted in works [3, 4] that the operation of a heat pump in the temperature range of up to –40 °C occurs, as a rule, at a system pressure above atmospheric pressure. The issue of evaporator operation at pressures close to atmospheric pressure is unresolved, which is dangerous from the point of view of possible suction of atmospheric air and its mixing with the refrigerant.

The authors [5–7] consider replacing inefficient steam jet devices with two-phase jet devices. In these works, the results of numerical and experimental studies are considered, proving the perspective of this application direction. In works [8, 9], the research of two-phase jet devices continues, and the ranges of their effective operation as part of heat pump systems are given. However, at the same time, it is noted that in such installations, implementing the operating cycle is possible only at pressures higher than atmospheric. The efficiency of such systems explains this, the working medium of which is any refrigerant.

The question arises of finding an alternative working environment that will make it possible to reduce the cost of a unit of heat received in such a heat pump installation and will allow maintaining or even increasing the efficiency of the whole installation. The authors of the work [10, 11] consider the possibility of using water as a refrigerant. They prove that this automatically transfers the operating pressures in the cycle to the vacuum area. Consequently, there is no room for using traditional compressors. It sets new challenges for finding alternative types of vacuum equipment. The authors of the work [12, 13] offer to use two-phase ejectors and present the results of studies of their working process in a vacuum mode. The authors of the works [14, 15] identify several significant advantages of water compared to existing refrigerants. The main among them are its low cost and environmental safety. However, it also has significant disadvantages, including a high crystallization temperature, which narrows the range of its use, and metal corrosion caused by oxygen in the air.

A possible way to create an efficient individual heating system based on a solar collector that combines all the above advantages is to use a heat pump where water (R718) is used instead of traditional refrigerants. This approach was used in the work [16]. Based on their own numerical and experimental studies of the working process of the liquid-steam ejector for similar technological schemes, the authors assume that this type of apparatus will be effective for individual heating heat pump systems.

The issue of the efficiency of implementing the cycle of a heat pump unit with a liquid-vapor ejector, which was studied in work [17], where the authors consider using the soil heat in the evaporator, remains unresolved. The main difference from the traditional scheme is the replacement of the traditional compressor with a liquid-vapor ejector and the switch to a vacuum mode of operation of the entire system.

3 Research Methodology

3.1 Object and hypothesis of the study

The object of study is the workflow of a liquid-vapor ejector as part of a heat pump unit of an individual heating system.

For the heat pump unit of an individual heating system as an object of analysis, we make the following assumptions and simplifications:

– there is no internal heat generation;

– the exergy of the heat flow is not taken out into the environment and returns to the system as the heat flow through the insulation of the heat pump;

– the heat pump is considered within the borders of the system, which includes the following components: ejector, condenser, regenerative heat exchanger, evaporator, and throttling device;

– the power supplied to the compressor is considered as effective power;

– the supply water pump removes the heat flow in the condenser.

The study aims to evaluate the effectiveness of using a liquid-vapor ejector based on the working medium R718 as part of a heat pump powered by a solar collector for a floor heating system. Such an approach will make it possible to increase the efficiency of heat pump systems for individual heating.

To achieve this aim, we have set the following tasks:

– to perform a thermodynamic calculation of the cycle of a traditional vapor-compressor heat pump unit (VCHPU) using R134a, R410a, and R32 working fluids and a heat pump unit based on liquid-vapor ejector (LVE) using R718 working fluid;

– to perform an exergy analysis of a traditional VCHPU using R134a, R410a, and R32 working fluids and a heat pump unit based on LVE using R718 working fluid, which will help determine the efficiency indicators of the new technology implementation;

– to perform a thermoeconomic analysis of a traditional VCHPU using R134a, R410a, and R32 working fluids and a heat pump unit based on LVE using R718 working fluid, which will help determine the cost-effectiveness of the new equipment.

To compare the heating scheme of a solar collector based on LVE with circulating water (R718), we took the SC scheme with traditional VCHPU, which uses refrigerants R134a, R410a, and R32 in the circuit. The heating circuit uses supply water, and the evaporator and solar collector circuits use a 45 % propylene glycol solution. The use of this particular solution results from the fact that its crystallization point is –25 °C. That is the minimum critical ambient temperature in winter in a temperate climate over the past five years, so using this propylene glycol mixture is a practical and effective solution for the proposed heating system. The heating area of the house is 75 m², the estimated outdoor temperature is between –20°C and +10 °C; the estimated indoor temperature is between +18 °C and +22 °C.

The temperature of the supply water at the outlet of the condenser is 55 °C, and the temperature of propylene glycol at the inlet to the evaporator is +20 °C. The condensation temperature of the refrigerant in the heat pump circuit is +55 °C, and the evaporation temperature is +10 °C.

For the LVE, the choice of initial and final parameters of the working fluids occurred based on the maximum efficiency of its operation. The initial pressure at the entrance to the LVE is an optimization parameter that allows the designing of a heat pump unit based on LVE with maximum efficiency. In the software complex developed by the authors, calculations allowed us to evaluate the influence of the initial parameters at the entrance to the LVE on the achievable efficiency indicators. These parameters are the ejection coefficient, the vapor overproduction degree, and the liquid-vapor ejector's energetic efficiency.

Figure 1 shows the dependence of the degree of pressure increase of the secondary flow on the achievable efficiency indicators, which allows for choosing the primary flow's initial parameters at the entrance to the LVE.

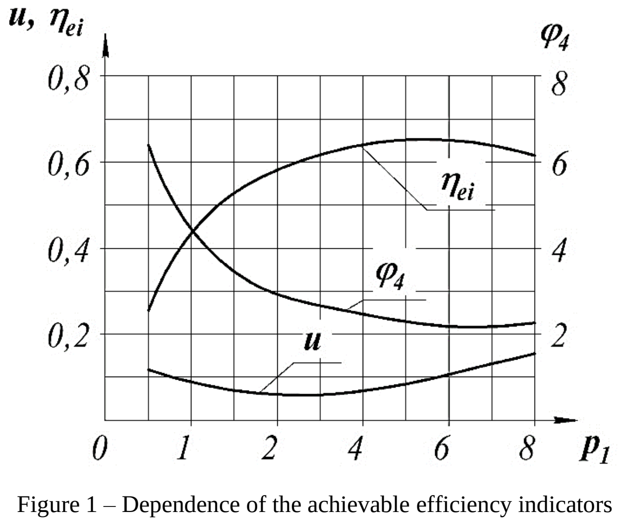

Figure 1 – Dependence of the achievable efficiency indicators of the liquid-vapor ejector on the pressure of the working flow at the entrance to the nozzle of the motive flow at p_{02} = 0.017–0.02 bar: u – injection ratio; η_{ei} – exergetic efficiency factor; φ_4 – vapor overproduction

To evaluate the possibility of modernizing a heat pump based on a solar collector using a liquid-vapor ejector, we apply the following research methods: thermodynamic, exergy, and thermoeconomic.

The thermodynamic calculation of traditional heat pump units involves the measurement of thermodynamic parameters at the nodal points of the heat pump cycle, followed by the definition of specific and total loads on all devices that are part of the traditional and proposed heat pump unit. We calculated this according to the methodology described in the works [18, 19]. As a result, we found the coefficient of performance (*COP*) of the heat pump cycle, which characterizes its thermodynamic efficiency:

$$COP = \frac{Q_T}{N_e}, \tag{1}$$

where Q_T – heating productivity of heat pump unit; N_e – effective compressor power in a basic scheme or liquid-vapor ejector in the proposed scheme.

When assessing the exergy efficiency of thermomechanical systems, it is reasonable to use the exergy method of thermodynamic analysis [20, 21], which is sufficiently accurate for those in which different types of energy undergo simultaneous conversion. The exergy analysis of the degree of perfection of energy transformations in the studied system relies on the correlation of the exergy of the system product flow (E_P) to the exergy of the fuel flow (E_F) [22]. Such a ratio is an exergy efficiency indicator of a thermomechanical system:

$$\varepsilon_{ex} = \frac{E_P}{E_F}. \tag{2}$$

The numerical value of destruction (E_D) and value of energy losses (E_L) in the energy conversion process is expressed as the difference between the values of exergy of the product flow and exergy of the fuel flow:

$$E_F - E_P = E_D + E_L. \tag{3}$$

Exergy analysis makes it possible to accurately determine the exergy efficiency of both each component of the system and the whole system.

From formula (3), the exergy balance of a separate system component is expressed as follows:

$$E_{F,k} = E_{P,k} + E_{D,k} + E_{L,k}, \tag{4}$$

where $E_{F,k}$ – exergy of fuel flow of component; $E_{P,k}$ – exergy of product flow of component; $E_{D,k}$ – absolute exergy destruction of components; $E_{L,k}$ – absolute exergy losses of a component that arise when the component comes into contact with the environment.

The exergy efficiency of the component according to formula (2):

$$\varepsilon_{ex,k} = \frac{E_{P,k}}{E_{F,k}} = 1 - \frac{E_{D,k}+E_{L,k}}{E_{F,k}}. \tag{5}$$

The exergy efficiency of the entire system is determined similarly and written in the following form:

$$E_{F,tot} = E_{P,tot} + E_{D,tot} + E_{L,tot}; \quad (6)$$

$$\varepsilon_{ex,tot} = \frac{E_{P,tot}}{E_{F,tot}} = 1 - \frac{E_{D,tot}+E_{L,tot}}{E_{F,tot}}, \quad (7)$$

where $E_{F,tot}$ – exergy of fuel flow of the system; $E_{P,tot}$ – exergy of product flow of the system; $E_{D,tot}$ – absolute exergy destruction of the system; $E_{D,tot}$ – absolute exergy losses of the system which arise when component contact with the environment.

Thermoeconomic analysis involves determining the cost of energy resources required for the primary and energy-saving schemes. It is a combination of exergy (thermodynamic) and cost analysis, the main criterion of which is the exergy cost of the system product (i.e., its part, component) [23, 24]. It is necessary to establish a correlation between the price of energy and energy tariffs characterized by the following expression to determine the expediency of introducing a new scheme. This correlation determines the equality of the exergy cost and the natural cost of the energy purchased by the system consumer.

Similarly, to the exergy analysis, as a result of which the value of the exergy flow is determined, as a result of the thermoeconomic analysis, the exergy price (specific exergy cost) of the flow of the system component and the system as a whole is determined. It can be expressed through thermodynamic and economic components [25, 26].

For the component of the system, it will be equal to:

$$c_{P,k} \cdot E_{P,k} = c_{F,k} \cdot E_{F,k} + Z_k, \quad (8)$$

where $c_{P,k}$ – exergy price (specific exergy cost) of product flow of component; $c_{F,k}$ – exergy price (specific exergy cost) of fuel flow of component; Z_k – economic part of the costs of the product:

$$c_{P,k} = c_{F,k} \cdot \frac{E_{F,k}}{E_{P,k}} + \frac{Z_k}{E_{P,k}}; \quad (9)$$

$$c_{P,k} = \frac{c_{F,k}}{\varepsilon_k} + \frac{Z_k}{E_{P,k}}; \quad (10)$$

$$c_{P,k} = c_{P,k}^F + c_{P,k}^Z, \quad (11)$$

where $c_{P,k}^F$ – thermodynamic imperfection of component, $c_{P,k}^Z$ – capital costs and exploitation for components.

Similarly, for the whole system, exergy price (specific exergy cost) will be equal to:

$$c_{P,tot} \cdot E_{P,tot} = c_{F,tot} \cdot E_{F,tot} + Z_{tot}, \quad (12)$$

where $c_{P,tot}$ – exergy price (specific exergy cost) of product flow of the system; $c_{F,tot}$ – exergy price (specific exergy cost) of fuel flow of the system; Z_{tot} – economic part of the costs for the system:

$$c_{P,tot} = c_{P,tot}^F + c_{P,tot}^Z, \quad (13)$$

where $c_{P,tot}^F$ – thermodynamic imperfection of the system; $c_{P,tot}^Z$ – capital costs and exploitation for the system.

3.2 Schemes of the heat pump unit

The basic unit of a vapor-compression heat pump for heating supply water based on a solar collector is illustrated in Figure 2.

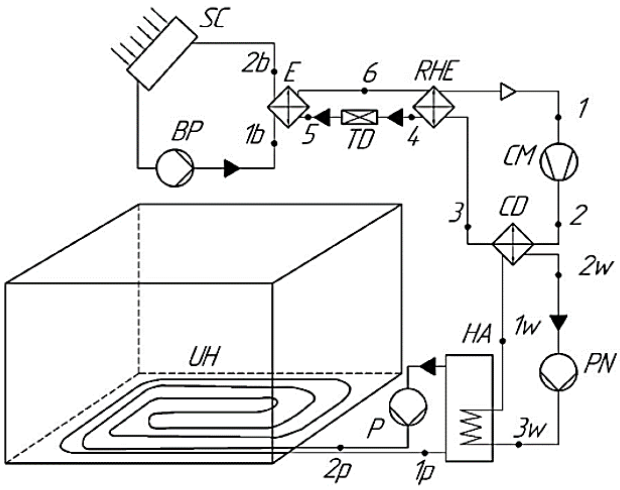

Figure 2 – The basic heat pump unit scheme: CM – compressor; CD – condenser; RHE – regenerative heat exchanger; E – evaporator; SC – solar collector; BP – brine pump (ethylene glycol); PN – mains water pump; HA – heat accumulator; TD – throttle device; UH – floor heating; P – supply pump floor heating.

As we can see from Figure 2, the generated heat from the condenser is transferred to the heat accumulator, which then transfers the heat to the selected floor heating system. This scheme also provides the use of a regenerative heat exchanger.

The proposed solution for the room heating system (Figure 3) suggests including a centralized heating system with the possibility of implementing a fully autonomous mode of operation.

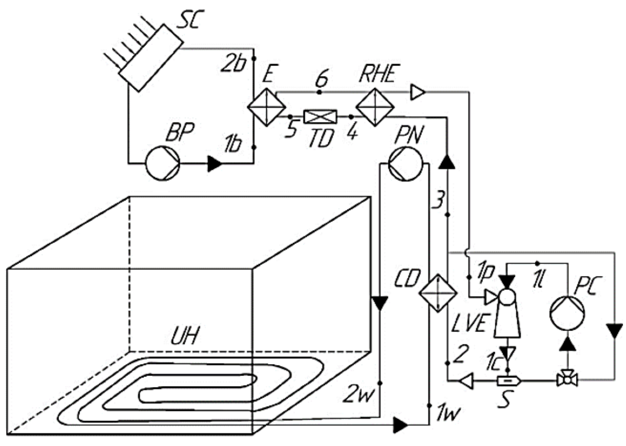

Figure 3 – Schematic diagram of the heat pump unit based on a liquid-vapor ejector: LVE – liquid-vapor ejector; S – separator; PC – pump of the liquid-vapor ejector circuit; CD – condenser; RHE – regenerative heat exchanger; TD – throttle device; E – evaporator; BP – brine pump; SC – solar collector; PN – mains water pump; UH – floor heating

Low-potential energy source utilization involves the use of heat generated by solar energy. The evaporator is of the shell-and-tube type, where water circulates in the tube space and a 45 % propylene glycol solution in the intertubular part. The mode of heat carrier flow in it is crossflow. In the proposed scheme, a condenser operates as a heat exchanger between the refrigerant in the heat pump circuit and the heat carrier in the individual heating system. The condenser is a highly efficient plate-type heat exchanger to provide maximum heat transfer to the heat carrier in an individual heating system. The system uses a regenerative heat exchanger. There is also a possibility of using a sub-cooler for subcooling and guaranteed condensation. In this scheme, there is no sub-cooler since the cooling of the supply water in the floor heating circuit is equal to 10 °C, which does not correspond to the parameters of this equipment.

The proposed scheme essentially differs from the traditional heating systems based on solar collectors and the VCHPU of various types. The authors of the work [17] describe the fundamental differences in the cycles of the traditional and proposed schemes. The LVE operates in the wet steam area, which is a fundamentally new way of converting energy, allowing it to reduce the cycle time and increase the conversion efficiency of the heat pump unit. It does not require an external generation of working steam, which goes into the nozzle of the active flow of the LVE. The production of working steam occurs directly in the heat pump cycle, namely in the nozzle of the active flow of the LVE, increasing its efficiency. Using water as a working medium in a heat pump based on a liquid-vapor ejector is promising, yet its effectiveness remains an open question and requires further research. The values of the optimization parameters by which the optimal initial operating and thermodynamic parameters for the LVE were selected, at which its efficiency would be maximum, are given in the work [17].

4 Results

4.1 Thermodynamic calculation results

The calculation of a heat pump unit based on a liquid-vapor ejector was performed according to the thermodynamic calculation methodology described in the work [18–20]. This method involves finding the main parameters at the nodal points of the cycle, with the following calculation of the thermal loads on the devices and the definition of the conversion factor of the heat pump cycle.

The values of thermodynamic parameters at the nodal points of the cycle of heat pump units operating on different working fluids are shown in Table 1.

Table 2 displays the results of the thermodynamic calculation.

Table 1 – Thermodynamic parameters at the nodal points of the heat pump cycle

R134a	1	2s	2	3	4	5	6
t, °C	25.0	76.0	82.0	60.0	55.0	10.0	16.8
p, bar	4.17	16.80	16.80	16.80	16.80	4.17	4.17
h, kJ/kg	417.4	448.0	455.7	287.2	279.3	279.3	409.5
v, m^3/kg	0.0533	–	–	–	–	–	–
R410a	1	2s	2	3	4	5	6
t, °C	25.0	87.2	118.2	60.0	55.0	7.9	15.9
p, bar	4.19	16.7	16.59	18.40	18.40	4.19	4.19
h, kJ/kg	424.3	458.9	487.6	281.1	273.9	273.9	417.1
v, m^3/kg	0.058	–	–	–	–	–	–
R32	1	2s	2	3	4	5	6
t, °C	25.0	116.5	128.5	60.0	55.0	9.7	12.6
p, bar	10.9	39.6	39.6	39.6	39.6	10.9	10.9
h, kJ/kg	536.0	597.7	613.1	323.9	308.5	308.5	520.6
v, m^3/kg	0.033	–	–	–	–	–	–
R718	1p	1c	2	3	4	5	6
t, °C	25	60	60	60	55	15	15
p, bar	0.032	0.200	0.200	0.200	0.200	0.017	0.017
h, kJ/kg	2545.2	2297.8	2608.7	253.5	230.2	230.2	2523.8
v, m^3/kg	42.99	–	–	–	–	–	–

Table 2 – Thermodynamic calculation results

Parameter name	R134a	R410a	R32	R718
Refrigerant mass flow rate, kg/s	0.473	0.427	0.274	0.034
The mass flow rate of propylene glycol, kg/s	3.224	3.200	3.040	4.083
The mass flow rate of supply water, kg/s	3.819	3.819	3.819	3.819
Condenser heat load, kW	79.73	79.73	79.73	79.73
Evaporator heat load, kW	61.58	61.12	58.11	77.98
Regenerative heat exchanger heat load, kW	3.722	3.048	4.219	0.790
Compressor power, kW	19.28	28.48	22.24	–
Liquid-vapor ejector power, kW	–	–	–	13.59
Brine pump power, kW	4.623	4.580	4.350	5.850
Supply pump power, kW	1.085	1.085	1.085	0.543
Circulation pump power, kW	–	–	–	0.135
Heat carrier pump power, kW	–	–	–	0.268
Cycle conversion factor	4.135	2.799	3.580	5.870

The results of the thermodynamic analysis indicate the prospects of applying the proposed solution, as evidenced by an increase in the cycle conversion efficiency by an average of 40 % compared to a traditional heat pump unit.

4.2 Results of exergy analysis

We performed the exergy analysis following the principles outlined in the works [21, 22]. The schemes of exergy transformations are like those given in [17].

The scheme of exergetic transformations in a basic unit and installation with the liquid-vapor ejector is shown in Figure 4.

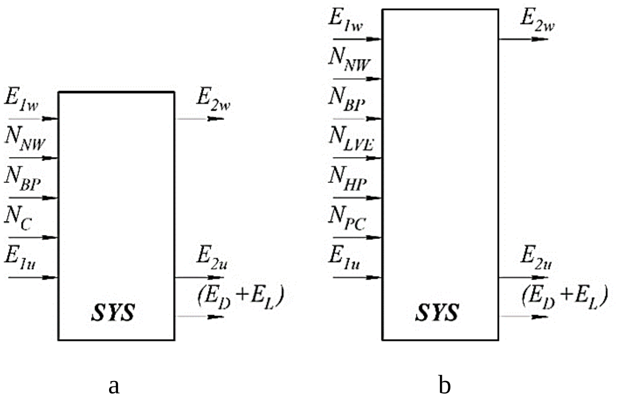

Figure 4 – Scheme of exergetic transformations: a – the basic scheme; b – the scheme with the liquid-vapor ejector

According to (2) with (5) and (6), the equations of exergy efficiency will be:

– for the basic scheme:

$$\varepsilon_{ex,BAS} = \frac{E_{2w} - E_{1w}}{N_{NW} + N_{BP} + N_C + (E_{1u} - E_{2u})}; \qquad (14)$$

– for the scheme with LVE:

$$\varepsilon_{ex,LVE} = \frac{E_{2w} - E_{1w}}{N_{NW} + N_{BP} + N_{LVE} + N_{HP} + N_{PC} + (E_{1u} - E_{2u})}, \qquad (15)$$

where E_{1w} – exergy of the mains water at the inlet to the condenser; E_{2w} – exergy of the mains water at the outlet of the condenser; N_{NW} – capacity of mains water pump; N_{BP} – capacity of brine pump; N_C – capacity of compressor in basic heat pump installation; N_{LVE} – the power of liquid-vapor ejector; N_{HP} – capacity of coolant pump; N_{PC} – the power of the pump circuit of the liquid-vapor ejector; E_{1u} – exergy of brine at the entrance to the evaporator; E_{2u} – exergy of brine at the outlet of the evaporator.

Table 3 shows the results of the exergy analysis.

Table 3 – Results of the exergy analysis

Parameter name	R134a	R410a	R32	R718
Product flow exergy, kW	515.43	515.43	515.43	515.43
Exergy of fuel flow, kW	2675.19	2684.34	2677.88	1795.92
Exergy efficiency	0.193	0.192	0.192	0.287

The exergy analysis shows that the efficiency of a heat pump unit based on liquid-vapor ejector increases by an average of 1.5 times compared to a traditional one.

4.3 Results of the thermoeconomic analysis

We performed the thermoeconomic analysis following the provisions outlined in [23–26].

The scheme of changes in the value of flows in a basic scheme and scheme with the liquid-vapor ejector is shown in Figure 5.

Table 4 shows the results of the thermoeconomic analysis.

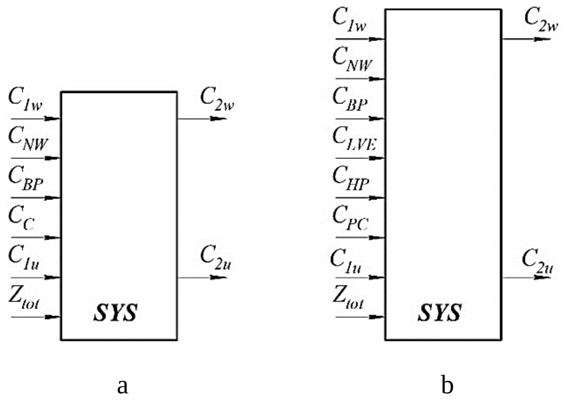

Figure 5 – Scheme of changes in the value of flows: a – the basic scheme; b – the scheme with the liquid-vapor ejector

Table 4 – Results of thermoeconomic analysis

Parameter name	R134a	R410a	R32	R718
The total cost of fuel, c.u.	2362.17	3119.37	2584.52	1981.79
Specific cost per unit of product, c.u./t	1.06	1.40	1.16	0.89
Specific cost per unit of heat, c.u./m^2	1.65	2.17	1.80	1.38

The thermoeconomic analysis has yielded results that confirm the feasibility of using a heat pump based on a liquid-vapor ejector for individual heating systems. In particular, the total cost of fuel, and the unit cost of product and heat, decreased by an average of 26.3 %.

5 Discussion

Assessing the results obtained after the thermodynamic, exergy, and thermo-economic analyses, we can identify several advantages of using liquid-vapor ejectors for heat pump units of individual heating systems. Firstly, it reduces the refrigerant cost since water is available from the centralized water supply system in case of system depressurization. Secondly, switching to vacuum operation improves the cycle performance of the heat pump system, as there is no need to increase the evaporation and condensation temperatures of the refrigerant to avoid a vacuum in the suction when using a scroll compressor. Thirdly, the principle of jet thermal compression in a liquid-vapor ejector makes it possible to reduce the mass flow rate of refrigerant and brine and the load on the equipment. All this made it possible to obtain the following efficiency indicators.

The thermodynamic analysis shows that the efficiency of the proposed scheme results from a reduction in the mass flow rate of the refrigerant. Consequently, there is a decrease in the specific and total loads on the devices that are part of the heat pump unit of the individual heating system, according to Table 2.

The exergy analysis resulted in energy efficiency indicators, and the thermoeconomic calculation gave us cost indicators of the feasibility of introducing a liquid-vapor ejector into a heat pump unit of an individual heating system.

Tables 3, 4 show that the exergy efficiency of the proposed scheme is higher than that of the traditional one. That is possible using a liquid-vapor ejector, which has a lower power than the compressor in the diagram shown in Figure 1. The total power consumption of the liquid-vapor ejector and auxiliary equipment (circulation pump and heat carrier pump) used in the proposed scheme is less than that of a standard compressor, which also increases the efficiency of the proposed one.

Unlike the existing methods of assessing the efficiency of heat pump units, which use outdated methods of Brodianskyi [17–19], this study is relevant and current. We used the latest methods for assessing the efficiency of heat pump units, such as exergy and thermoeconomic analysis, according to the Tsatsaronis approach [21–25]. These methods make it possible to obtain reliable and accurate results for comparing thermomechanical systems in which the simultaneous conversion of different types of energy occurs.

The results of the exergy analysis, supplemented by the thermoeconomic indicators given in Table 4, provide complete information on the shortcomings of the existing heat pump unit of the individual heating system. It allows us to talk about achieving the research goal and fulfilling all the tasks because the study obtained both thermodynamic and cost indicators of the feasibility of implementing a new scheme.

However, simultaneously, there are certain limitations of using liquid-vapor ejectors, namely, the values of the passive flow vacuum at the inlet to the device, which are achievable in the range of 10–15 kPa. It is necessary to use a forevacuum pump (booster or molecular one) to increase the vacuum values.

A drawback of the study is the choice of assumptions and simplifications used in the comparative analysis, which reduces the accuracy of the results. At the same time, reducing the number of simplifications in the calculation will make it more complicated but will not significantly improve the accuracy of the results.

It is possible to continue this study and further investigate the operation of the solar collector, compare different types, and determine the most efficient ranges of its operation.

Overall, the article is the first part of the research into water use in heat pumps for individual heating systems and of liquid-vapor ejectors for these purposes. It is based on the results of theoretical and experimental research [17, 18] and requires further experimental research for the operation mode given in Table 1.

6 Conclusions

As a result of thermodynamic calculations, we determined that using a liquid-vapor ejector in individual residential heating systems is promising. It makes it possible to increase the conversion factor of the heat pump cycle by an average of 40 % compared to traditional schemes of the same type.

As a result of the exergy analysis, we determined the exergy efficiency of the liquid-vapor ejector as part of a heat pump and the feasibility of its application for an individual heating system. It is 0.287, 1.5 times higher on average than traditional ones. These indicators result from the transition to the vacuum mode of operation of the proposed heat pump unit, which leads to lower mass flow rates of heat flows, hence a decrease in the exergy of the fuel flow and an increase in overall efficiency.

As a result of the thermoeconomic analysis, we determined the estimated cost per unit of heat per ton of product and unit of heated area of the room in the new and traditional schemes of heat pump units. The new scheme reduces the specific one per heat unit by an average of 26.3 %. Considering the refrigerant expenses in traditional systems, these savings are even more significant.

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