The study explores the possibility of using water (R718) as a refrigerant for a heat pump installation of a heating system. This unit is a vapor compression heat pump with a regenerative heat exchanger in which the vacuum unit based on a liquid-vapor ejector is used instead of a scroll refrigeration compressor. The working process of such an apparatus is based on implementing a fundamentally new cycle that does not require the supply of working steam from the outside. Instead, steam is generated inside the vacuum unit. The article describes the proposed installation and its differences from the traditional one, both in terms of circuit solutions and in terms of the operating cycle. A thermodynamic calculation was performed for the proposed installation with R718 as the working medium and the traditional heat pump systems operating on refrigerants R142b, R254fa, and R410a. As a result of the calculation, the parameters of all the devices included in these schemes were obtained, and the conversion factors of the cycles were determined. To assess the feasibility of using R718 as a working substance and replacing the scroll refrigeration compressor with a liquid-vapor ejector, an exergy analysis was performed. This made it possible to fairly accurately determine the effectiveness of each circuit, since it implemented the possibility of comparing systems using several types of energy (for example, electrical and thermal). As a result, the values of exergetic efficiency of traditional and proposed schemes were obtained. The final stage of the study was the performance of a thermoeconomic analysis. The estimated cost was determined for a unit of heat quantity per ton of the product and per unit of the heated area obtained in a unit with the working substance R718 and traditional installations with the working substances R142b, R254fa, and R410a

Keywords: heat pump unit, heating system, liquid-vapor ejector, exergetic efficiency, thermoeconomic analysis

UDC 31.371:620.92
DOI: 10.15587/1729-4061.2020.217274

ANALYSIS OF THE POSSIBILITY OF USING R718 FOR A HEAT PUMP OF A HEATING SYSTEM BASED ON A LIQUID-VAPOR EJECTOR

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Received date 26.10.2020
Accepted date 30.11.2020
Published date 21.12.2020

1. Introduction

One of the main problems currently being solved by the world community is energy conservation. Two goals are being achieved simultaneously – the conservation of non-renewable energy resources and the reduction of harmful atmospheric emissions of combustion products, which, in particular, are a major factor in global warming.

One of the most important ways to solve this problem is to apply energy-saving technologies based on the use of heat pumps.

Heat pumps, performing the reverse thermodynamic cycle on a low-boiling working substance, utilize the low-potential heat of natural, technological and domestic sources and transform it to a higher temperature level. In addition, primary energy is consumed 1.2–2.3 times less than in the case of direct fuel combustion.

Modern heat pumps use mainly ammonia and freons as refrigerants. The issue of using water as a working medium for such installations is innovative and promising. In the world technical practice, water is successfully used in steam ejector refrigeration systems.

The researched question is important in the framework of scientific problems aimed at modernizing the existing systems of heat supply. In particular, it would be convenient to have such an affordable alternative to modern expensive refrigerants as water, which is a cheap working medium for a refrigeration cycle able to produce high efficiency. In order to assess the expected effect of implementing a new scheme, it is necessary to conduct a comparative analysis with the existing systems.

2. Literature review and problem statement

Modern heat pumps are quite highly efficient and, as was noted by the authors of [1, 2], this efficiency primarily depends on the characteristics of heat sources involved in thermal transformation: namely, on the temperature level of the heating medium of the consumer of the heat load and on the flow temperature of the utilized low-potential medium. In [3] it was stated that the thermodynamic properties of these substances are such that the production of cold in a wide range of low temperatures (from 0 °C to –40 °C) is usually carried out at a pressure in the system above atmospheric. Moreover, the operation of the heat pump evaporator at pressures close to atmospheric is considered a freelance mode, which is dangerous to install in terms of possible suction of atmospheric air.

The authors of [4] investigated the possibility of using water as a cheap and affordable refrigerant. It was shown that the use of water as a refrigerant automatically leads to operating pressures below atmospheric, which is implemented in heat pump systems with steam jet vacuum pumps. It is known that water has a number of unique properties, including the high heat of vaporization r, which is for vacuum regimes about 2,500 kJ/kg, 10 times higher than that of freon R22. The specific heat of water C_p is also high and is approximately 4,186 J/(kg·K). Accordingly, the ratio of C_p/r is much smaller compared to other substances and is approximately equal to $1.87\cdot10^{-3}$ 1/K. For ethanol, for example, this figure is equal to $2.373\cdot10^{-3}$ 1/K, for methyl it is close to $2.1\cdot10^{-3}$ 1/K. From the physics of the vacuum cooling process it follows that its efficiency is best for substances where the ratio of C_p/r is less. However, there is one significant drawback, namely the high freezing point, which imposes certain restrictions on the use of the solutions proposed in [4]. A description of such limitations can be found in [5], among which the most important is the corrosion of the metal in the presence of oxygen. One possible way to solve this problem is to expand the temperature range of water-based substances possible with the use of salts, alcohols, and esters.

One of the potential ways to create a highly efficient heating system is to use a steam-compression heat pump based on a liquid-vapor ejector the working process of which is based on the principle of jet thermal compression [6]. The main difference from the traditional scheme is the absence of a scroll compressor and the transition to vacuum operation of the entire system.

3. The aim and objectives of the study

The aim of this study is to evaluate the effectiveness of the liquid-vapor ejector with the working medium R718 as part of the heat pump for the heating system.

To achieve this aim, the following tasks were set and done:

– to perform thermodynamic calculation of the cycle of the traditional vapor compression heat pump (VCHP) with the working media R142b, R245fa, and R410a and a heat pump installation based on the liquid-vapor ejector (LVE) with the working medium R718;

– to carry out exergy analysis of the traditional VCHP with the working media R142b, R245fa, and R410a and the heat pump installation based on the LVE with the working medium R718, as a result of which to determine the efficiency of the introduction of new equipment;

– to perform thermoeconomic analysis of the traditional VCHP with the working media R142b, R245fa, and R410a and the heat pump installation based on the LVE with the working medium R718, as a result of which to determine the cost indicators of efficiency of new equipment.

4. Selection of operating parameters and description of research methods

Freons R142b, R245fa, and R410a are used as refrigerants of the traditional VCHP circuit, and water (R718) is used for the circuit based on the LVE. Mains water is used in the heating circuit, with 27.4 % propylene glycol solution circulating in the evaporator circuit. The heated area is 46.5 m^2, the estimated outdoor temperature is –20...+10 °C, the estimated indoor temperature is +16...+22 °C, and the estimated soil temperature is +5 °C. The temperature of the mains water at the inlet to the subcooler is 40 °C; the temperature of the mains water at the outlet of the condenser is 55 °C. The condensing temperature of the refrigerant in the heat pump circuit is +60 °C, and the evaporation temperature is +5 °C. The choice of initial and final parameters of the working medium circulating in the LVE was based on the maximum efficiency of its work. Therefore, on the basis of the software developed by the authors for the calculation of the vacuum installation, calculations were performed to assess the impact of the degree of increase in the pressure of the passive flow in the LVE on the injection ratio and energy efficiency of the device [7]. Fig. 1 shows this dependence, which makes it possible to select the intermediate pressure between the compression ratios for the vacuum system.

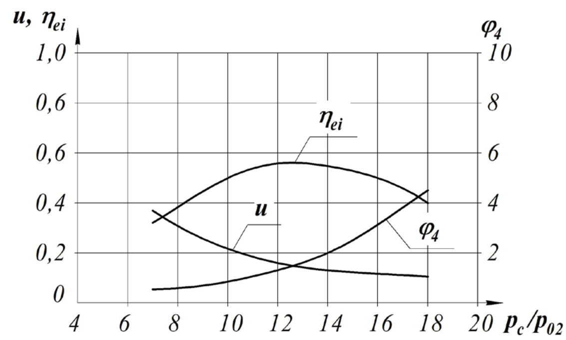


Fig. 1. The graph of the dependence of the degree of overproduction of steam ψ_4, the injection coefficient and the effective efficiency η_{ei} on the magnitude of the increase in the pressure of the passive flow p_c/p_{02} at t_{01}=121–149 °C, p_{01}=300–500 kPa, and p_{02}=5 kPa

Numerical research methods such as thermodynamic, exergetic and thermoeconomic were used to evaluate the possibility of using water as a working medium for the VCHP.

Thermodynamic calculation of traditional heat pump units was performed according to the method described in [7].

To assess the energy efficiency of compressor systems, it is most expedient to use the exergy method of thermodynamic analysis [9]. The use of this method helps to unambiguously express and rank heterogeneous energy flows in thermomechanical systems.

Exergy assessment of the degree of perfection of energy transformations in the studied system was based on modern terminology and the provisions set out in [7, 8].

According to this methodology, the main indicator when comparing circuit solutions is the value of exergetic efficiency ε_{ex}:

$$\varepsilon_{ex} = \frac{E_P}{E_F}, \qquad (1)$$

where E_P is the exergy of the product stream of the system; E_F is the exergy of the fuel flow system.

Thermoeconomic analysis is a new method of evaluating the efficiency of thermomechanical systems that is aimed at determining the cost of energy required for basic and energy saving schemes. The thermoeconomic method of analyzing thermomechanical systems is a combination of exergy (thermodynamic) and cost analyses. The main criterion of the thermoeconomic method of analysis is the exergetic value of the system product (its part, component, etc.) [9].

5. Results of researching the efficiency of introducing the heat pump on the basis of a liquid-vapor ejector

5. 1. The suggested scheme of the heat pump installation

The proposed circuit solution of the space heating system (Fig. 2) provides for its inclusion in the central heating system line with the possibility of its autonomous operation. Utilization of a low-potential energy source involves the use of soil heat. The scheme provides for the operation of the heat pump unit (HPU) in both monovalent and bivalent modes. The evaporator is made a shell-and-tube type, where water circulates in the tubular space, and in the intertube there is a 27.4 % solution of propylene glycol. The flow mode of the heat carriers is cross. The condenser in the HPU circuit acts as an intermediate heat exchanger between the refrigerant of the HPU circuit and the coolant of the heating system. The condenser is made as a highly efficient plate-type heat exchanger to ensure maximum heat transfer to the heating system fluid.

The cycle of the steam-compression heat pump on the basis of the liquid-vapor ejector has fundamental differences from the traditional one shown in Fig. 3, *a* [7]. The LVE works in the field of wet steam, which allows reducing the cycle and increasing the conversion factor of the heat pump installation on its basis (Fig. 3, *b*). This cycle is a fundamentally new way of energy conversion, as its implementation does not require external generation of working steam that is fed into the nozzle of the active stream LVE. The generation of the working vapor occurs within the cycle, namely in the nozzle of the active flow of the LVE, which increases its efficiency.

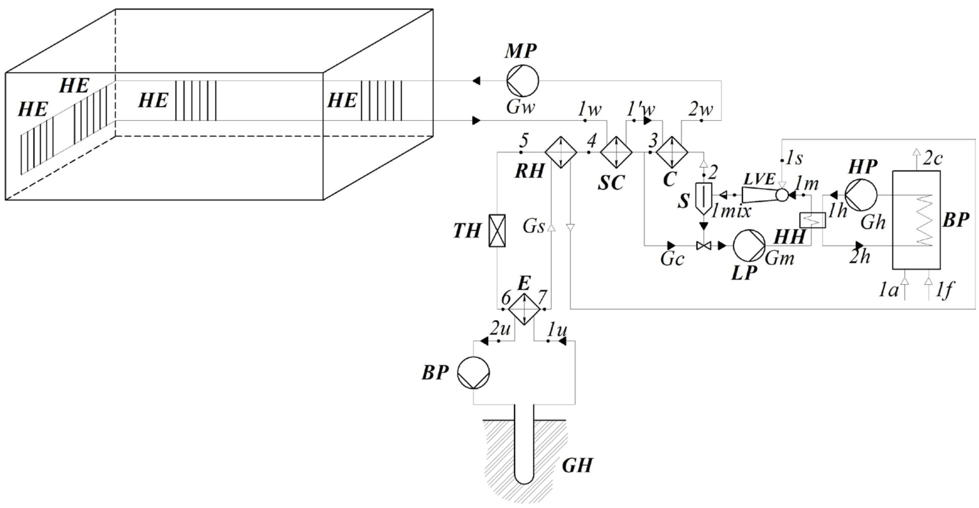
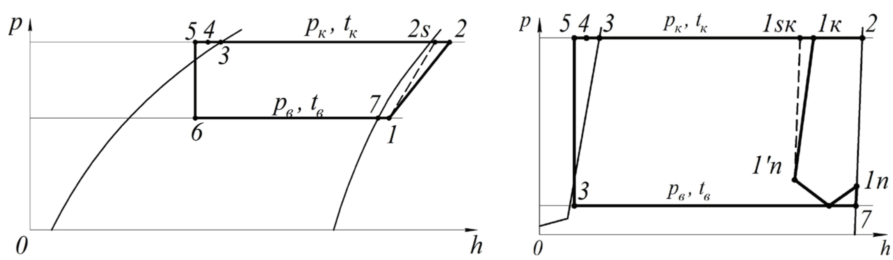


Fig. 2. The scheme of a heat pump based on a liquid-vapor ejector: LVE is the liquid-vapor ejector; S is the separator; LP is the liquid-vapor ejector circuit pump; HH is the heat exchanger-heater; HP is the heat pump; HB is the boiler; C is the condenser; SC is the subcooler; RH is the regenerative heat exchanger; TH is the throttle device; E is the evaporator; BP is the brine pump; GH is the ground heat exchanger; MP is the mains water pump; HE is the heating element



a *b*

Fig. 3. A comparison of the cycles: *a* is the traditional VCHP with a scroll compressor; *b* is based on the LVE

Thus, there is a reason to believe that the use of water as a working medium of a heat pump based on a liquid-vapor ejector is promising. However, the question of its efficiency compared to traditional heat pump systems remains open and needs to be studied.

5. 2. The results of the thermodynamic calculation

The calculation of the heat pump installation on the basis of the liquid-vapor ejector requires a preliminary thermodynamic calculation according to the method described in [10]. This technique involves finding the main parameters at the nodal points of the cycle with the subsequent calculation of thermal loads on the devices and determining the conversion factor of the refrigeration cycle.

The mode parameters of the heat pump installations operating with different working media are given in Table 1. The results of the thermodynamic calculation are given in Table 2.

Table 1

Mode parameters of the heat pump units

R142b	1	2s	2	3	4	5	6	7
t, °C	15	76	86	60	50	45	5	5
p, bar	1.82	8.9	8.9	8.9	8.9	1.82	1.82	1.82
h, kJ/kg	648.52	690.36	700.82	493.71	468.08	460.24	460.24	644.34
s, kJ/(kg·K)	1.18	1.18	1.206	1.07	1.015	1.01	1.03	1.15
ν, m^3/kg	0.13	–	–	–	–	–	–	–
R245fa	1	2s	2	3	4	5	6	7
t, °C	15	64.5	74	60	50	45	5	5
p, bar	0.655	4.64	4.64	4.64	4.64	0.655	0.655	0.655
h, kJ/kg	417	453.8	463	280.3	266	255.6	255.6	407.7
s, kJ/(kg·K)	1.782	1.782	1.814	1.264	1.22	1.2	1.22	1.748
ν, m^3/kg	0.2726	–	–	–	–	–	–	–
R410a	1	2s	2	3	4	5	6	7
t, °C	15	95		60	50	45	5	5
p, bar	9.3	37.865	37.865	37.865	37.865	9.3	9.3	9.3
h, kJ/kg	436.05	476.45	486.55	319.67	292.64	280.87	280.87	426.96
s, kJ/(kg·K)	1.848	1.848	1.875	1.38	1.302	1.291	1.294	1.816
ν, m^3/kg	0.0306	–	–	–	–	–	–	–
R718	1p	1c	2	3	4	5	6	7
t, °C	15	60	60	60	50	45	5	5
p, bar	0.02	0.2	0.2	0.2	0.2	0.02	0.02	0.02
h, kJ/kg	2,533.1	1,896.5	3,125.23	253.461	209.8	188.58	188.58	2,509.38
s, kJ/(kg·K)	8.7238	4.8684	9.091	0.833	0.706	0.641	0.68	9.03
ν, m^3/kg	67.07	–	–	–	–	–	–	–

Table 2

Results of the thermodynamic calculation

No.	Name of the parameter	Refrigerant			
		R142b	R245fa	R410a	R718
1	Mass consumption of the refrigerant, kg/s	0.0332	0.0392	0.0398	0.0026
2	Mass consumption of the brine, kg/s	0.3367	0.341	0.333	0.1673
3	Mass consumption of the mains water, kg/s	0.1231	0.1231	0.1231	0.1231
4	Specific loads on the devices, kJ/kg: – the capacitor – the evaporator – the subcooler – the regenerative heat exchanger	 207.11 184.1 25.63 4.18	 182.7 152.1 14.3 9.3	 166.88 146.09 27.03 9.09	 2,871.77 2,320.8 43.66 23.72
5	Heat loads on the devices, kW: – the capacitor – the evaporator – the subcooler – the regenerative heat exchanger	 6.8699 6.1066 0.8501 0.1387	 7.1596 5.9605 0.5604 0.3644	 6.6439 5.8162 1.0761 0.3619	 7.6044 6.1454 0.1156 0.0628
6	Power of the compressor, kW	2.4783	2.5752	2.8722	–
7	Power of the liquid-vapor ejector, kW	–	–	–	2.4081
8	Power of the brine pump, kW	0.5205	0.5271	0.5149	0.2587
9	Power of the mains pump, kW	0.1976	0.1976	0.1976	0.0988
10	Power of the circulation pump, kW	–	–	–	0.0212
11	Power of the coolant pump, kW	–	–	–	0.0518
12	Factor of the cycle conversion	3.12	3.00	2.69	3.21

The obtained results testify to the prospects of applying the proposed solution due to the reduced mass consumption of the refrigerant and the brine, the corresponding reduction of the capacity of the mains pump and the brine pump, as well as the increase of the cycle conversion factor.

5. 3. The results of the exergy analysis

The scheme of the exergetic transformations in a traditional heat pump installation and in an installation based on the liquid-vapor ejector is shown in Fig. 4.

Let us describe the equation of exergetic efficiency:

– for the traditional scheme

$$\varepsilon_{ex1} = \frac{E_{2w} - E_{1w}}{N_{MP} + N_{BP} + N_C + \left(E_{1u} - E_{2u}\right)}; \quad (2)$$

– for the scheme with the liquid-vapor ejector:

$$\varepsilon_{ex1} = \frac{E_{2w} - E_{1w}}{N_{MP} + N_{BP} + N_{LVE} + N_{HP} + N_{LP} + \left(E_{1u} - E_{2u}\right)}, \quad (3)$$

where E_{1w} is the exergy of the mains water at the inlet to the subcooler, E_{2w} is the exergy of the mains water at the outlet of the condenser, N_{MP} is the mains water pump capacity, N_{BP} is the brine pump capacity, N_C is the compressor capacity of a traditional heat pump installation, N_{LVE} is the liquid-vapor ejector power, N_{HP} is the coolant pump capacity, N_{LP} is the power of the pump circuit of the liquid-vapor ejector, E_{1u} is the exergy of brine at the entrance to the evaporator, E_{2u} is the exergy of brine at the outlet of the evaporator, (E_D+E_L) is the destruction (loss) of exergy in the process.

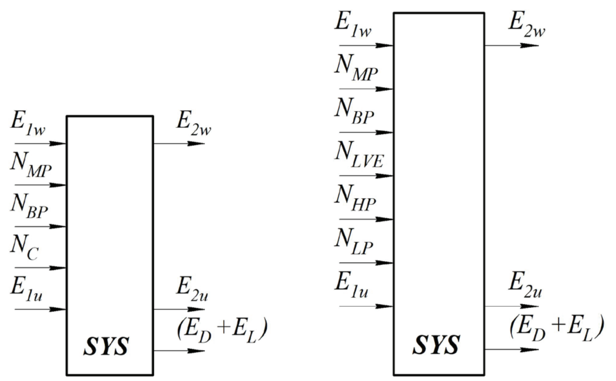


Fig. 4. The scheme of the exergetic transformations: *a* is the traditional heat pump installation; *b* is the LVE-based installation

The results of the exergy analysis are given in Table 3.

Table 3

Results of the exergy analysis

No.	Name of the parameter	Refrigerant			
		R142b	R245fa	R410a	R718
1	Exergy of the product stream, kW	247.654	247.654	247.654	247.654
2	Exergy of the fuel flow, kW	1,273.335	1,289.573	1,259.638	632.963
3	Exergetic efficiency	0.194	0.192	0.197	0.391

As a result of the exergy analysis, it can be concluded that the efficiency of the heat pump installation based on the liquid-vapor ejector is on average twice higher than with the traditional one.

5. 4. The results of the thermoeconomic analysis

The total cost of fuel for traditional schemes is determined by the formula:

$$C_1 = C_{w1} \cdot \dot{V}_{w1} \cdot \tau_p + C_{e1} \cdot \sum N_1 \cdot \tau_p, \quad (4)$$

where C_{w1} is the cost of 1 m^3 of mains water, $\dot{V}_{w1}$ is the volumetric consumption of mains water, C_{e1} is the cost of electricity, $\sum N_1$ is the amount of power consumed by the drive of the compressor and pumps, and τ_p is the estimated operation time of the installation.

The total cost of fuel for the proposed scheme is determined by the formula:

$$C_2 = C_{w2} \cdot \dot{V}_{w2} \cdot \tau_p + C_{e2} \cdot \sum N_2 \cdot \tau_p, \quad (5)$$

where C_{w2} is the cost of 1 m^3 of mains water, $\dot{V}_{w2}$ is the volumetric consumption of mains water, C_{e2} is the cost of electricity, $\sum N_2$ is the amount of power consumed by the pump drive, and τ_p is the estimated operation time of the installation.

The results of the thermoeconomic analysis are given in Table 4.

Table 4

Results of the thermoeconomic analysis

No.	Name of the parameter	Refrigerant			
		R142b	R245fa	R410a	R718
1	Total cost of fuel, c.u.	753.83	778.25	845.39	669.40
2	The unit cost of the product, c.u./t	1.53	1.58	1.72	1.36
3	The unit cost of heat, c.u./m^2	1.88	1.95	2.11	1.67

The obtained results make it possible to state that the use of water as a refrigerant of steam compression heat pumps helps to obtain a cheap heat source for the heating system and to reduce the unit cost of heat by approximately 18.5 %.

6. Discussion of the feasibility of using water as a refrigerant for heat pump systems

With the results of thermodynamic, exergetic and thermoeconomic analyses, we can identify several significant advantages of the proposed scheme (Fig. 1) in comparison with the traditional ones on the basis of scroll compressors. A feature in favor of the proposed circuit solution is the ability to implement a fundamentally new cycle of energy conversion that leads to a reduction in the mass consumption of the refrigerant and brine and smaller loads on the respective devices.

The following characteristics have been identified. Under the initial conditions, in the heat pump installation that operates with the working medium R245fa there appears a vacuum mode for the suction into the compressor. This is unacceptable for heat pumps with scroll compressors, so it is necessary to increase the evaporation and condensation temperatures of the refrigerant, which, in turn, will reduce its efficiency.

The proposed solution in the form of a diagram shown in Fig. 1 eliminated such problems by replacing the scroll compressor with a liquid-vapor ejector operating in the vacuum mode. It is this and the replacement of traditional refrigerants with cheap and affordable R718 that allowed obtaining such performance indicators.

The closest in design to the proposed scheme are steam ejector refrigeration machines, which use steam jet ejectors with water vapor as a working medium. However, they are usually multi-stage and have a total efficiency of 2–5 %. This low efficiency is due to the fact that one stage of the steam jet ejector can create a pressure drop by only 2–3 times. In the liquid-vapor ejector, such a difference is at the level of 8–10.

Limitations in applying this type of ejectors may include the value of the vacuum at the nozzle entrance of the passive flow, which can be achieved at the level of 10–15 kPa. To obtain lower values of this pressure, it is necessary to use forevacuum pumps (booster or molecular).

This study can be continued and further used to increase the efficiency of absorption heat pump systems. However, the limitation of the maximum size of the critical diameter of the LVE active flow nozzle, associated with the consumption of the working medium, requires installing several parallel ejectors, which complicates the design of the unit.

7. Conclusions

1. As a result of the thermodynamic calculation, it was found that the use of a liquid-vapor ejector that works by the principle of jet thermocompression increases the conversion factor of the heat pump cycle compared to traditional equivalents by an average of 10 %.

2. As a result of the exergy analysis, the exergetic efficiency of the liquid-vapor ejector in the heat pump and the expediency of its application in the heating system were determined. The exergy efficiency of the new equipment is 0.391, which is on average twice higher than of the traditional ones. Such indicators are achieved due to the transition to new operating parameters in the cycle, which results in reduced thermal loads on the devices, lower exergy of the fuel flow, and higher overall efficiency.

3. As a result of the thermoeconomic analysis, the total cost of fuel and the unit cost of the product in the new and traditional schemes of heat pump installations were found. The use of the LVE makes it possible to reduce the total cost of fuel by an average of 123.09 c.u. a year and lower the unit cost of the product by an average of 15.5 %, excluding refrigerant costs in traditional schemes.

Acknowledgment

The authors are grateful to Viacheslav Mykhailovych Arsenyev, Candidate of Technical Sciences, Professor of the Department of Technical Thermophysics of Sumy State University, Ukraine, for assistance in selecting the research methods and finding relevant information sources.

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