UDC 621.21:620.92
DOI: 10.15587/1729-4061.2022.263331

IMPROVING THE EFFICIENCY OF CONDENSATION INSTALLATIONS OF STEAM TURBINES BY APPLYING LIQUID-VAPOR EJECTOR

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This paper considers the possibility of using liquid-vapor ejectors in condensing units of steam turbines. This unit is designed for pumping out a steam-air mixture from a steam turbine condenser, in which the process occurs at a pressure lower than atmospheric. In the traditional scheme, this is provided by a two-stage steam-jet ejector unit. The proposed scheme involves the use of a single-stage liquid-vapor ejector and its possible pre-vacuum mode of operation in conjunction with a liquid-ring vacuum pump. A working process of the liquid-vapor ejector does not require the supply of working steam from the outside since its generation occurs in the active nozzle of the liquid-vapor ejector. A description of the traditional scheme and the proposed options is given, which are different both in the scheme solution and in the operating parameters. The object of this study is a liquid-vapor ejector, which is used in the condensing system of a steam turbine. Thermodynamic calculation of the proposed circuit solutions was carried out. As a result, the necessary mode parameters of the schemes were determined. To assess the feasibility of using a liquid-vapor ejector in the condensation systems of steam turbines, an exergy analysis was performed. The proposed scheme makes it possible to increase efficiency by 2.3 times, and when used with a liquid-ring vacuum pump – by 2.44 times. To assess the economic efficiency of the modernization of the condensing system, thermoeconomic analysis was performed. The use of the proposed scheme makes it possible to reduce the cost of generating boiler steam and reduce the cost of the resulting product of the steam turbine unit by about 51 %. The estimated cost of a unit of the amount of boiler steam consumed per ton of product and the unit cost of steam were established

Keywords: condensing unit, steam turbine, liquid-vapor ejector, liquid-ring vacuum pump, exergy efficiency, thermoeconomic analysis

Received date 22.06.2022
Accepted date 15.08.2022
Published date 29.08.2022

How to Cite: *Sharapov, S., Yevtushenko, S., Panchenko, V., Kozin, V., Ivchenko, O. (2022). Improving the efficiency of condensation installations of steam turbines by applying liquid-vapor ejector. Eastern-European Journal of Enterprise Technologies, 4 (8 (118)), 44–50. doi: https://doi.org/10.15587/1729-4061.2022.263331*

1. Introduction

One of the main problems that is now being solved by the world's energy sector is its environmental safety, which must be ensured while maintaining the necessary capacities with increasingly growing energy consumers. One of the solutions is the transition to decentralized low-capacity installations but this only applies to new systems that will be built in accordance with new requirements and standards. As for the existing installations, in recent years, the main strategy for their modernization and bringing them under existing European and world standards is to equip them with gas turbine and steam turbine installations of low power. These installations have special designs of the main and auxiliary equipment, operating and control modes. Such installations on natural gas are the only power plants that produce electricity with an electrical efficiency of more than 58 % under the condensation mode of operation.

One of the main ways to achieve high thermal efficiency of a steam turbine unit is to reduce the mode parameters of steam behind the turbine. With a decrease in pressure and temperature of the steam used in the turbine, the amount of heat transferred to the cold source decreases. With constant parameters, fresh steam increases turbine power and increases the efficiency of the cycle as a whole by increasing the heat transfer in the turbine.

The reduction of steam parameters behind the turbine is usually carried out to a pressure below atmospheric. There is a need to ensure the best possible condensation of steam used in the turbine. That is why the steam turbine unit is equipped with a condensing unit, which, in addition to the main purpose, also provides clean condensate to power the steam boiler (steam generator), closing the cycle.

In modern condensation plants for pumping steam-air mixture, multi-stage steam-ejector units based on steam-jet ejectors are used, with a number of drawbacks that significantly reduce their efficiency.

The studied issue is relevant from the point of view of scientific tasks for the modernization of existing power supply systems. In particular, it is necessary to have existing energy sources while new energy-saving installations of the new generation are being built. In order to assess the expected effect of their modernization, it is necessary to conduct a comparative analysis of the proposed schemes with the existing ones and select the best ones.

2. Literature review and problem statement

Existing condensation systems, which are an integral part of steam turbine installations, are built on the basis of steam-jet ejectors. Works [1, 2] revealed their main advantages and disadvantages, including the ability to work only in a narrow range of operating parameters. In addition, it is noted in those works that for almost 50 years of operation in such installations they have not been greatly improved. Study [3] describes the main improvements that were carried out to optimize the flow part and determine the specific design mode for each case of ejector operation.

The authors of [4, 5] conducted theoretical and practical studies that showed that the maximum efficiency of steam-jet ejectors has already been achieved and cannot be increased. In [6], it is noted that in order to improve the condensation process in steam-gas plants, it is necessary to search for new, alternative devices that would be more efficient and economical than steam jets. There are many attempts to do this but all of them make it possible to increase the efficiency of the condensation process by several percent, compared to steam jets. The authors of [7, 8] conducted a study into a fundamentally new class of devices, which are two-phase jet devices and revealed their main advantages compared to steam-jet ejectors.

The authors of [9] propose to use a liquid-vapor ejector as part of a vacuum unit operating on the principle of jet thermocompression. This principle implies that the working jet of steam is formed directly in the nozzle of the active flow and does not require an additional source of boiler steam, as for steam-jet ejectors. Boiler steam for a liquid-vapor ejector is needed only in the heat exchanger-heater, where a working medium of the active flow is heated. However, its consumption is ten times less than steam jet ejectors. Also, its main advantage is a single-stage design while steam-jet ejectors are multistage. This is the main reason for their low efficiency.

As a working substance of the active flow in the liquid-steam ejector, water is used, which is an affordable and cheap heat carrier. The possibility of using water in two-phase jet devices was investigated on the example of refrigeration and heat pump systems by the authors of [10]. Since the operating modes of these installations are similar to the condensation system of steam turbine plant, one can conclude that in this case the use of water is promising. It also makes a significant contribution to the efficiency of the proposed scheme.

Summarizing the review of the above sources, we can conclude that the existing condensing systems of steam turbines are equipped with low-efficiency multistage steam-jet units. This significantly reduces the efficiency of condensation systems in general and requires significant refinement.

One of the possible ways to design a highly efficient condensing system based on a liquid-vapor ejector is to combine it with a liquid-ring vacuum pump. In this case, the liquid-vapor ejector will work as a pre-vacuum unit. The main difference from the traditional scheme is the absence of a two-stage steam-jet ejector and the studying the operation of the liquid-vapor ejector under the pre-vacuum mode of operation.

3. The aim and objectives of the study

The purpose of this study is to assess the effectiveness of the use of a liquid-vapor ejector (LVE) as part of a condensing unit in a steam turbine and the consistency of its operation in combination with a liquid-ring vacuum pump (LRVP).

To accomplish the aim, the following tasks have been set:

– to describe a traditional condensing unit and the proposed circuit solutions based on a liquid-vapor ejector and a liquid-vapor ejector and a liquid-ring vacuum pump;

– to perform thermodynamic calculation of the cycle of a traditional condensing unit based on a steam-jet ejector and alternative schemes, one of which is executed on the basis of LVE, and the other on the basis of LVE+LRVP;

– to perform an exergy analysis of a traditional condensing unit and the proposed schemes based on LVE and LVE+LRVP and determine the achievable indicators of exergy efficiency of modernization of the steam turbine unit;

– to perform thermoeconomic analysis of the traditional condensing unit and the proposed schemes based on LVE and LVE+LRVP to determine the cost indicators of the efficiency of modernization of the steam turbine unit.

4. The study materials and methods

A modernized steam-gas plant for pumping out a steam-air mixture using a liquid-vapor ejector was considered, for greater energy savings. We also considered the operation of LVE in combination with a liquid-ring vacuum pump, where LVE performs the role of a pre-vacuum unit.

A working environment of the installation is n-pentane, the design capacity is 4 MW. Water from the waste heat boiler is used as a heat carrier for overheating and evaporation in a low-pressure turbine. The parameters of the working medium at the inlet to the active nozzle of LVE are $t_{p1}=104$ °C, $p_{p1}=1.6\cdot10^5$ Pa. Pressure at the outlet of the ejector is different and depends on the design of the scheme. For a scheme based on LVE, it is $p_{out}=1\cdot10^5$ Pa, for the LVE+LRVP scheme – $p_{out}=0.8\cdot10^5$ Pa. A vapor-air mixture pressure at the inlet to LVE $p_{s1}=0.17\cdot10^3$ Pa.

The optimization parameter in the exergy analysis is the difference in the temperatures of the active flow at the inlet to LVE and the liquid phase at the outlet of the separator Δt_n, which determines the load and flow rate of the boiler steam on the heat exchanger-heater. Numerical studies into the influence of this value on the efficiency indicators of the working process were performed when varying the initial parameters of the working fluid of the active flow at the inlet to LVE. Fig. 1 shows the relationship between the mode parameters of LVE in the interval of optimal values for this condensing plant.

To assess the possibility of upgrading a condensing unit of a steam turbine by using LVE, numerical research methods are used in this work, namely thermodynamic, exergy, and thermoeconomic.

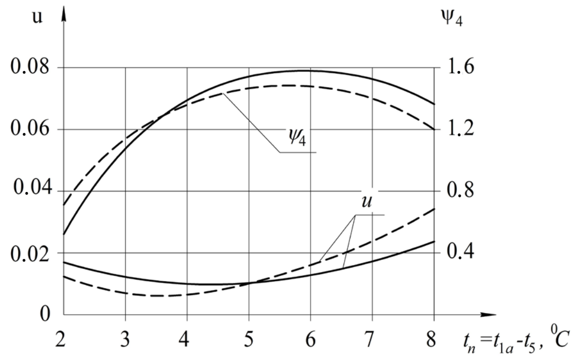

Fig. 1. Mode parameters of the liquid-vapor ejector for the conditions: p_{p1}=1.5–2.5·10^5 Pa, t_{p1}=92–104 °C: —— p_{s1}=0.17·10^3 Pa, – – – p_{s1}=0.2·10^3 Pa; u – injection coefficient, ψ_4 – degree of vapor overproduction, t_5 – temperature of mixed flow at the outlet of the ejector, t_{1a} – temperature of the active flow at the inlet to the ejector

The thermodynamic calculation of traditional condensing plants is carried out according to the procedure described in work [11].

To assess the exergy efficiency of thermomechanical systems, the most correct is the use of the exergy method of thermodynamic analysis [12]. It is sufficiently accurate for systems in which several types of energy (electrical and thermal) are simultaneously converted.

The exergy assessment of the degree of perfection of energy transformations in the system under study is based on the introduction into consideration of a new value – the exergy efficiency indicator – which is the ratio of the exergy of the system product flow to the exergy of the fuel flow [11, 13].

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

$$\varepsilon_{ex}=\frac{E_P}{E_F}, \tag{1}$$

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

The difference between the values of E_F and E_P gives the value of the destruction E_D and the loss of exergy E_L in the processes of energy transformations in a given system, that is,

$$E_D+E_L=E_F-E_P. \tag{2}$$

It should be noted that the value of E_D characterizes the level of dissipative losses due to internal irreversibility, and E_L is due to the presence of external heat transfer of the components of the system with the environment. The use of exergy analysis of this type does not require the involvement of entropy analysis to calculate the total destruction and loss of exergy in the system.

Thermoeconomic analysis is a new method for assessing the efficiency of thermomechanical systems and involves determining the cost of energy resources necessary for basic and energy-saving schemes. The thermoeconomic method for analyzing thermomechanical systems is a combination of exergy (thermodynamic) and cost analyses. The main criterion of the thermoeconomic method of analysis is the exergy value of the system product (its part, component, etc.) [12].

For any flow of exergy, the exergy cost takes the form:

$$C_j=c_j\cdot E_j,\ \text{a.u./h}, \tag{3}$$

where c_j is the price of exergy, a.u./kWh, a.u./kJ.

When calculating the cost of exergy for incoming flows crossing the boundaries of the system, the general form of the relationship between the cost of exergy and energy tariffs is characterized by the following expression:

$$c_{in}\cdot E_{in}=F_{in}\cdot I_{in},\ \text{a.u./h}, \tag{4}$$

which determines the equality of the exergy value and the natural cost of the amount of energy that the consumer of the system buys. Here, I_{in} is a parameter of the intensity of the flow of energy carrier (mass or volumetric flow rate, power, etc.).

5. Results of studying the effectiveness of the introduction of a liquid-vapor ejector for condensing units of steam turbines

5. 1. Description of scheme solutions

For comparison, the basic installation of an autonomous power plant based on a gas turbine engine with a steam unit was initially considered. It uses a two-stage ejector unit operating on a process steam to remove air from the condenser circuit (Fig. 2).

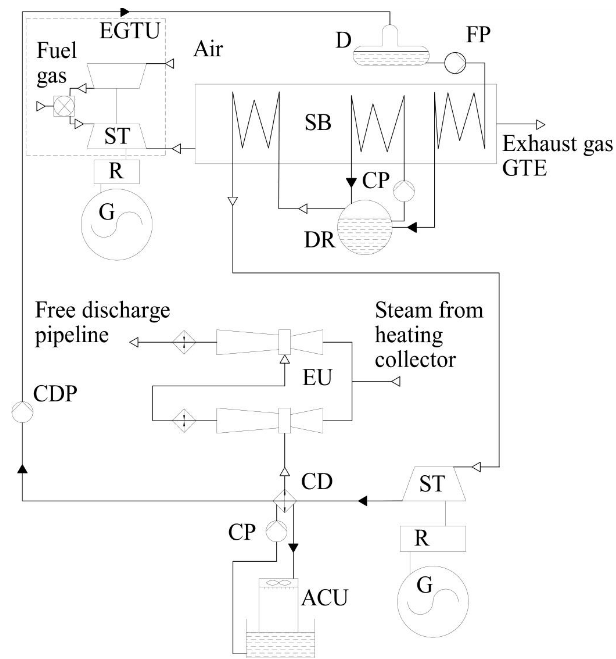

Fig. 2. Basic scheme of the condensing unit: EU – two-stage ejector unit, SB – steam boiler, ST – steam turbine, CD – condenser, CP – circulation pump, CDP – condensing pump, D – deaerator, FP – feed pump, DR – drum, G – generator, R – reducer, EGTU – energy gas turbine unit, ACU – air cooling unit

With a decrease in pressure and temperature of the steam that has worked in the turbine, the amount of heat transferred to the cold source decreases. As is known from thermodynamics, with constant parameters fresh steam increases the turbine power (by increasing the heat transfer to it) and the efficiency of the cycle as a whole. The steam turbine addition to the gas turbine engine is implemented by limiting the parameters of the generated water vapor for the use of an axis-radial steam turbine, which makes it possible to increase the condensation pressure acceptable for these installations. That makes it possible to achieve high thermal efficiency of the entire installation.

The proposed scheme was used (Fig. 3) as an application of a vacuum unit based on LVE, which allows replacing a two-stage steam-jet ejector with a single-stage liquid-steam, with high efficiency. This leads to a decrease in the consumption of boiler steam and a decrease in the initial parameters of a working medium of the active flow at the inlet to the nozzle, which is a more perfect energy conversion cycle. The LVE scheme in the vacuum unit was also considered, where it is used as a pre-vacuum unit to increase the pressure of the passive flow in LRVP (Fig. 4).

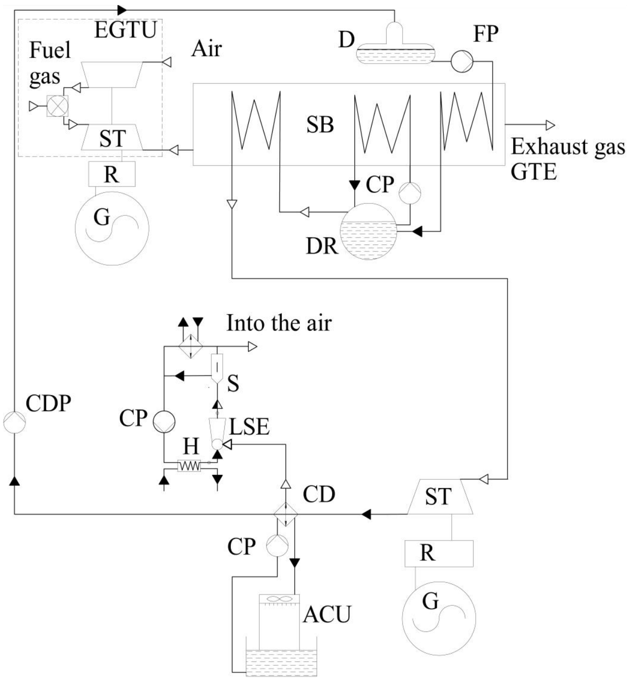

Fig. 3. Alternative scheme of a condensing unit based on a liquid-vapor ejector: LVE — liquid-vapor ejector, S — separator, CP — circulation pump, H — heat exchanger-heater, SB — steam boiler, ST — steam turbine, CD — condenser, CP — circulation pump, CDP — condensing pump, D — deaerator, FP — feed pump, DR — drum, G — generator, R — reducer, EGTU — energy gas turbine unit, ACU — air cooling unit

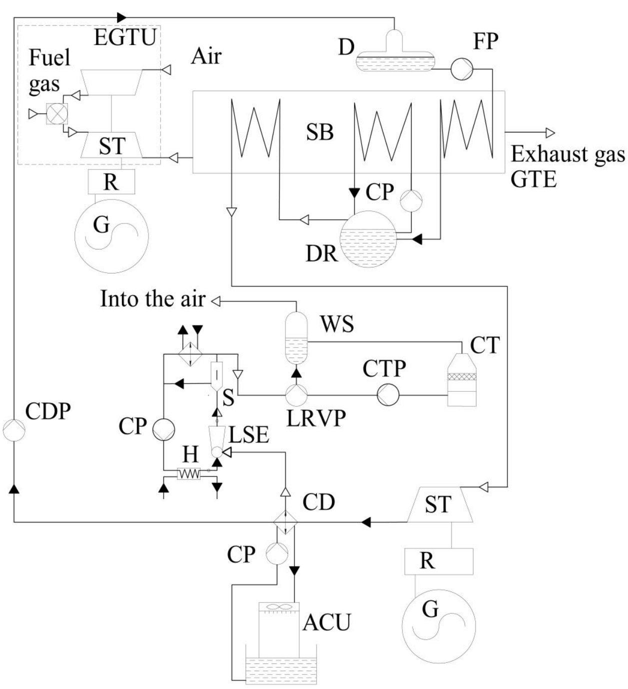

Fig. 4. Alternative scheme of the condensing unit on the basis of «liquid-vapor ejector+liquid-ring vacuum pump»: LVE — liquid-vapor ejector, S — separator, CP — circulation pump, H — heat exchanger-heater, LRVP — liquid-ring vacuum pump, WS — water separator, CT — cooling tower, CTP — cooling tower pump, SB — steam boiler, ST — steam turbine, CD — condenser, CP — circulation pump, CDP — condensing pump, D — deaerator, FP — feed pump, D — drum, G — generator, R — reducer, EGTU — energy gas turbine unit, ACU — air cooling unit

Thus, there is reason to believe that the use of a liquid-steam ejector in condensing plants of steam turbines is promising. However, the question of its effectiveness compared to traditional steam-jet ejector units remains open and needs to be investigated.

5. 2. Results of thermodynamic calculation

The calculation of the efficiency of the condensing unit based on the liquid-vapor ejector requires a preliminary thermodynamic calculation according to the procedure described in [14]. This procedure involves finding the regime parameters at the nodal points of the cycle. The calculations were carried out for two variants of alternative schemes: on the basis of LVE and on the basis of LVE+LRVP.

The mode parameters of the two alternatives are listed in Table 1. The results of thermodynamic calculation are given in Table 2.

Our results of the thermodynamic analysis indicate the prospect of applying the proposed solution by reducing the initial pressure and mass consumption of boiler steam.

Table 1

Mode parameters of condensing plants

No. of entry	Indicator designation	Scheme option	
		with LVE	with LVE+LRVP
1	Liquid pressure at the inlet to the active nozzle of LVE, bar	1.6	1.6
2	Temperature at the entrance to LVE, °C	104	104
3	The pressure of the passive flow at the inlet to RPE, bar	0.17	0.17
4	The pressure of the mixed flow at the outlet of LVE, bar	1	0.8
5	LVE injection coefficient	0.04147	0.0334
6	The degree of overproduction of steam	1.165	1.209
7	The efficiency of LVE	0.657	0.714

Table 2

Results of thermodynamic calculation

No. of entry	Indicator designation	Scheme option		
		basic	with LVE	with LVE+LRVP
1	Initial pressure in the vacuum system, bar	0.17	0.17	0.17
2	Boiler steam pressure, bar	9	1.6	1.6
3	Boiler steam temperature, °C	210	104	104
4	Mass consumption of boiler steam, kg/s	448	1.489	1.489
5	Mass flow of air, kg/s	28	28	28
6	Steam mass consumption, kg/s	25	25	25
7	Specific power of the circulation pump, kW	–	0.09	0.04
8	Specific power of the coolant pump, kW	–	–	0.01
9	Specific power of the cooling tower fan, kW	–	–	0.007
10	Specific power of liquid ring vacuum pump, kW	–	–	0.03

5. 3. Results of exergy analysis

The scheme of exergy transformations in a traditional condensing plant and alternative schemes is shown in Fig. 5.

Exergy efficiency equations are:

– for a traditional scheme:

$$\varepsilon_{ex1} = \frac{E_{P1}}{E_{F1}} = \frac{E_{4mix} - E_{1mix}}{E_{1st} - E_{4st}}; \tag{2}$$

– for a scheme with LVE:

$$\varepsilon_{ex2} = \frac{E_{P2}}{E_{F2}} = \frac{E_{5mix} - E_{1mix}}{\left(E_{1heat} - E_{2heat}\right) + N_P}; \tag{3}$$

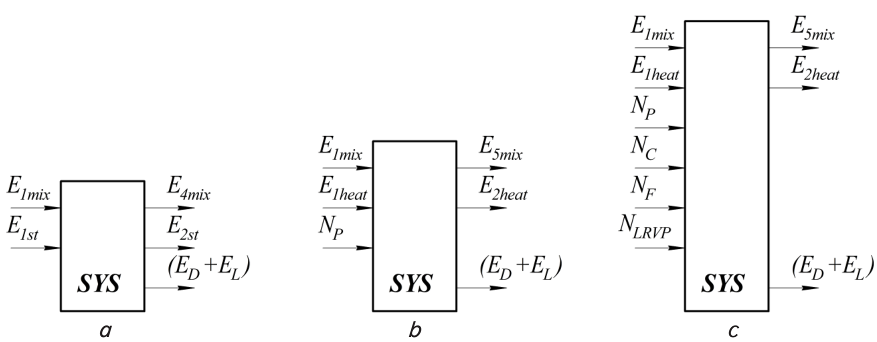

Fig. 5. Scheme of exergy transformations: *a* — traditional condensing unit, *b* — installation based on a liquid-vapor ejector, *c* — installation based on the «liquid-vapor ejector+liquid-ring vacuum pump» (E_{1mix} — exergy of the steam-air mixture at the inlet to the ejector unit, E_{4mix} — exergy of the vapor-air mixture at the outlet of the ejector unit, E_{1st} — exergy of boiler steam at the inlet to the ejector unit, E_{2st} — exergy of boiler steam at the outlet of the ejector unit, E_{1mix} — exergy of steam-air mixture at the inlet to the liquid-vapor ejector, E_{5mix} — exergy of steam-air mixture at the outlet of the liquid-vapor ejector, E_{1heat} — exergy of cooling water at the inlet to the heat exchanger, E_{2heat} — exergy of cooling water at the outlet of the heat exchanger, N_P — circulation pump power, N_C — heat carrier pump power, N_F — cooling tower fan power, N_{LRVP} — power of the liquid-ring vacuum pump, (E_D+E_L) — absolute destruction of exergy and absolute loss of exergy)

– for a scheme with LVE+LRVP:

$$\varepsilon_{ex3} = \frac{E_{P3}}{E_{F3}} = \frac{E_{5mix} - E_{1mix}}{(E_{1heat} - E_{2heat}) + N_P + N_C + N_F + N_{LRVP}}, \quad (4)$$

where E_{1mix} is the exergy of the steam-air mixture at the inlet to the ejector unit, E_{4mix} – exergy of steam-air mixture at the outlet of the ejector unit, E_{1st} – exergy of boiler steam at the inlet to the ejector unit, E_{2st} – exergy of boiler steam at the outlet of the ejector unit, E_{1mix} – exergy of steam-air mixture at the inlet to LVE, E_{5mix} – exergy of steam-air mixture at the outlet of LVE, E_{1heat} is the exergy of cooling water at the inlet to the heat exchanger, E_{2heat} – exergy of cooling water at the outlet of the heat exchanger, N_P – circulation pump power, N_C – heat carrier pump power, N_F – cooling tower fan power, N_{LRVP} – power of the liquid-ring vacuum pump.

The results of exergy analysis are given in Table 3.

Table 3

Results of exergy analysis

No. of entry	Indicator designation	Scheme option		
		basic	with LVE	with LVE+LRVP
1	Exergy of fuel flow, kW	297.2	62.95	58.74
2	Exergy of product flow, kW	93.05	44.86	44.86
3	Exergy efficiency	0.313	0.713	0.764

As a result of the exergy analysis, it can be concluded that the efficiency of the condensing unit scheme based on a liquid-vapor ejector is 2.3 times greater than that of the traditional one. The use of LRVP in the alternative scheme and setting LVE to a pre-vacuum mode allows for an additional increase in efficiency by 17 % compared to the LVE-based scheme, which is 2.44 times more compared to the alternative scheme.

5. 4. Results of thermoeconomic analysis

The total cost of fuel for the traditional scheme is determined from the formula:

$$C_1 = C_{st1} \cdot \dot{V}_{w1} \cdot \tau_p + C_{e1} \cdot \sum N_1 \cdot \tau_p, \quad (4)$$

where C_{st1} is the cost of 1 m^3 of boiler steam water, $\dot{V}_{st1}$ – volumetric consumption of boiler steam, C_{e1} – the cost of electricity, $\sum N_1$ – the amount of consumed power, which is spent on the drive and pumps, τ_p – the estimated period of operation of the installation.

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

$$C_2 = C_{st2} \cdot \dot{V}_{w2} \cdot \tau_p + C_{e2} \cdot \sum N_2 \cdot \tau_p, \quad (5)$$

where C_{st2} is the cost of 1 m^3 of boiler steam, $\dot{V}_{st2}$ – volumetric consumption of boiler steam, C_{e2} – the cost of electricity, $\sum N_2$ – the amount of consumed power, which is spent on the pump drive, τ_p – the estimated period of operation of the installation. The results of thermoeconomic analysis are given in Table 4.

Table 4

Results of thermoeconomic analysis

No. of entry	Indicator designation	Scheme option		
		basic	with LVE	with LVE+LRVP
1	The total cost of fuel, a.u.	1348.57	643.88	644.71
2	The specific cost of a product unit, a.u./t	2.17	1.06	1.08
3	Specific value of a unit of steam, a.u./m^3	3.01	2.11	2.13

The obtained results of calculating the total cost of fuel and the unit cost of a unit of product make it possible to assert that the use of LVE in condensing plants of steam turbines is appropriate. This reduces the cost of generating boiler steam and reduces the cost of the resulting product of the steam turbine unit by about 51 %.

6. Discussion of the feasibility of using a liquid-vapor ejector to increase the efficiency of condensing units of steam turbines

Evaluating our results of the thermodynamic, exergy, and thermoeconomic analyzes of both proposed schemes, we can distinguish several significant advantages of the proposed scheme based on LVE (Fig. 3), related to simplifying the design and increasing the efficiency of the traditional condensing system. However, the use of a liquid-vapor ejector as a pre-vacuum one in combination with a liquid-ring vacuum pump (Fig. 4) makes it possible to reduce the degree of increase in the pressure of the passive flow in the LVE and transfer it to a more moderate mode of operation. This increases the efficiency of LVE and reduces the degree of overproduction of steam, which must be returned to the cycle from an external source.

The following features were identified. For the operation of the steam-jet ejector, a constant external generation of the boiler steam of the specified parameters is necessary. This is especially difficult to ensure if there is no constant source of this steam in production since its consumption under different modes of operation is in the range of 350–700 kg/s.

Both proposed solutions avoid such problems due to the fact that the generation of working steam occurs inside the liquid-vapor ejector, namely in the nozzle of the active flow. In the diffuser part of the nozzle, the water that is not heated to saturation begins to boil and generate a working steam to eject the passive flow. This is what has made it possible to obtain such indicators of its effectiveness.

The closest in design to the proposed ones is single-phase steam-ejector units, in which steam-jet ejectors with a working medium are used – boiler steam. However, they, as a rule, are multistage and their overall effectiveness usually does not exceed 2–5 %. This is due to the fact that one stage of the steam-jet ejector can create a pressure drop of only 2–3 times. In one liquid-vapor ejector, such a difference is at the level of 8–10.

Limitation in the application of this type of ejectors is the degree of increase in the pressure of the passive flow in one liquid-vapor ejector. If a significant increase in pressure of more than 10–12 is required, then it is still necessary to use a two-stage unit or pre-vacuum pumps (booster or molecular).

Our study can be continued and further applied to increase the efficiency of similar steam-gas installations. Nevertheless, limiting the degree of pressure increase in one liquid-steam ejector restrains this area of application. However, studies are underway on the influence of a large-scale factor on its effectiveness and a possible way out is to increase the diameter of the critical section of the active flow nozzle or additional profiling of its flow part.

7. Conclusions

1. We have described and analyzed a traditional condensing unit based on a two-stage steam-jet ejector with the identification of the main shortcomings of this scheme. Alternative scheme solutions based on liquid-vapor ejector and liquid-steam ejector and liquid-ring vacuum pump are proposed.

2. As a result of thermodynamic calculation, it was revealed that the use of a liquid-vapor ejector operating on the principle of jet thermocompression is promising for condensing plants of steam turbines. It can also be used together with a liquid-ring vacuum pump as a pre-vacuum unit.

3. As a result of exergy analysis, the exergy efficiency of the liquid-vapor ejector in the condensation unit and the feasibility of its use for steam turbine installations were determined. The exergy efficiency of the new equipment is 0.713, which is 2.3 times higher than that of traditional ones. Additionally, it is possible to increase efficiency by 17 % by using this ejector as a pre-vacuum one together with LRVP. Such indicators are achieved due to the transition to smaller degrees of pressure increase in LVE, which leads to a decrease in thermal loads on the auxiliary equipment of the scheme, a decrease in the exergy of the fuel flow, and an increase in overall efficiency.

4. As a result of thermoeconomic analysis, the total cost of fuel and the unit cost of a unit of product in the new and traditional scheme of the condensing unit have been determined. The use of LVE makes it possible to reduce the total cost of fuel by an average of 704.28 a.u. per year. It is also possible to reduce the unit cost of a unit of product by an average of 51 %, excluding the cost of generating boiler steam in traditional schemes. The use of the LVE+LRVP scheme increases the unit cost of the product by 2 %, which is a consequence of additional costs for the drive of auxiliary equipment (pumps, cooling tower fan, etc.).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Acknowledgments

We express our gratitude to Professor at the Department of Technical Thermophysics, Candidate of Technical Sciences, Vyacheslav Mikhailovich Arsenyev (Sumy State University, Ukraine) for his help in choosing research methods and finding relevant information sources.

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UDC 536.248.2

DOI: 10.15587/1729-4061.2022.263180

DETERMINING THE INFLUENCE OF GEOMETRIC FACTORS AND THE TYPE OF HEAT CARRIER ON THE THERMAL RESISTANCE OF MINIATURE TWO-PHASE THERMOSYPHONS

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This paper reports experimental data on the total thermal resistance of copper two-phase thermosiphons with internal diameters of 3 mm, 5 mm, and 9 mm, 700 mm long. Water, ethanol, methanol, and freon-113 were used as heat carriers. During the study, thermosiphons were located vertically. The length of the heating zone varied from 45 mm to 200 mm while the length of the condensation zone was constant and equaled 200 mm. The filling coefficient of thermosiphons varied from 0.3 to 2.0. Two series of experiments were conducted. The first series was distinguished by the fact that the filling coefficient of three thermosiphons with an internal diameter of 9 mm varied from 0.3 to 0.8 with the same length of the heating zone of 200 mm. The second series of experiments was carried out on thermosiphons with internal diameters of 3 mm and 5 mm. With the same amount of heat carrier, the length of the heating zone changed from 45 mm to 200 mm. As a result of research, it was determined that the total thermal resistance of thermosiphons is influenced by both their geometric factors (internal diameter and filling coefficient) and the type of heat carrier. The main factor that influenced the value of thermal resistance was also the transmitted heat flux. An increase in heat flow led to a significant decrease in thermal resistance. The maximum heat flux was determined with minimal thermal resistance. To calculate the value of the thermal resistance of thermosiphons, two dimensionless dependences were derived, which hold for two ranges of Reynolds numbers. For small Reynolds numbers (until 2000), which characterize the beginning of the action of vaporization centers and their gradual increase, the degree indicator was –0.8, and for larger Reynolds numbers, up to critical phenomena, the degree indicator was at the level of –0.3

Keywords: miniature thermosiphon, heat transfer intensity, thermal resistance, heat flux, heat carrier, filling coefficient

Received date 08.06.2022
Accepted date 04.08.2022
Published date 29.08.2022

How to Cite: *Kravets, V., Konshin, V., Hurov, D., Vorobiov, M., Shevel, I. (2022). Determining the influence of geometric factors and the type of heat carrier on the thermal resistance of miniature two-phase thermosyphons. Eastern-European Journal of Enterprise Technologies, 4 (8 (118)), 51–59. doi: https://doi.org/10.15587/1729-4061.2022.263180*

1. Introduction

The current trend of reducing the mass and size characteristics of electronic equipment while increasing its functionality predetermines an urgent task of designing effective thermal stabilization systems for such miniature devices. The use of devices for heat dissipation, which employ the evaporation-condensation cycle for this purpose, makes it possible to some extent to solve this problem. A thermosiphon can be used as such a device. It is a two-phase closed heat transfer device containing a certain amount of liquid that uses the latent heat of evaporation and condensation to transfer heat