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Heat Utilization in Boiler Plants by Using Liquid-Vapor Jet Apparatus

Sharapov S. O.[1][0000-0002-8433-8580], Krmela J.[2][0000-0001-9767-9870], Husiev D. M.[1*][0000-0003-4505-9084],
Verbytskiy A. R.[1][0009-0002-7552-0142], Bocko J.[3][0000-0002-3158-3507]

[1] Department of Technical Thermophysics, Sumy State University, 116, Kharkivska St., 40007, Sumy, Ukraine;
[2] Department of Numerical Methods and Computational Modelling, Alexander Dubček University of Trenčín,
491/30, Ivana Krasku St., 020 01, Púchov, Slovak Republic;
[3] Department of Applied Mechanics and Mechanical Engineering, Technical University of Košice,
1/9, Letná St., 040 01, Košice, Slovak Republic

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***Corresponding email:**
d.husiev@kttf.sumdu.edu.ua

Abstract. The article solves the problem of heat utilization from combustion products in boiler plants. The proposed solution involves extracting heat to preheat the network water for the heating system and implementing additional heat utilization using a liquid-vapor jet apparatus. This will allow for additional working steam generation in the main steam generator and the unit based on the liquid-vapor jet apparatus. The article provides schemes and descriptions of traditional and proposed plants, indicating their design differences from the basic scheme. Comparative thermodynamic analysis of the proposed installation for additional recuperative heat utilization and the basic scheme is carried out, in which heat utilization occurs due to the extraction of heat from combustion products to preheat the network water of the heating system. As a result, the main thermodynamic parameters of the cycles of basic and proposed schemes are obtained, and the values of the capacities on the apparatuses included in these installations are determined. The energetic potential obtained from additional heat utilization is 8 %, which can be used for electricity generation. Exergy analysis assesses the efficiency of additional heat utilization in boiler plants using units based on liquid-vapor jet apparatus. As a result of the exergy analysis, the value of the exergetic efficiency of the scheme with additional heat utilization was obtained, which is 1.47 times higher than that of the basic scheme. A thermoeconomic analysis was performed to determine the cost values. Implementing the new scheme enables reducing the specific cost of the heating unit by 48 % and increasing the amount of steam generated in the installation by an additional 18 %.

Keywords: energy efficiency, boiler plant, recuperative heat recovery, liquid-vapor jet apparatus, additional steam generation.

1 Introduction

Considering the russian invasion of Ukraine and constant enemy attacks on critical infrastructure, it is necessary now to find ways of improving the energy efficiency of existing boiler plants. New modern heat and power supply systems cannot be built in some regions of our country.

Another issue is the combination of energy types produced by these facilities. It would help ensure that heat and electricity supplies are not interrupted by attacks on objects. That is called cogeneration — the simultaneous production of heat and electricity. It provides heating, hot water, and power supply.

Most existing boiler plants in Eastern Europe date back to the 50s and 60s of the 20th century. They are centralized and powerful enough to supply heat to numerous consumers. Simultaneously, their efficiency is relatively low, primarily depending on the lack of actions aimed at utilizing these facilities' heat discharged into the atmosphere. In the last few years, the cost of heat supply for consumers has been constantly increasing, so the issue of heat utilization and improving the efficiency of existing boiler plants has become quite acute. It has escalated in recent years due to the military operations on the territory of our country.

Possible solutions to the problems described above may include the creation of new decentralized low-capacity boiler plants and upgrading existing ones through recuperative heat recovery from combustion products. In this regard, the issue of heat removal and rational use of combustion products remains crucial because their temperature is high and is at the level of 220–260 °C at the steam generator outlet.

2 Literature Review

Heat supply to industrial and domestic consumers using boiler plants in Eastern Europe began in the mid-twentieth century and includes a system of plants with a capacity of more than 500 kW [1, 2]. A single unit provides heat to an entire district or even a small town. The exception is industrial facilities, which, as a rule, have separate boiler plants used exclusively for the needs of a particular production. This approach is outdated and inefficient, as it excludes the possibility of smooth regulation of operating modes and, if an accident occurs, makes it impossible to supply consumers with power from another heat source [3–5].

The current energy-saving program focuses on decentralizing heat suppliers and installing small boiler plants with a capacity of up to 500 kW in some neighborhoods and even in individual houses. It allows for increasing their efficiency and minimizing heat losses due to the transportation of heat carriers through an extensive system of steam pipelines [6–8]. However, there are areas in our country where it is impossible to build new energy-efficient boiler plants, so there is an urgent need to modernize existing systems.

The authors of works [9, 10] analyze the main factors affecting the efficiency of available boiler plants and conclude that recuperative heat recovery is the simplest and most affordable way to implement. This method implies using various types of heat exchange equipment, and the generated heat can be used for heating or hot water supply to consumers [11].

Studies conducted in works [12–14] have shown that such heat recovery measures can decrease the temperature of combustion products discharged through the chimney into the atmosphere by 90-100 °C.

The next step towards intensifying the steam generation process in such boiler plants is additional steam generation by using the heat of combustion products in special steam generating units. These can be units based on liquid-vapor jet apparatus (LVJA), whose operating process is based on the jet thermal compression principle [15, 16]. These devices include a steam generator and an ejector (or compressor, depending on the operating mode). Unheated to saturation, the working fluid (water) boils in the nozzle of the active flow, followed by the ejection of combustion products. The separator divides the mixed stream into liquid and vapor phases. The liquid one is returned to the unit cycle based on the LVJA using a circulation pump, and the vapor phase, together with the main steam flow generated in the steam generator, is supplied to the consumer.

The authors of the work [17] analyzed the reasonability for using LVJA in other vacuum systems. The application of these apparatus made it possible to increase the efficiency of technological systems by 1.5–3.0 times. Considering the data from theoretical and experimental studies of domestic and foreign researchers, the authors find it reasonable to study the effectiveness of using LVJA for additional heat recovery in boiler plants to increase their efficiency.

Considering all of the above, the following main problems remain unresolved: lowering the temperature of the combustion products at the exit from the chimney to the level of 50–60 °C and the possibility of switching the boiler plant to cogeneration mode.

So, the main aim of the article is additional heat recovery of the heat of combustion products in boiler plants in order to reduce the temperature of combustion products at the exit from the chimney with the possibility of additional steam generation in the liquid-vapor jet apparatus, which will allow additional electricity generation.

3 Research Methodology

3.1 Object and hypothesis of the study

This study aims to analyze the efficiency of using a unit based on a liquid-vapor jet apparatus for additional heat recovery in boiler plants.

To achieve this objective, the following tasks were set:

– to perform a thermodynamic calculation of the basic scheme of a boiler plant with recuperative heat recovery and the proposed system with a unit based on LVJA for additional heat recovery, as a result of which it is necessary to estimate the value of the energy potential of both schemes and determine the share of additional steam generated in the cycle based on LVJA;

– to perform an exergy analysis of the basic scheme of the boiler plant with recuperative heat recovery and the proposed system with a unit based on LVJA for additional heat recovery, as a result of which to determine the values of exergy efficiency of both schemes;

– to perform a thermoeconomic analysis of the basic scheme of a boiler plant with recuperative heat recovery and the proposed system with a unit based on LVJA for additional heat recovery, as a result of which to determine the cost per unit of steam and the amount of economic effect from the new scheme.

The object of study is a boiler plant with additional equipment for recuperative heat recovery, consisting of a heat recovery unit and a unit based on a liquid-vapor jet apparatus.

Thermodynamic, exergy and thermoeconomic analyses of the basic and proposed technological schemes should be performed. The achievable efficiency indicators to assess the feasibility of additional heat recovery in boiler plants using a liquid-vapor jet apparatus should be determined. For thermodynamic analysis, this indicator is the value of energy potential; exergy analysis is the value of exergy efficiency; thermoeconomic analysis is the cost of steam produced and the economic effect of the new scheme implementation. A part of the methodology for these calculations is briefly described in [17].

3.2 Schemes of the heat pump unit

The basic boiler plant is used at “Mondelēz International, Inc.” (Trostianets, Ukraine).

As shown in Figure 1, the plant includes a steam generator where fuel burns, and combustion products discharge into the atmosphere through the chimney.

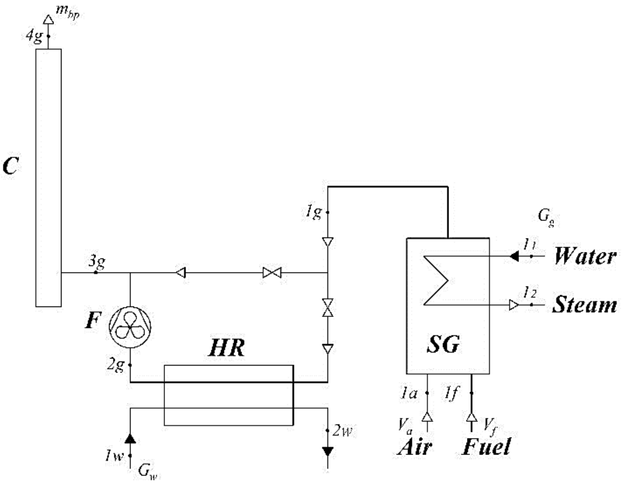


Figure 1 – The basic scheme of a boiler plant with recuperative heat recovery: SG – steam generator; C – chimney; HR – heat recovery; F – fan

The combustion products’ final temperature without heat recovery is t_{4g} = 160 °C.

Preliminary, the initial stage of recuperative heat recovery took place to reduce the final temperature of the combustion products by using a heat recovery device and a fan. The last one is to intensify the process of combustion products passing through the heat recovery device. The recovered heat is for warming up the heating system’s mains water from t_{1w} = 70 °C to t_{2w} = 90 °C. Thus, this helped to reduce the final temperature of the combustion products to t_{4g} = 60–65 °C.

A scheme of efficient heat recovery using a unit based on a liquid-vapor jet apparatus is proposed (Figure 2). It operates on the principle of jet thermal compression and has some significant advantages over similar steam jet models. In particular, it works as a steam generator because the active flow nozzle generates working steam.

Heat recovery in this scheme involves lowering the final temperature of the combustion products to t_{4g} = 40–45°C by additional heat extraction from the steam generator, which is for heating the working fluid of the active flow in the heat exchanger-heater. Additional heat produced in the working cycle of the LVJA-based unit will be used to generate electricity.

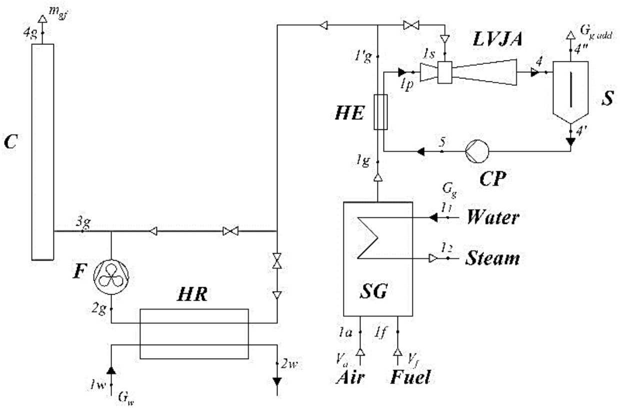


Figure 2 – Alternative scheme of a boiler plant with additional heat recovery based on LVJA: SG – steam generator; C – chimney; HR – heat recovery; F – fan; LVJA – liquid-vapor jet apparatus; HE – heat exchanger; S – separator; CP – circulation pump

4 Results

4.1 Thermodynamic calculation results

A thermodynamic analysis is necessary to assess the feasibility of applying LVJA in a given boiler plant for additional heat recovery. Its purpose is to determine the main parameters of the devices used in the standard and alternative schemes. The results of the thermodynamic analysis are presented in Table 1.

Table 1 – Thermodynamic analysis results

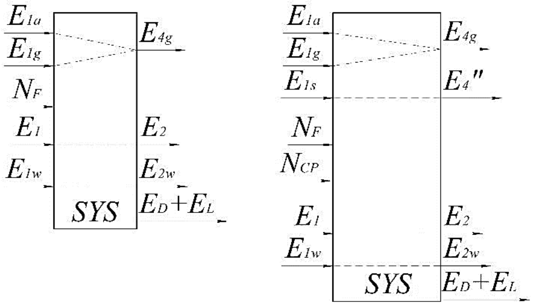
Parameter	Design scheme	
	basic	with LVJA
Steam output of the boiler plant, kg/h	7800	7800
Heat output of the steam generator, kW	5238	5238
Temperature of combustion products at the steam generator outlet, °C	260	260
The pressure of combustion products at the steam generator outlet, kPa	101.3	101.3
Temperature of combustion products at the chimney outlet, °C	60	45
The mass flow rate of combustion products at the chimney outlet, kg/h	9360	5220
The average temperature of the heat recovery process, °C	160	160
The temperature of mains water at the heat recovery device inlet, °C	70	70
Mains water temperature at the heat recovery device outlet, °C	90	90
The mass flow rate of mains water, kg/h	23 800	23 800
The pressure of combustion products at the inlet to the LVJA, kPa	–	20
The mass flow rate of combustion products at the inlet to the LVJA, kg/h	–	4140
Fan capacity, kW	0.072	0.072
Circulation pump capacity, kW	–	0.038
Energy potential, kW	581.7	628.5

As a result of the thermodynamic analysis, it can be concluded that the integration of additional heat recovery using a unit based on LVJA allows for increasing the energy potential of the proposed scheme by 46.7 kW, which is 8 %. This extra value can serve to generate electricity. The calculations also show that the additional heat recovery gives a possibility to reduce the share of combustion products discharged through the chimney by 44 %. It generates additional steam in the LVJA, and its share is 18 % of the main steam.

4.2 Results of exergy analysis

The exergy analysis follows the methods described in [18–21]. The schemes of exergy transformations were drawn up under the methodology of exergy analysis [17].

Figure 3 shows the schemes of exergy transformations in the basic scheme and the proposed one with a unit based on LVJA.



a b

Figure 3 – Scheme of exergy transformations: a – basic scheme; b – the scheme with the liquid-vapor jet apparatus

Considering the transformations shown in Figure 3 that occur in the schemes (for the basic one), the following formulas can be obtained:

– for the exergy of the fuel flow:

$$E_{F1} = \left(E_{1f} - E_{1a}\right) - E_{4g} + N_F; \qquad (1)$$

$$E_{F1} = E_{fuel} - \left(E_{4g} - E_{1a}\right) + N_F; \qquad (2)$$

– for product flow exergy:

$$E_{P1} = (E_2 - E_1) + (E_{2w} - E_{1w}). \qquad (3)$$

For the alternative scheme, the fuel flow exergy is defined the same way as for the basic one, with consideration of the capacity N_{CP} of the pump for the LVJA circulation circuit:

$$E_{F2} = \left(E_{1f} - E_{1a}\right) - E_{4g} + N_F + N_{CP}; \qquad (4)$$

$$E_{F2} = E_{fuel} - \left(E_{4g} - E_{1a}\right) + N_F + N_{CP}. \qquad (5)$$

Since the alternative scheme involves additional steam generation in the LVJA, the flow exergy of the product is measured similarly to the basic scheme, but with consideration of the exergy of this steam generation flow:

$$E_{P2} = (E_2 - E_1) + (E_{2w} - E_{1w}) + (E_4'' - E_{1s}), \qquad (6)$$

where E_{1f} – fuel flow exergy at the inlet to the steam generator; E_{1a} – air flow exergy at the inlet to the steam generator; E_{fuel} – fuel flow exergy; E_{4g} – exergy of the combustion product flow at the chimney outlet; N_F – fan capacity; E_1 – exergy of the water flow at the inlet to the steam generator; E_2 – exergy of the steam flow at the outlet of the steam generator; E_{1w} – exergy of the water flow at the inlet to the heat recovery device; E_{2w} – exergy of the water flow at the outlet of the heat recovery device; E_4'' – flow exergy at the separator outlet; E_{1s} – exergy of the passive flow at the inlet to the LVJA.

After performing the exergy transformations for the basic scheme, it can be obtained:

– fuel flow exergy:

$$E_{fuel} = \dot{Q}_{gas} = \dot{Q}_{SG} + \dot{Q}_{env}, \qquad (7)$$

where $\dot{Q}_{gas}$ – heat flux from compressed gas; $\dot{Q}_{SG}$ – heat output of the steam generator; $\dot{Q}_{env}$ – heat flux from energy losses into the environment:

$$E_{4g} - E_{1a} = \dot{G}_f \cdot \left(e_{4g} - e_{1a}\right), \qquad (8)$$

where $\dot{G}_f$ – mass fuel consumption; e_{4g} – specific exergy of the combustion product flow at the chimney outlet; e_{1a} – specific exergy of the airflow at the inlet to the steam generator ($e_{1a} = e_{env} = 0$):

$$e_{4g} - e_{1a} = \tilde{c}_p \cdot \left(t_{4g} - t_{env}\right) - \\ - T_{env} \cdot \left(\tilde{c}_p \cdot ln\frac{T_{4g}}{T_{env}} - R \cdot ln\frac{p_{4g}}{p_{env}}\right), \qquad (9)$$

where $\tilde{c}_p$ – heat content of the combustion products at an average temperature; t_{4g}, p_{4g} – temperature and pressure of combustion products at the chimney outlet; t_{env}, T_{env}, p_{env} – temperature and pressure of the environment; R – gas constant of the combustion products.

It is necessary to substitute formulas (8) and (9) into formula (2) to determine the exergy of the fuel flow in the basic scheme.

– exergy of the product flow:

$$E_2 - E_1 = \dot{G}_g \cdot (e_2 - e_1), \qquad (10)$$

where $\dot{G}_g$ – steam output of the boiler plant; e_1 – specific exergy of the water flow at the inlet to the steam generator; e_2 – specific exergy of the steam flow at the outlet of the steam generator:

$$e_2 - e_1 = \tilde{c} \cdot (t_2 - t_1) - \frac{p_2 - p_1}{\tilde{\rho}} - T_{env} \cdot \tilde{c} \cdot ln\frac{T_2}{T_1}, \qquad (11)$$

where $\tilde{c}$ – heat capacity of water at an average temperature; t_1, p_1 – temperature and pressure of water at the inlet to the steam generator; t_2, p_2 – temperature and pressure of steam at the outlet of the steam generator; $\tilde{\rho}$ – water density at an average temperature:

$$E_{2w} - E_{1w} = \dot{G}_w \cdot (e_{2w} - e_{1w}), \qquad (12)$$

where $\dot{G}_w$ – mass flow rate of mains water; e_{1w} – specific exergy of the water flow at the inlet to the heat recovery device; e_{2w} – specific exergy of the steam flow at the outlet of the heat recovery device:

$$e_{1w} - e_{2w} = \tilde{c}_w \cdot (t_{2w} - t_{1w}) - \frac{p_{2w} - p_{1w}}{\tilde{\rho}_w} -$$
$$- T_{env} \cdot \tilde{c}_w \cdot ln \frac{T_{2w}}{T_{1w}} , \qquad (13)$$

where $\tilde{c}_w$ – heat capacity of the mains water at an average temperature; t_{1w}, p_{1w} – temperature and pressure of water at the inlet to the heat recovery device; t_{2w}, p_{2w} – temperature and pressure of steam at the outlet of the heat recovery device; $\widetilde{\rho}_w$ – the density of the mains water at an average temperature.

It is necessary to substitute formulas (11) and (13) into formula (3) to determine the exergy of the product flow in the basic scheme.

After the exergy transformations, to determine the exergy of the fuel flow in the proposed scheme, it is necessary to substitute formulas (8) and (9) into formula (5).

After the exergy transformations to determine the exergy of the product flow in the proposed scheme, it can be obtained:

$$E_4'' - E_{1s} = \dot{G}_{g\,add} \cdot [(h_4'' - h_{02}) - (s_4'' - s_{02})], \qquad (14)$$

where $\dot{G}_{g\,add}$ – mass flow rate of combustion products at the inlet to the LVJA; h_{02}, s_{02} – enthalpy and entropy of the passive flow at the inlet to the LVJA; h_4'', s_4'' – enthalpy and entropy of the passive flow at the outlet of the LVJA.

It is necessary to substitute formulas (11), (13), and (14) into formula (6) to determine the exergy of the product flow in the proposed scheme.

The results of calculating the exergy efficiency indicators are in Table 2.

Table 2 – Results of the exergy analysis

Parameter name	Scheme option	
	basic	with LVJA
Product flow exergy, kW	1188.0	1755.0
Exergy of fuel flow, kW	5283.2	5294.3
Exergy efficiency	0.225	0.331

The exergy analysis shows that the efficiency of a boiler plant with additional heat recovery based on a liquid-vapor jet apparatus is 1.47 times higher than that of the basic one.

4.3 Results of thermoeconomic analysis

The thermoeconomic analysis is conducted by following the principles outlined in the works [22–25]. Schemes of changes in the cost of flows were drawn up under the methodology of exergy analysis [17].

Figure 4 shows a scheme of changes in the cost of flows in the basic model and the one with a liquid-vapor jet apparatus.

To determine the prices of exergy flows in the basic scheme, a system of equations that describes the flows through all elements of the plant can be written:

$$\begin{cases} c_{P,\,SG} \cdot E_{P,\,SG} = c_{F,\,SG} \cdot E_{F,\,SG} + Z_{SG} \\ c_{P,\,HR} \cdot E_{P,\,HR} = c_{F,\,HR} \cdot E_{F,\,HR} + Z_{HR} \\ c_{P,\,F} \cdot E_{P,\,F} = c_{F,\,F} \cdot E_{F,\,F} + Z_F \\ c_{P,\,C} \cdot E_{P,\,C} = Z_C \end{cases}, \qquad (15)$$

where $c_{P,\,SG}$, $c_{F,\,SG}$ – the price of the product flow and fuel for the steam generator; Z_{SG} – the cost of capital investment for a steam generator; $c_{P,\,HR}$, $c_{F,\,HR}$ – the price of the product and fuel flow for the heat recovery device; Z_{HR} – the cost of capital investment for the heat recovery device; $c_{P,\,F}$, $c_{F,\,F}$ – the price of the product and fuel flow for the fan; Z_F – the cost of capital investment for the fan; $c_{P,\,C}$ – product flow price for the chimney (fuel flow price for the chimney $c_{F,\,C} = 0$ (since the final cooling of the combustion products takes place in it); Z_{SG} – the cost of capital investment for the chimney.

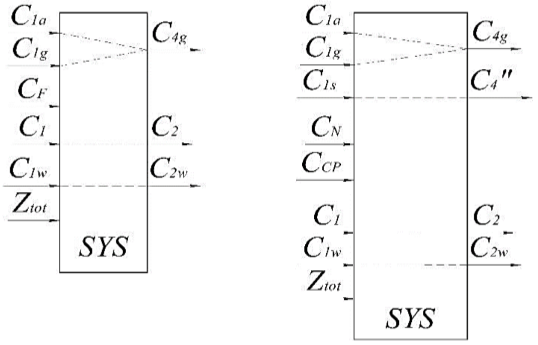


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Figure 4 – Scheme of changes in the cost of flows: a – basic scheme; b – the scheme with the liquid-vapor jet apparatus

Let us determine the exergy price of the product $(c_{P1})_{tot}$ and the fuel $(c_{F1})_{tot}$ for the basic scheme overall:

$$(c_{P1})_{tot} = \frac{(E_2 \cdot c_2 - E_1 \cdot c_1) + (E_{2w} \cdot c_{2w} - E_{1w} \cdot c_{1w})}{E_{P1}}, \qquad (16)$$

where c_1 – the price of water flow at the inlet to the steam generator; c_2 – the price of steam flow at the outlet of the steam generator; c_{1w} – the price of water flow at the inlet to the heat recovery device; $c_2 w$ – price of the water flow at the outlet of the heat recovery device:

$$(c_{F1})_{tot} = \frac{\dot{Q}_{SG} \cdot c_{SG} - E_{4g} \cdot c_{4g} + p_{E_F} \cdot N_F}{E_{F1}}, \qquad (17)$$

where c_{SG} – the price of the fuel flow at the inlet to the steam generator; c_{4g} – the price of the flow of combustion products at the chimney outlet; p_{E_F} – the price of electricity to power the fan.

To determine the prices of exergy flows in the proposed scheme, a system of equations that describes the flows through all elements of the plant can be written:

$$\begin{cases} c_{P,SG}\cdot E_{P,\,SG} = c_{F,\,SG}\cdot E_{F,\,SG} + Z_{SG}; \\ c_{P,HR}\cdot E_{P,HR} = c_{F,HR}\cdot E_{F,HR} + Z_{HR}; \\ c_{P,F}\cdot E_{P,F} = c_{F,F}\cdot E_{F,F} + Z_{F}; \\ c_{P,C}\cdot E_{P,C} = Z_{C}; \\ c_{P,LVJA}\cdot E_{P,LVJA} = c_{F,\,LVJA}\cdot E_{F,\,LVJA} + Z_{LVJA}; \\ c_{P,HE}\cdot E_{P,HE} = c_{F,\,HE}\cdot E_{F,\,HE} + Z_{HE}; \\ c_{P,CP}\cdot E_{P,CP} = c_{F,\,CP}\cdot E_{F,\,CP} + Z_{CP}; \\ c_{P,S}\cdot E_{P,S} = c_{F,S}\cdot E_{F,\,S} + Z_{S}, \end{cases} \quad (18)$$

where $c_{P,\,LVJA}$, $c_{F,\,LVJA}$ – the price of product and fuel flow for the LVJA; Z_{LVJA} – the cost of capital investment for the LVJA; $c_{P,\,HE}$, $c_{F,\,HE}$ – the price of the product and fuel flow for the heat exchanger; Z_{HE} – the cost of capital investment for the heat exchanger; $c_{P,\,CP}$, $c_{F,\,CP}$ – the price of the product and fuel flow for the circulation pump; Z_{CP} – the cost of capital investment for the circulation pump; $c_{P,\,S}$, $c_{F,\,S}$ – the price of the product and fuel flow for the separator; Z_S – the cost of capital investment for the separator.

Let's determine the exergy price of the product $(c_{P2})_{tot}$ and the fuel $(c_{F2})_{tot}$ for the proposed scheme overall:

$$(c_{P2})_{tot} = \\ = \frac{(E_2\cdot c_2 - E_1\cdot c_1) + (E_{2w}\cdot c_{2w} - E_{1w}\cdot c_{1w}) + \left(E_4''\cdot c_4'' - E_{1s}\cdot c_{1s}\right),}{E_{P1}}, \quad (19)$$

where c_1 – the price of water flow at the inlet to the steam generator; c_2 – the price of steam flow at the outlet of the steam generator; c_{1w} – the price of water flow at the inlet to the heat recovery device; c_2w – the price of water flow at the outlet of the heat recovery device; c_{1s} – the price of the combustion product flow at the inlet to the LVJA; c_4'' – the price of steam flow at the separator outlet:

$$(c_{F2})_{tot} = \frac{\dot{Q}_{SG}\cdot c_{SG} - E_{4g}\cdot c_{4g} + p_{E_F}\cdot N_F + p_{E_{CP}}\cdot N_{CP}}{E_{F1}}, \quad (20)$$

where c_{SG} – the price of the fuel flow at the steam generator inlet; c_{4g} – the price of the flow of combustion products at the chimney outlet; p_{E_F} – the price of electricity to power the fan; $p_{E_{CP}}$ – the price of electricity to power the circulation pump.

Table 3 shows the results of the thermoeconomic analysis.

Table 3 – Results of thermoeconomic analysis

Parameter name	Scheme option	
	basic	with LVJA
Total cost of fuel, USD	23 532.43	12 171.71
Specific cost per unit of product, USD per ton	67.75	35.06
Economic effect, USD	–	11 360.72

The LVJA application increases steam generation by 18 %, which brings the number to 1400 kg/h. The economic effect of implementing additional heat recovery is 11 360.72 USD. The specific cost of steam gets lower by 48 %.

5 Discussion

After analyzing the results of the calculations and the results of thermodynamic, exergy, and thermoeconomic analysis, several advantages of implementing a liquid-vapor jet apparatus for additional heat recovery in boiler plants can be identified. Firstly, it reduces the amount of combustion product emissions into the atmosphere, which positively affects the environment and helps lower the greenhouse effect in the atmosphere. Secondly, the combustion products are integrated into the unit cycle based on the LVJA, which has a functional application. The LVJA generates steam that is released from the separator. This steam is practical for electricity generation. Thirdly, the LVJA-based unit, despite having extra devices (heat exchanger-heater, circulation pump, and separator), which requires additional investment, has a short payback period due to its efficiency. It is about 4–6 months, in other words, one heating season. All these factors make it possible to speak about the prospects of applying LVJA in this scheme.

The thermodynamic analysis shows that the efficiency of the proposed scheme increases, and the value of the energy potential can be seen (Table 1). Thus, by rationally utilizing a part of the combustion products, which is 44 %, in the unit cycle based on LVJA, it is possible to obtain an additional 18 % of the working steam. The latter is suitable for electricity generation. In general, it helps increase the energy potential of the entire boiler plant by 8 %.

As a result of the exergy analysis, indicators of exergy efficiency were obtained. As a result of the thermoeconomic analysis, indicators of reducing the specific cost of heat produced by the boiler plant and the economic effect of introducing additional heat recovery were obtained. Tables 2 and 3 show that the exergy efficiency of the proposed scheme is 1.47 times higher than that of the basic one. It can be seen that this is due to the same extra heat recovery and generation of an additional part of steam. Even the supplementary equipment that is part of the LVJA-based unit does not reduce the overall value of the exergy efficiency since additional energy sources do not power it. The active flow is heated in the heat exchanger-heater by combustion products from the steam generator, and a part of the combustion products taken from the discharge pipeline is used as a passive flow. The only exception is the circulation pump, but Table 1 shows that its capacity is only 38 W, which is no more than 1 % of the entire system's power.

The relevancy of the study is because it can be used in the latest methods for assessing the efficiency of thermomechanical systems proposed by Professor Tsatsaronis, namely exergy and thermoeconomic analyses [21–25]. These methods are essential for analyzing systems in which several types of the energy are converted simultaneously. The overall use of these methods makes it possible to obtain both energy and financial efficiency indicators for the existing and proposed schemes, with the efficiency of each system's component determined. It will make it easier to choose the right areas of energy saving, and it can be known which component will have the lowest efficiency.

The scientific novelty of this article can be considered as the fact that the authors used a fundamentally new approach to analyze the effectiveness of existing thermomechanical systems, a combination of thermodynamic calculations and an economic component. This is called thermoeconomic analysis. This approach allows for finding the elements of the system with the lowest efficiency and directs all the energy-saving measures to them. When modernizing existing boiler plants, thermoeconomic analysis provides a clear understanding of the correctness of the chosen path because its results can determine not only the cost of the plant but also the cost of a unit of products that will be produced by it.

Simultaneously, specific limitations exist in implementing the liquid-vapor jet apparatus described by the authors in the works [17]. That is because of their working process and the limited degree of pressure increase of the passive flow at the level of 8-10. This pressure drop is critical for maintaining the efficiency of the mixing process in the LVJA.

The formulated assumptions and simplifications that lead to the choice of methodology for the conducted analysis can be considered a drawback of the research, which leads to a decrease in the accuracy of the obtained results. Simultaneously, reducing the number of simplifications does not contribute to a noticeable improvement in the results. The accuracy of the analysis is 2.5–3.5 % and is sufficient for engineering calculations.

The potential of this research lies in the absence of consideration of the price of electricity produced from additionally generated steam. All of this will additionally increase the efficiency of the boiler plant because part of the electricity can be practical for the functioning of the plant itself. For example, to power a fan and circulation pump.

Further development of this research can occur when experimental studies of the liquid-vapor jet apparatus are carried out on the proposed parameters, and its effectiveness is confirmed in the given range of operating parameters. For this, it is necessary to conduct additional numerical calculations of its thermodynamic and geometric parameters and model the work process using CFD and CFX software.

6 Conclusions

Based on thermodynamic calculation, the efficiencies of a liquid-vapor jet apparatus for additional heat recovery and working steam generation in boiler plants were determined. Its use makes it possible to increase the energy potential of the proposed scheme by 46.74 kW, which is 8 %. This additional value has the potential to be used to generate electricity. The calculations show that the share of combustion products discharged through the chimney decreases by 44 % due to the implementation of additional heat recovery. The boiler plant uses it to generate steam, and its part is 18 % of the total.

The exergy analysis determined the exergy efficiency of the existing and proposed schemes with LVJA and its feasibility for additional heat recovery in boiler plants. The exergy analysis shows that the efficiency of the boiler plant with additional heat recovery based on the liquid-vapor jet apparatus is 1.47 times higher than the basic one. This change is due to a decrease in the share of combustion products discharged through the chimney and additional steam generation in the LVJA.

3. Based on the thermoeconomic analysis, the specific cost of a unit of heat generated in the existing and proposed schemes was determined, as well as the fuel cost required for the steam generator and the economic effect of the new scheme implementation. The LVJA application increases steam generation by 18 %, which brings the number to 1400 kg/h. The economic effect of implementing additional heat recovery is 11 360.72 USD. The specific cost of steam gets lower by 48 %.

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