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Methodology for assessing the heat potential recovery regime at food industry enterprises

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Abstract. Areas of improving energy saving and the environmental situation in the processing and food industry in Ukraine are relevant, as technologies and equipment by their nature and degree for efficient use of fuel resources are practically achievable for their improvement, especially today. The purpose of the study is to improve the methodology for the optimisation of the mode of reuse of the thermal potential of exhaust process gases in the implementation of a two-stage cooling process. The indicators of process gas emissions with a volume consumption of $0.54 \text{ m}^3/\text{s}$ and temperature – 1600°C with the parameters of the furnace operation A2-SHBG were used to construct local temperature characteristics. Their construction is carried out based on the heat balance and heat transfer at short surface intervals, considering the parameters of coolant flows. The results were analysed by the Flow Vision software suite under the structure of the graph, according to the laws of thermodynamics. A method for calculating the amount of cold heat agent for reuse in the technological process is proposed. It is established that under the accepted heat exchange conditions, the required amount of atmospheric air with an initial temperature of -300°C can be heated to a temperature of $+640^\circ\text{C}$, and with an initial temperature of $+300^\circ\text{C}$, can be heated to $+1450^\circ\text{C}$. Natural gas consumption will change from $20 \text{ m}^3/\text{h}$, without preheating atmospheric air, up to $12.7 \text{ m}^3/\text{h}$ when heating atmospheric air in the heat exchanger at an initial temperature of $+300^\circ\text{C}$. It is stipulated that when calculating energy resource savings, it is necessary to consider the initial temperature of the cold heat agent when using the heat of exhaust process gases. The proposed method for calculating the optimal heat recovery mode allows calculating changes in the consumption of the primary fuel and energy resource and creating a database for the effective implementation of energy-saving technologies when reusing waste gas heat into production.

Keywords: energy saving; heat exchanger; heat pump; primary fuel and energy resource; food industry

Introduction

Given the current situation caused by Russia's full-scale invasion of Ukraine, the international community is making great efforts to develop a technological and technical solution to reduce energy consumption. The solution of rational use of energy resources can be solved by the energy-saving policy of the state and the modernisation and creation of efficient equipment.

According to the energy strategy of Ukraine until 2035 (Order of the Cabinet Ministers of Ukraine No. 605, 2017) "Safety, energy efficiency, competitiveness", the priority of energy saving is to reduce the energy intensity of production and consumption of fuel and energy resources. This can be facilitated by an event to

introduce the latest energy-efficient and energy-saving technological equipment.

Waste heat from industrial ovens in the food industry is the energy generated during the baking process. It is practically not used, but is consumed and released into the environment. Maximum positive results in this area can be achieved only by introducing comprehensive and effective energy-saving measures into industrial and household activities. Special attention should be paid to intensive energy saving in heat technology, which has popularity in developed countries (Pili *et al.*, 2020). C. Wieland, *et al.* (2023) evaluated in more detail Central and Eastern Europe as the regions with the

highest energy growth potential and small heat recovery plants. It is noted that these regions will be the most relevant sources of heat recovery in the coming years.

Ukraine has not yet received such a general spread due to the lack of interest from some enterprises, state incentives, and lack of a standard for certification of heat exchangers of the research system for the conditions of Ukraine.

Since about 2/3 of organic fuel is spent on all the variety of heat-technological processes, and the integral useful factor of primary fuel and energy resources in heat-technological complexes, based on the final result of using primary raw materials of material production, does not exceed 10-15%, the areas of energy saving and environmental improvement are relevant (Kim, 2019).

Among the effective energy-saving measures, special attention should be paid to the heat recovery of exhaust process gases, which provides for their cooling and reuse of accumulated heat. The level of recovery is estimated by the recovery coefficient. Its value indicates the level of heat utilisation of the exhaust process gas. The higher the recovery coefficient, the lower the specific costs of primary fuel and energy resources. There are various schemes for restoring latent heat in flue gases. To reduce these problems, various approaches are being developed to summarise experimental data in the construction of efficient use of energy resources. Research and analysis of energy for waste heat recovery in the manufacturing sector were reviewed by Abrar Inayat (2023). The researcher provided information on the potential of using waste heat in the metallurgical sector with further application. He also noted that in the development, design and analysis of the efficiency of surface heat exchangers, models and a technique that has a simplified empirical relationship in determining the integral

characteristic are used. J.F. Wang, *et al.* (2020) considered traditional ways in the technical representation of heat exchange processes are logically supplemented by heat recovery options in drying units of the food industry. They noted the influence of the correct calculation of average temperatures of heat carriers when estimating the thermophysical properties and material of the pipe wall and on the parameters of heat transfer and heat transfer coefficients during cooling or heating in a heat exchanger.

Phenomenological analysis of energy integration and strategies for applying technologies for using energy potentials in heat resource redistribution systems and prospects for using secondary energy resources in the food industry creates conditions for a global review of the use of heat exchangers.

Thus, the purpose of the study is to further search for and develop analytical dependencies and methods for estimating the calculation of thermal potential based on the main provisions of the theory of thermodynamics and heat and mass transfer. The created dependencies and methods should adequately reflect the processes in the developed heat exchanger design, considering the design and technological thermal and hydraulic parameters, operating mode and conditions. Thus, parameters for regulating the main characteristics of the heat exchanger appear in the general balance of all thermophysical variable modes of heat reuse of exhaust process gases. Solving the search and development of analytical dependence and methodology will help reduce losses of fuel, energy, and material resources. This will definitely reduce the negative impact on the environment and improve the quality of energy sources supplied to consumers.

Literature Review

There are a large number of literature sources devoted to energy conservation and reduction

of the negative impact of energy-intensive industries on the environment. H. Jouhara *et al.*, (2020) conducted a comprehensive review of waste heat utilisation methodologies and state-of-the-art technologies used in industrial processes. They considered the possibility of heat recovery to optimise energy in the metallurgical, food, and ceramic industries. From the review of sources, it can be stated that the vast majority of them relate to energy generating, metallurgical, chemical, construction, and other branches of the economy. All these enterprises are characterised by technologies that take place at high temperatures, high productivity, and energy intensity. Energy-saving measures in such industries allow getting a significant economic effect and achieving a quick return on invested funds. In European countries and the United States, the use of heat exchangers is consolidated by the ANSI/AHRI standards (Standard 1060-2005 (2005) and ASHRAE (Standard 62.2-2003). It considers the basic principles of building heat recovery systems, energy indicators of operation, and the efficiency of heat exchangers in general. Moreover, the indicator of the efficiency of total heat should be at least 50%.

M. Kum Ja *et al.*, (2022) investigated a flat plate module with a diagonal channel and a countercurrent heat exchanger configuration. In such a heat exchanger, the ratio of “fresh” air to “exhaust” had the least positive effect (8-10%) on overall efficiency. The authors propose the design of a heat exchanger (Bulejko *et al.*, 2022) and the stability of polyamide hollow fibres in the heat exchanger, which were tested at various temperatures in the range from -40 to 160°C was analysed. The results showed differences in theoretical models with experimental data, which fluctuated significantly. The results indicated the practical use of such heat exchangers in the automotive industry. Jafarizave (2019)

and H. Jouhara *et al.* (2021) reduced gas heating costs by properly stabilising the temperature of the gas process flow by means of automation. A study was also conducted to regulate temperature changes at the outlet of the pressure-reducing valve. This allowed effectively using the heat in the heater. Gendebien *et al.* (2018) note that the maximum heat flow of a hypothetical heat exchanger is possible with an extremely large heat transfer surface. This result, in practice, can be achieved by using a surface made of materials with high heat transfer coefficients.

Despite the absolute expediency, energy-saving measures do not find proper attention in the processing and food industries (Tchuen *et al.*, 2021). Among the reasons for the appearance of this situation, researchers I. Stadnyk *et al.*, (2021) note that the analysis in the conditions and modes of operation of the device and the method of heat recovery are insufficient. From the materials of the Duda and Balaban conference (2021), it is known that a temperature drop of 1 m³ process gas emissions by 10°C allows saving 10 KJ of heat energy. With a calorific value of 1 m³ of 33.5 MJ and 1 m³/s of exhaust process gas cooled by 10°C, 1.4 m³/h of natural gas can be saved. In this case, the amount of savings in primary fuel and energy resources depends on the cooling of the exhaust process gases.

General issues of design and operation in justifying the use of heat recovery schemes for process gas emissions at an enterprise are considered by Stadnyk *et al.* (2022). This study is mainly focused on the optimal selection and functioning of the recovery system, issues of heat utilisation of exhaust process gases, and the exhaust heated medium is described quite superficially. No less attention is paid to the introduction of energy-saving technologies in the food industry (Yevtushenko, 2019). The author described in more detail and considered the disposal system with an intermediate heat

carrier. Formulas for calculating the efficiency of heat exchangers are also presented.

Waste heat can be used using various recycling technologies to provide valuable energy sources and reduce overall energy consumption (Bulejko, 2022). Today, thermal pumps are used for high-quality deep cooling of process gas emissions. Thus, the study (Stadnyk et al., 2021) shows the use of a heat-upgraded pump in brewing. They considered cooling of exhaust process gases to lower temperatures from the dew point temperatures in the heat pump condenser. In this case, water vapour condenses, which helps to obtain additional energy for heating cold thermal agents and reducing the release of water vapour into the atmosphere, which is a greenhouse gas. Researchers of the Institute of Thermophysics of the Academy of Sciences of Ukraine and the National Technical University of Ukraine “Kyiv Polytechnic Institute” publish information on the successful use of heat pumps during the drying of grain and other products of the processing and food industry, which are subjected to heat and mass transfer processes at low temperatures. General requirements in the design and operation of production lines with installed heat pumps show that an increase in the temperature of heat agents accompanies an increase in the cost of their organisational work. After all, heat pumps must be used if they do not exceed 40°C temperature of the hot heat agent.

Exhaust process gases with a temperature above 40°C are cooled in a heat exchanger before being cooled in the heat pump. These considerations relate to the intended ways and intentions of the approach to improving and improving the characteristics of individual processes. The above methods of energy saving in local areas of power equipment, i.e., confectionery ovens, are not enough. Therefore, calculations and economic indicators in the to-

tal result should be considered in two planes. Having separate possibilities for minimising heat costs in local areas of the furnace, it is advisable to formulate requirements for the parameters of the total heat agent, which should be considered by a specific methodological approach. The issue of calculating the parameters of a cold heat agent remains particularly insufficiently studied under conditions when the constant amount of hot heat agent is cooled to a constant temperature, and the initial temperature of the cold heat agent changes.

Materials and Methods

Materials. The calculation of optimal recovery modes is based on the use of heat readings of exhaust process gases formed during the operation of the A2SHBG-type working furnace. The primary fuel is natural gas. Its calorific value is 33.5 MJ/m³ and the highest temperature of the process gas in the furnace is 280°C. Gas outlet parameter of exhaust systems: volume flow – 0.54 m³/C; temperature – 160°C.

Features of the study. The use of the seasonal energy potential of a confectionery oven for the reuse of reclaimed heat is considered. The proposed scheme for implementing such heat exchange is shown in Figure 1. The scheme includes the main components of the main and auxiliary equipment for the normal operation of the power confectionery oven.

Given the complexity of performing calculations in the proposed scheme (Fig. 1) operating power equipment, the model method for their implementation according to optimal heat recovery modes, provides for two stages. The first stage involves the installation of an air-to-air heat exchanger 3, and the second stage involves the use of a heat pump 4. During the period of heat exchange, the exhaust process gases have the function of hot thermal agents. Accordingly, ϕ ir performs the function of cold thermal agents.

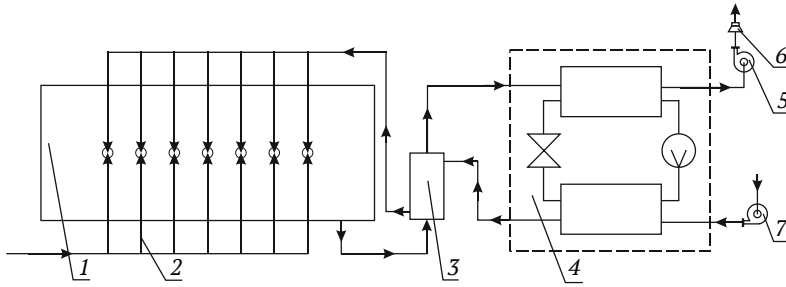


Figure 1. Diagram of two-stage cooling of exhaust process gases of power generating equipment
Notes: 1 – housing of power generating equipment; 2 – supply system of primary fuel and energy resources; 3 – heat exchanger; 4 – heat pump; 5 – exhaust fan; 6 – exhaust gas exhaust system; 7 – fan of heated atmospheric air supply

Source: 1 – developed by the author

Research methodology. The object of study is a confectionery shop with an installed ventilation system. The ventilation system is used to utilise explicit and latent heat. The supply and exhaust ducts have air flow rates in the range of 70-150 m³/h, depending on the operating

modes of the fans. The ventilation system under study consists of air ducts, filters, anemostats, louver grilles, gates and sleeves for measuring air parameters. Heat exchange scheme (Fig. 2) and the design of the heat exchanger (Fig. 3) provides for its operation in offline mode.

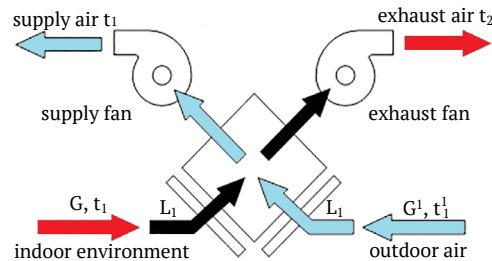


Figure 2. Diagram of heat exchanger in the installation

Source: developed by the author

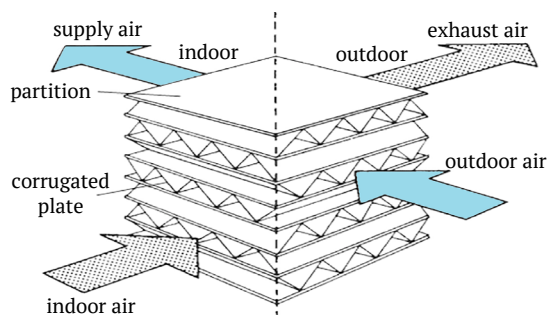


Figure 3. Heat exchanger design

Source: developed by the author

In a heat exchanger with partitions and corrugated plates (Fig. 3), a thin polymer film with low thermal resistance is used. This heat exchanger allows you to utilise heat and hidden water vapour contained in the exhaust air. The heat exchanger channels are separated by a corrugated plate. The two streams of medium and air are not mixed.

The proposed model method for calculating heat recovery involves the use of a plate heat exchanger with countercurrent movement of thermal agents. This heat exchanger design allows organising heat exchange in two modes. The first mode provides heating of a constant amount of cold heat agent to a constant temperature. In this case, if the initial temperature of the cold heat agent changes, the temperature of the hot heat agent will change.

The second mode provides cooling of hot thermal agents to a constant temperature with the appropriate amount. In this case, the final temperature of the cold heat agent will change. Stability in the operation of the heat pump requires ensuring the supply of hot heat agent at constant temperatures. Because of this, it is advisable to carry out heat exchange in the heat exchanger according to the second mode.

The proposed model method for calculating optimal heat recovery modes provides for the passage of the heat exchange process in the heat exchanger under conditions of constant and variable values of the initial and final temperatures of the hot heat agent. Their value depends on the time of year and the initial and final temperatures of the cold heat agent.

Preheating of the cold heat agent enters the combustion zone of primary fuel and energy resources. During fuel combustion, the resulting process gases provide technological conditions for the temperature and aerodynamic regime.

A change in the temperature of a cold heat agent affects the variable consumption of the

initial fuel and energy resource. At the stage of research on the consumption of this resource, the economic efficiency of reusing the heat of exhaust process gases is evaluated. Therefore, it is necessary to have data on the effect of the final temperature of the cold heat agent on its consumption.

Measuring devices. According to the diagram (Fig. 1), the following devices were used:

- exhaust and supply air anemostats;
- measurement of temperature and relative humidity, with the testo 605 device;
- temperature and relative humidity measurement using DS 1923-F5;
- air velocity measurement (testo 405).

Substantiation of the model methodology. The main task of the proposed model methodology for calculating heat on power-generating equipment is to develop the procedure for preliminary calculation. It is based on changes in the consumption of the initial value of the fuel and energy resource when the final temperature of the cold heat agent changes. Therefore, the solution of this problem requires knowing the data of the maximum temperature to which a cold thermal agent can be heated under known conditions. This order of research was followed by the authors (Kouemou Hatou *et al.*, 2021), (Kim, 2019) when developing a mathematical model for use as a tool in designing and predicting efficiency, under various load conditions of input parameters. Known methods for calculating heat exchange processes (Chakravarty & Kumar, 2020) do not solve this problem. Therefore, the volume consumption of a cold heat agent at different values of the initial and final temperatures allows establishing the dependence for the heat exchanger and the parameters of the technological process. Using the resulting dependency $L_x = f(T_x)$ sets the parameters of the heating temperatures of the cold heat agent at a known initial temperature.

Clearly, the dependence also determines the change in the primary fuel and energy resource relative to the consumption of a cold heat agent and its final temperature.

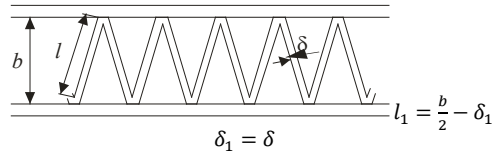
Studies have determined the influence of the initial temperatures of thermal agents (cold) on the final temperature at various costs. Therefore, the limit of change in the initial temperatures of thermal agents $-30^{\circ}\text{C} \leq T_x \leq +30^{\circ}\text{C}$ sets the dependences of the final temperatures of the cold heat agent $T_{x_2} = f(T_{x_1})$ with straightforward character. The process can be described by an expression using numerical coefficients: $T_{x_2} = AT_{x_1} + B$.

The obtained dependence allows performing an updated calculation of the consumption of the primary fuel and energy resource and the optimal mode of heat recovery of exhaust process gases.

Temperature distribution of heat carriers during cross-flow. To increase the heat exchange area, a plate heat exchanger with a triangular fin is used. Its calculation of the

heat exchange process in a cross-plate heat exchanger is based on the work of Hausen (2012). The edge efficiency equation is defined by the

expression: $N = \sqrt{\frac{2\alpha}{\lambda\delta_1}} l_1, \eta_f = \frac{th(N)}{N}$, where



In the case of cross-current, the temperature distribution of heat carriers is calculated by dividing the heat exchanger plate by $n \times n$ individual elements. The heat balance is calculated for each one. In Figure 4, the point of the plate is characterised by coordinates x and x' . Value L and L' reflect the length of the wall. Moreover: G, G' – mass consumption of the first and second heat carriers; mass consumption of two heat carriers; t_1, t_2 – temperature of the first coolant at the inlet and outlet; t_1', t_2' – temperature of the second coolant at the inlet and outlet

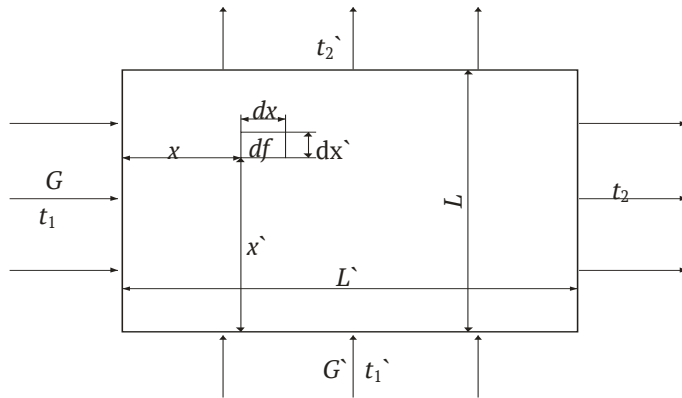


Figure 4. Cross-flow heat exchange of a flat plate: G, G' – mass consumption of two heat carriers; t_1, t_2 – temperature of the first coolant at the inlet and outlet; t_1', t_2' – temperature of the second coolant at the inlet and outlet

Surface element $df = dx \cdot dx'$ at the point (x, x') transfers heat per unit of time (dq):

$$dq = k dx dx' (t - t'). \quad (1)$$

A unit of time near the surface of the first heat carrier df equals $\frac{G dx}{L}$. The change in cooling is $\frac{\partial t}{\partial x} dx$. Amount of second heat carrier $\frac{G' dx'}{L}$

heats up on $\frac{\partial t}{\partial x}$. Accordingly c_p, c_p' – heat capacity of both heat carriers. Determination of the heat flow through the element df is carried out by the expression: $dq = -c_p G \frac{dx}{L} \frac{\partial t}{\partial x} dx$,

$$dq = c_p G \frac{dx}{L} \frac{\partial t}{\partial x} dx \tag{2}$$

These solutions of system (1-2) determine the temperature of both heat carriers at the outlet and their distribution along the coordinates x and x' . The exact solution of diffraction

patterns can be obtained by the finite difference method. To do this, set the coordinate function x : linear ($T_{wall, x} = a_0 + a_1 x$) or polynomial ($T_{wall, x} = a_0 + a_1 x + a_2 x^2 + a_3 x^3$).

Figure 5 shows a local heat flow with a uniform velocity profile at the inlet, according to numerical coefficients: $a_0 = 276,71$; $a_1 = 313,4$; $a_2 = -2334,6$; $a_3 = 6395,5$.

These coefficients correspond to the temperature of the cold air channel of the heat exchanger, according to the study (Helmuth, 2018).

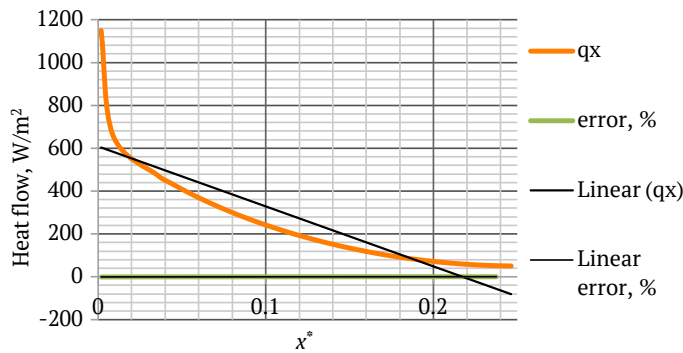


Figure 5. Local temperature change in the heat flow of the wall with the definition of errors

Local heat flow error within the tolerance range of $\pm 2\%$. Figure 6a shows a simulation of the temperature distribution of both heat carriers over the heat exchange surface with an

airflow rate of $150 \text{ m}^3/\text{h}$, and Figure 6b shows temperature change along the length of the plate in increments of 0.045 m in its average cross-section.

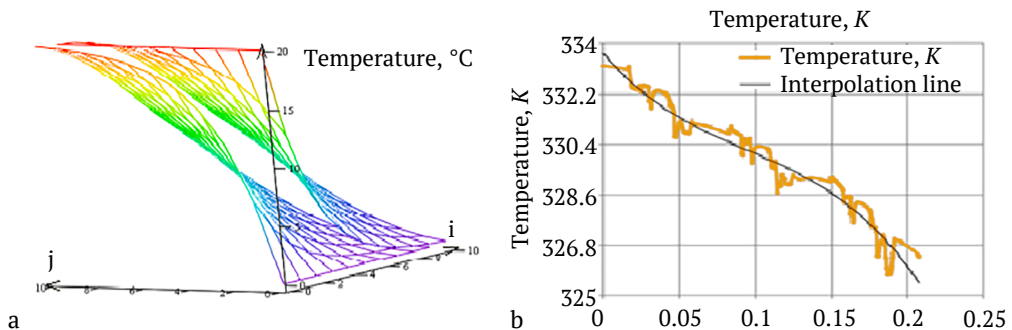


Figure 6. Graphs: a – surface temperature distribution of the coolant: (i, j) – elements; \rightarrow – exhaust air (hot coolant); \rightarrow – supply air; b – temperature change along the length of the plate in increments of 0.045 m

Comparative analysis of mathematical modelling of graphical curves (Fig. 6 a, b) reveals the essence of the characteristics of temperature fields in a heat exchanger with cross current along the length of the sides of the heat exchanger L .

Results and Discussion

The analysis shows that energy indicators should not be the only criterion that should be considered at the design stage of the heat exchanger. Prior to this, in many previous studies, theoretical correlations or optimisation techniques were commonly used to develop the overall process. Technical, economic, and environmental aspects should also be considered. After all, any development of a heat exchanger is practically impossible without an experiment.

During the study, the speed of heat carrier flows, temperature changes along triangular fins, and the average temperature of the heat exchange surface at the inlet and outlet of the heat exchanger. Moreover, verification of theoretical calculations using criterion equations allowed generalising the results obtained. Graphical curves (Fig. 6 a, b) reveal the essence of temperature fields along the length of the sides of the heat exchanger L . Thus, the curves (Fig. 6 a, b) show that the calculated heat transfer area of a heat exchanger with side lengths equal to L and L' is within the specified average efficiency value. In turn, the input temperature of the exhaust gases and cold coolant in the middle plate is $t_1 = 64^\circ\text{C}$ and $t_2 = 31^\circ\text{C}$. Temperature difference between the initial and final temperature of heat carriers: $\Delta t = 33^\circ\text{C}$.

Thus, in cross-current, the temperature distribution of heat carriers in the heat exchanger has a certain distribution of data on temperature, heat flow, and surface heat transfer efficiency.

Analysis of energy efficiency optimisation of the use of regenerative and regenerative

burners at the expense of heat exchanger surfaces for capturing and using waste heat in the combustion process (BDF Industries 2017), allowed providing for heat transfer to the incoming air to the burner in the furnace under study. A scheme for using a heat exchanger when selecting a hot medium for heating a colder one for the burner has been developed. Based on this, a methodology is proposed to determine the best trade-off between reclaimed heat and energy for a particular geometry. This considers a certain temperature difference in the room/outside. All these analyses were aimed at designing the heat exchanger configuration using an optimisation algorithm. Under such conditions, improving the efficiency of the heat exchanger in using the energy potential, recovery was carried out according to the proposed scheme in Figure 1. As noted, the study of the recovery system was carried out in two stages using air, the temperature of which varies from -30°C to $+30^\circ\text{C}$. The calculation of the heat exchanger, considering the cooling of the exhaust process gas in the heat pump condenser, allowed choosing a plate heat exchanger with a heat exchange area of 16.7 m^2 . The temperature of the exhaust process gas at the outlet of the heat exchanger established by the study was up to $+40^\circ\text{C}$, which made it possible to calculate the heat balance.

The calculation of the heat balance established that maintaining the thermal regime of the furnace must burn 20 m^3 of natural gas per hour or $5.47 \cdot 10^{-3} \text{ m}^3/\text{s}$. At the same time, to ensure temperature and aerodynamic conditions, the furnace receives air from the production room in the amount of $0.53 \text{ m}^3/\text{s}$ at a temperature of $+20^\circ\text{C}$. The temperature of atmospheric air changes both throughout the year and during the day. Based on the considered conditions and results of heat exchange and temperature changes (Fig. 4, 5) preheated atmospheric air,

will lead to a change in the flow rate of natural gas. To visually display changes in the volume flow rate of natural gas and the economic effect of the supply of preheated atmospheric air at different values of the final temperature, it is shown in Figure 7.

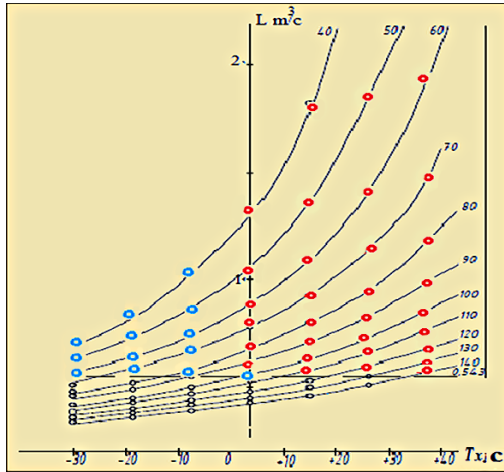


Figure 7. Dependence of the effect of the initial temperature at different values of the final temperature on the volume flow rate of a cold heat agent: 1 – $T_{X_2} = 40^\circ\text{C}$; 2 – $T_{X_2} = 50^\circ\text{C}$; 3 – $T_{X_2} = 60^\circ\text{C}$; 4 – $T_{X_2} = 70^\circ\text{C}$; 5 – $T_{X_2} = 80^\circ\text{C}$; 6 – $T_{X_2} = 90^\circ\text{C}$; 7 – $T_{X_2} = 100^\circ\text{C}$; 8 – $T_{X_2} = 110^\circ\text{C}$; 9 – $T_{X_2} = 120^\circ\text{C}$; 10 – $T_{X_2} = 130^\circ\text{C}$; 11 – $T_{X_2} = 140^\circ\text{C}$

The resulting dependence (Figure 7) indicates that under the accepted heat exchange conditions, the required amount of atmospheric air with an initial temperature of -30°C can be heated to a temperature of $+64^\circ\text{C}$, and with an initial temperature of $+30^\circ\text{C}$, can be heated to $+145^\circ\text{C}$. Accordingly, the consumption of natural gas will vary from $20 \text{ m}^3/\text{h}$, without preheating atmospheric air, up to $12.7 \text{ m}^3/\text{h}$ when preheating atmospheric air in the heat exchanger at its initial temperature of $+30^\circ\text{C}$.

The design and technological operating conditions of the furnace under study require compliance with a stable aerodynamic regime. In this case, a decrease in the supply of natural

gas leads to an increase in the supply of atmospheric air. Within the studied temperatures, this change is $5.1 \cdot 10^{-3} \text{ m}^3/\text{s} - 3.5 \cdot 10^{-3} \text{ m}^3/\text{s}$. The influence of the initial temperature of atmospheric air on its final temperature for various flows is determined. The results of the assessment of the dependence of the final temperature of a cold heat agent on its initial temperature are shown in Figure 8.

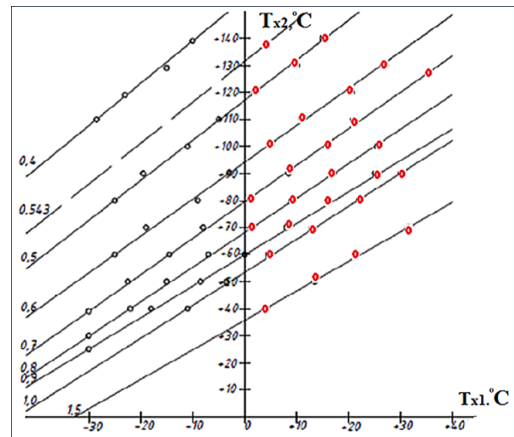


Figure 8. Dependence of the effect of the initial temperature at different values of the volume flow rate on the final temperature of the cold heat agent: 1 – $L_x = 0.4 \text{ m}^3/\text{s}$; 2 – $L_x = 0.5 \text{ m}^3/\text{s}$; 3 – $L_x = 0.6 \text{ m}^3/\text{s}$; 4 – $L_x = 0.7 \text{ m}^3/\text{s}$; 5 – $L_x = 0.8 \text{ m}^3/\text{s}$; 6 – $L_x = 0.9 \text{ m}^3/\text{s}$; 7 – $L_x = 1.0 \text{ m}^3/\text{s}$; 8 – $L_x = 1.5 \text{ m}^3/\text{s}$.

The obtained calculation results indicate that within the studied initial temperatures of the cold heat agent T_{X_1} influence of changes in its consumption L_x at the final temperature T_{X_2} can be neglected.

Despite a wide range of research on the problem, the issues of energy saving and the use of secondary resources in the food industry remain relevant and require further development. Therefore, like the researchers (Kamarul Aizat Abdul Khalid 2016), the authors focused on the development of a heat exchanger for a

ventilation unit with heat recovery using numerical approaches. Consideration of a mathematical model (Shuichiro Miwa *et al.*, 2022) of heat and mass transfer to determine the effect of internal airflow leakage on the efficiency of the heat exchanger allowed the proposed heat exchanger to be studied at low ambient air temperatures. Changing the internal design by installing turbulators in the internal section in a compact air-to-air heat exchanger (Ahmad *et al.*, 2022), resulted in an improvement in ΔT at the pipe outlet. However, it has been proven (Javanjal *et al.*, 2019), that plate heat exchangers with gaskets provide efficient and efficient heat transfer with a recovery rate of up to 90%. Consideration of the characteristics of the internal air flow inside the heat exchanger made it possible to envisage the design of a plate heat exchanger with the countercurrent movement of heat transfer agents.

The main indicator of creating any ventilation system is based on the norms of air consumption from the medium and air exchange multiplicity, and the criterion for evaluating the effect of recovery methods is its level, according to the authors (Galish *et al.*, 2021). This hypothesis allowed proposing and conducting a model method for calculating optimal thermal recovery modes.

Reducing fuel consumption emissions is the main topic in the implementation of complex technological and design parameters, the interaction of which must ensure proper and reliable operation of the control of such a system (Zamboni *et al.*, 2021). Studies of the emission of gases from the furnace and studies by G. Zamboni *et al.* (2021) were aimed at developing integrated management strategies for gas recovery and fuel consumption systems, analysing their mutual impact on the expansion of working conditions. The presented and discussed characteristics of systems in a

wide range of operating modes show how this affects the performance and emissions of thermal agents with their subsequent use. The interaction of parameters confirms the potential for a significant reduction and improvement in fuel consumption if the recovery control scheme is followed.

Review of the studies noted the effect of complex apparatuses that depend on shutdown schemes, the number of sections, and rows of pipes in one section and their arrangement by moves, the degree of mixing of each coolant (Manente *et al.*, 2021). This opens up another way to improve the efficiency of surface recombination, considering the distribution of local thermohydraulic parameters. Based on this consideration of the problem, it is reflected in the local temperature distribution of heat carriers when determining the thermal state of the surface of the developed heat exchanger, considering the operating modes of the confectionery oven. The researchers (Manuel Jiménez-Arreola, *et al.* 2023) also confirmed the achievement of final under-recovery. So the local advantage of the heat reserve of the heating flow is in the warmer part of the heat exchanger, the cooling heat reserve is in the colder part. This conclusion of their study is also shown in this paper.

G. Tchien *et al.*, (2021) raised the issue of energy savings with an analysis of the possible use of heat from the exhaust ventilation flow of gas for the needs of hot water supply. Their research reveals the efficiency of using a heat pump in the recovery of a low-potential heat source. In comparison with this study, at the second stage, the use of a heat pump allows the exhaust process gases to perform the function of hot thermal agents for heating the air. Consideration in choosing a refrigerating agent for heat pumps also deserves attention. In addition, the researchers (Jiménez-Arreola *et al.*, 2019) noted, that the dynamic behaviour of heat exchangers

when recuperation of industrial thermal waste in the system approach is assessed at the level of limiting negative impacts on the environment.

The analysis of the heat consumption of the exhaust gases of the drying and cooling zone of the mine grain dryer using various heat recovery schemes based on the wet content of gases allowed the author (Gaponyuk, 2017) to theoretically substantiate the possible and economic feasibility of using the exhaust operating heat of the gas. He proposed a method for heating stationary grain layers with exhaust gases and substantiated heat exchange by semi-empirical equations. These equations involve the use of different values of moisture gradients and temperature differences in determining the heat balance, but without determining the heat flow through the element of a stationary grain layer. The approach proposed in this study allows simplifying the use of semi-empirical equations and improving the heat recovery scheme of the cooling zone of a mine grain dryer using a plate heat exchanger. Ultimately, supply and exhaust systems with plate heat exchangers can reduce the cost of heating the supply air by 60-70% (Tchuen *et al.*, 2021).

Conclusions

Based on observations and studies, a calculation model is proposed under real operating conditions of a confectionery oven. The temperature fluxes of heat carriers obtained from measuring devices and consistent with modelling, as well as those mentioned in other studies, indicate a change in the local heat flow of the variable wall temperature in the heat exchanger from 1,200 to 200 W/m². Improving the efficiency of a surface recuperative heat exchanger with the given design, mode and operating conditions and layout features, under the accepted heat exchange conditions, the consumption of natural gas can be changed from 20 m³/h up

to 12.7 m³/h. In addition, the negative impact on the environment is reduced.

Evaluation of both dependences showed that the mode movement of heat carriers affects the efficient operation of the heat exchanger. Therefore, choosing the optimal mode of movement of heat carriers will ensure maximum heat transfer. The proposed model method for calculating the optimal heat recovery mode allows:

- pre-calculate the variable consumption of the initial fuel and energy resource when reusing the heat of exhaust process gases of power generating equipment;
- the base of the results obtained can be used to calculate the economic efficiency of implementing energy-saving technologies in production;
- when calculating the savings of the primary fuel and energy resource when reusing the heat of exhaust process gases, it is necessary to consider the initial temperature of the cold heat agent
- evaluation of the effect of energy-saving systems and comparison of heat exchangers of different types, it is advisable to use the efficiency indicator of heat exchangers.

This technical solution is conditioned by the ability to control the characteristics of temperature carriers and create high-efficiency heat exchangers. This is provided for by reducing the size of the heat exchange surface, but also does not exclude the possibility of using other areas to improve the efficiency of the heat exchanger.

The use of such heat exchangers or their elements, methods for evaluating the heat potential recovery mode, is relevant due to their simplicity, reliability, and practical safety. This makes allows continuing the promising line of increasing energy and resource savings in the utilisation of heat not only in confectionery furnaces, but also in internal combustion engines (diesel generators, steam boilers).

Special attention should be paid to combining the thermal potential into a single complex of heat recuperators when using compact, high-efficiency, regenerative heat exchangers. This approach allows controlling the characteristics of temperature carriers and creating heat exchangers of increased efficiency while reducing the size of the heat exchange surface.

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Conflict of Interest

None.

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Методика оцінки режиму рекуперації теплового потенціалу на підприємствах харчової галузі

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Анотація. Напрями підвищення енергозбереження та екологічної ситуації у переробній і харчовій промисловості України є актуальними, оскільки технології й обладнання за характером та ступенем для ефективного використання паливних ресурсів практично досяжні для їх удосконалення, особливо сьогодні. Мета дослідження – удосконалення методики оптимізації режиму повторного використання теплового потенціалу відпрацьованих технологічних газів при реалізації двоетапного процесу їх охолодження. Використано показники викидів технологічного газу за розходу об'єму – 0,54 м³/с й температурі – 1600°C із параметрами роботи печі А2-ШБГ у побудові локальних температурних характеристик. Їх побудову проведено на основі теплового балансу й теплопередач при малих інтервалах поверхні з врахуванням параметрів течій теплоносія. Аналіз результатів виконано програмним комплексом Flow Vision при будові графіку, згідно законів термодинаміки. Запропоновано методику розрахунку кількості холодного теплового агенту для повторного використання у технологічному процесі. Встановлено, що за прийнятих умов теплообміну,

необхідну кількість атмосферного повітря з початковою температурою -300°C можна нагріти до температури $+640^{\circ}\text{C}$, а з початковою температурою $+300^{\circ}\text{C}$, можна нагріти до $+1450^{\circ}\text{C}$. Розхід природного газу зміниться від $20 \text{ м}^3/\text{год}$, без попереднього підігріву атмосферного повітря, до $12,7 \text{ м}^3/\text{год}$ за підігріву атмосферного повітря у теплообміннику при початковій температурі $+300^{\circ}\text{C}$. Передбачено, що під час розрахунків економії енергетичного ресурсу, необхідно враховувати початкову температуру холодного теплового агенту при використанні тепла відпрацьованих технологічних газів. Запропонована методика розрахунку оптимального режиму рекуперації тепла дозволяє розрахувати зміни розходу первинного паливно-енергетичного ресурсу, створити базу даних для ефективного впровадження енергозберігаючих технологій при повторному використанні тепла відпрацьованих технологічних газів у виробництво

Ключові слова: енергозбереження; теплообмінник; тепловий насос; первинний паливно-енергетичний ресурс; харчова індустрія