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MODEL FOR CALCULATING THE OPTIMAL MODE OF HEAT RECOVERY AT POWER GENERATING EQUIPMENT OF THE PROCESSING AND FOOD INDUSTRY

Stepan Balaban; Volodymyr Kaspruk

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *The article deals with the influence of heat recovery measures of exhaust process gases on reducing the negative impact of production on the environment and increasing the competitive ability of products. The analysis of heat reuse schemes for periodically operating power generating equipment in the processing and food industry is carried out. A model for calculating the amount of cold heat transfer agent for reuse in the technological process is suggested.*

Key words: *Recuperation, energy-generating equipment, heat exchanger, heat pump, primary fuel-energy. resource.*

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Statement of the problem. According to the Energy Strategy of Ukraine until 2035 ‘Security, Energy Efficiency, Competitiveness’, the priority of energy saving is to reduce energy intensity of production, decrease the consumption of primary fuel and energy resources through the implementation of the latest energy efficiency and energy saving measures.

Maximum positive results in this area can be achieved only through the introduction of comprehensive and effective energy saving measures in industrial and domestic activities. Intensive energy saving in thermal technology deserves special attention, since the entire variety of thermal processes consumes about 2/3 of organic fuel, and the integrated coefficient of useful use of primary fuel and energy resources in thermal technology complexes in terms of the final result of the use of primary raw materials of material production does not exceed 10–15%.

One of the effective energy saving measures, the heat recovery of exhaust process gases, which involves their cooling and reuse of the accumulated heat, deserves special attention. The level of recovery is assessed by the recovery coefficient, which shows the degree of heat utilization of exhaust process gases. The higher the recovery factor, the lower the specific consumption of primary fuel and energy resources.

Analysis of recent research. There is a large number of sources which deal with energy saving and reducing the negative impact of energy-intensive industries on the environment. The vast majority of them relate to the energy generating, metallurgical, chemical, construction and other industries, whose enterprises are characterized by technologies that operate at high temperatures, high productivity and energy intensity. Energy-saving measures in such industries can generate significant economic benefits and achieve a quick return on investment. Despite the undoubted expediency, energy saving measures do not receive due attention at the enterprises of the processing and food industry [1]. Among the reasons for this situation, researchers name insufficient analysis of the conditions and operating modes of equipment and methods of heat recovery.

Corresponding author: Volodymyr Kaspruk; e-mail: Kasprukv@gmail.com

It is known that reducing the temperature of 1 m^3 of exhaust process gases by 10^0C can save 10 kJ of thermal energy [2, 3]. If the calorific value of 1 m^3 is 33.5 mJ and 1 m^3/h of exhaust process gases is cooled by 10^0C, 1.4 m^3/h of natural gas can be saved. In this case, the amount of primary fuel and energy resources savings depends on the depth of cooling of the exhaust process gases.

The maximum cooling depth of the process gases can be achieved with heat pumps. In the condenser of a heat pump, the process gases can be cooled to a temperature below the dew point. In this case, water vapor condenses, which provides additional energy for heating the cold heat transfer agent and reduces emissions of water vapor, which is classified as a greenhouse gas. Researchers from the Institute of Thermal Physics 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 in drying grain and other products of the processing and food industry that are subjected to heat and mass transfer processes at low temperatures [4, 5]. The experience of designing and operating technological lines using heat pumps shows that as the temperature of the hot heat transfer agent increases, the costs of organizing the operation of heat pumps increase dramatically. It is considered that heat pumps should be used in cases where the temperature of hot heat transfer agents does not exceed 40^0C.

Before cooling in the heat pump, the exhaust process gases with a temperature exceeding 40^0C are cooled in a heat exchanger. However, the issue of calculating the parameters of the cold heat transfer agent under conditions when a constant amount of hot heat transfer agent is cooled to a constant temperature and the initial temperature of the cold heat transfer agent changes remains insufficiently studied.

The purpose of this paper is to create a model for calculating the optimal mode of heat reuse of exhaust process gases during the implementation of a two-stage process of their cooling.

Justification of the model. To create a model for calculating the optimal mode of heat recovery on power generating equipment, the choice of ways to reuse the recovered heat is of particular importance. Such a choice affects the peculiarities of heat exchange equipment operation, the parameters of the heat exchange process, and the payback period of heat recovery measures. Thus, the heat obtained as a result of cooling the exhaust process gases of low-capacity power generating equipment with seasonal and periodic operation is advisable to use for heating the air that ensures its operation. The scheme of realization of such heat exchange is shown in Fig. 1.

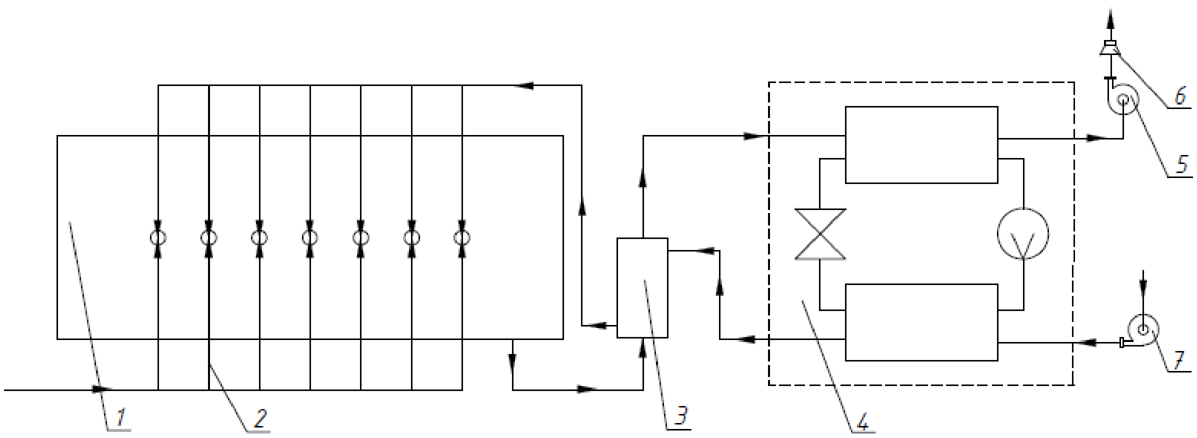

Figure 1. Scheme of two-stage cooling of exhaust process gases of energy-generating equipment: 1 – body of energy-generating equipment; 2 – primary fuel and energy supply system; 3 – heat exchanger; 4 – heat pump; 5 – exhaust fan; 6 – exhaust gas removal system; 7 – fan for supplying heated atmospheric air

Considering the complexity of reconstruction of existing power-generating equipment and the cost of heat exchange units, the model for calculating the optimal heat recovery mode provides for reconstruction in two stages. In the first stage, it is proposed to install an air-to-air heat exchanger. The second stage of reconstruction involves the installation of a heat pump. During maintaining the heat exchange process, the exhaust process gases act as a hot heat agent, while the atmospheric air acts as a cold heat agent.

The proposed heat exchange scheme provides for the operation of the heat exchanger in an autonomous mode. Subsequently, the proposed model for calculating heat recovery involves the use of a plate heat exchanger with countercurrent movement of heat agents. This model of the heat exchanger allows organizing heat exchange in two modes. The first mode provides heating of a constant amount of cold heat transfer agent to a constant temperature. In this case, if the initial temperature of the cold heat transfer agent changes, the temperature of the hot heat transfer agent will change. The second mode provides cooling of a constant amount of hot thermal agent to a constant temperature. Here, the final temperature of the cold heat transfer agent will change.

To ensure the stable operation of the heat pump, it is necessary to provide a supply of hot heat transfer fluid with a constant temperature, so it is reasonable to perform heat exchange in the heat exchanger in the second mode. Therefore, the model for calculating the optimal heat recovery mode assumes that the heat exchange process in the heat exchanger occurs under conditions of constant initial and final temperatures of the hot heat transfer medium and variable initial and final temperatures of the cold heat transfer medium, depending on the season. The preheated cold heat agent is supplied to the combustion zone of the primary fuel and energy resource. In the process of combustion, process gases are formed, which maintain the temperature and aerodynamic conditions provided by the technological conditions. As a result of changes in the temperature of the cold heat agent, the consumption of the primary fuel and energy resource also changes. Since, at this stage of research, the consumption of the primary fuel and energy resource is used to assess the economic efficiency of implementation of heat reuse of exhaust process gases, it is important to know the effect of the final temperature of the cold heat agent on this consumption.

The development of a procedure for preliminary calculation of changes in the consumption of the primary fuel and energy resource when the final temperature of the cold heat agent changes is the main task of the proposed model for calculating heat at power generating equipment. To solve this problem, it is necessary to know the maximum temperature to which a cold heat agent can be heated under given conditions. The known methods of calculating heat exchange processes do not resolve this issue. Therefore, it is necessary to estimate the dependence of the volume flow rate of the cold heat transfer agent on its initial temperature at different values of the final temperature for a particular equipment and process parameters. Based on the obtained dependence $Lx=f(Tx)$, it is possible to determine the maximum temperature to which a cold heat transfer agent can be heated if its initial temperature is known. The obtained results are used to calculate the change in the consumption of the primary fuel and energy resource. The change in the consumption of the primary fuel and energy resource leads to a corresponding change in the consumption of the cold heat agent and, accordingly, its final temperature. To calculate this process, it is necessary to determine the effect of the initial temperature of the cold heat agent on its final temperature for various flow rates. As a result of the studies, within the range of changes in the initial temperature of the cold heat transfer agent $-30^0C \le Tx \le +30^0C$, it was found that the dependence $Tx_2=f(Tx_1)$ is straightforward, and the process can be described by the equation $Tx_2=ATx_1+B$.

The obtained dependence makes it possible to perform a refined calculation of the primary fuel and energy resource consumption and the optimal mode of heat recovery of exhaust process gases.

Calculation model:

1. Analysis of operation of power generating equipment.
2. Justification of the heat recovery scheme for exhaust process gases and the use of recovered heat.
3. Calculation of the recovery process and preliminary selection of heat exchange equipment.
4. Calculation of dependence of the volume flow rate of a cold heat transfer agent on its initial temperature at different values of the final temperature.
5. Determination of the initial temperature effect of the required amount of cold heat transfer agent on its final temperature.
6. Calculation of primary fuel and energy resource consumption changes due to changes in the final temperature of the cold heat agent.
7. Calculation of dependence of the cold heat agent final temperature on its initial temperature at different values of the volume flow rate.
8. Calculation of the change in the required amount of cold heat agent as a result of a change in the consumption of the primary fuel and energy resource and clarification of the effect of its initial temperature on the final temperature.

Calculation results and their analysis. To calculate the optimal mode of heat recovery of the exhaust process gases, we used the indicators and parameters of the А2ШБГ furnace. The use of natural gas with a calorific value of 33.5 mJ/m^3 is assumed as the primary fuel and energy resource. The maximum temperature of the process gases in the furnace is 280^{0}C. Parameters of the exhaust process gases at the output of the exhaust system: volume flow rate – 0.54 m^3/s; temperature – 160^{0}C. Recuperation is planned to be organized according to the scheme shown in Fig. 1. Commissioning of the recuperation system is planned in two stages. At the first stage, it is proposed to install an air-to-air plate heat exchanger. Air with a temperature varying from -30^{0}C to +30^{0}C is used as a cold heat agent.

The heat exchanger was designed taking into account the subsequent cooling of the exhaust process gases in the heat pump condenser. That is, the temperature of the exhaust process gases at the output of the heat exchanger is +40^{0}C. According to the calculation results, such a mode of cooling the exhaust process gases is provided by a plate heat exchanger with a heat exchange surface area of 16.7 m^2.

As a result of the heat balance calculation, it was found that in order to maintain the thermal regime of the furnace, it is necessary to burn 20 m^3 of natural gas per hour or 5.47 10-^{3} m^3/s. Meanwhile, to ensure the temperature and aerodynamic conditions in the furnace, air is supplied from the production facility in the amount of 0.53 m^3/s at a temperature of +20^{0}C. To provide for the reuse of heat from the exhaust process gases, the heat exchanger is supplied with atmospheric air, the temperature of which varies both throughout the year and throughout the day. In accordance with the accepted heat exchange conditions, the temperature of the preheated atmospheric air will change, which will lead to a change in natural gas consumption. To calculate the change in natural gas consumption and the economic effect of supplying preheated atmospheric air, the effect of the initial temperature of the cold heat agent on its volumetric flow rate at different values of the final temperature was calculated. The calculation results are shown in Fig. 2.

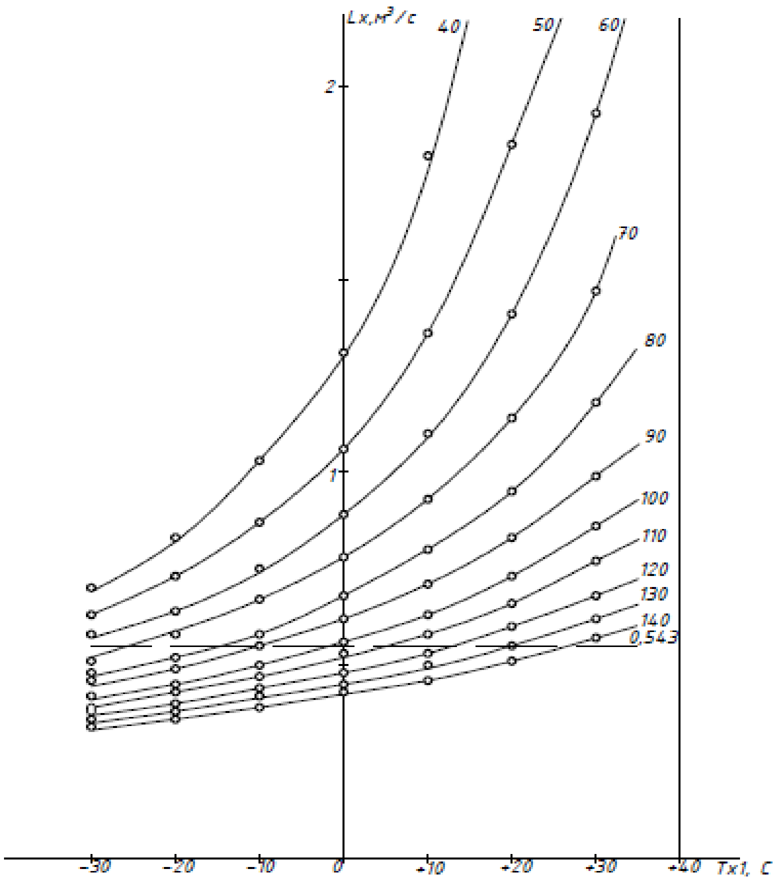

Figure 2. Dependence of the volume consumption of a cold heat agent on its initial temperature at different values of the final temperature. 1 – $Tx_2=40^0C$; 2 – $Tx_2=50^0C$; 3 – $Tx_2=60^0C$; 4 – $Tx_2=70^0C$; 5 – $Tx_2=80^0C$; 6 – $Tx_2=90^0C$; 7 – $Tx_2=100^0C$; 8 – $Tx_2=110^0C$; 9 – $Tx_2=120^0C$; 10 – $Tx_2=130^0C$; 11 – $Tx_2=140^0C$

The obtained dependence suggests that, under the accepted heat exchange conditions, the required amount of atmospheric air with an initial temperature of -30^{0}C can be heated to a temperature of +64^{0}C, and with an initial temperature of +30^{0}C can be heated to +145^{0}C. Accordingly, the natural gas consumption will vary from 20 m^3/h without preheating the atmospheric air to 12.7 m^3/h with preheating of the atmospheric air in the heat exchanger at an initial temperature of +30^{0}C.

To determine its effect on the final temperature of preheated atmospheric air, the effect of the initial temperature of atmospheric air on its final temperature was calculated for different flow rates.

Table 1

Influence of cold heat transfer agent parameters on natural gas consumption

Temperature of atm. air. (^{0}K(^{0}C)) T_{x1}	293 (+20)	243 (-30)	253 (-20)	263 (-10)	273 (0)	283 (+10)	293 (+20)	273 (+30)
Temperature of atm. air. (^{0}K(^{0}C)) Tx_2	293 (+20)	337 (+64)	352 (+79)	363 (+90)	378 (+105)	393 (+120)	405 (+132)	418 (+145)
Heat content, I_1.*kJ/kg*	41	70	85	96	117	136	159	200
Natural gas consumption, L_g (m^3/s; m^3/h))	0.00543 20	0.00508 18.3	0.00489 17.6	0.00476 17.1	0.0045 16.2	0.0044 15.8	0.004 14.3	0.0035 12.7
Efficiency due to air heating, m^3/h	0	1.7	2.4	2.9	3.8	4.2	5.7	7.3

The technological conditions of the furnace under study require 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 $5.1*10^{-3}m^3/s$ – $3.5*10^{-3}m^3/s$. The obtained calculation results make it possible to establish that within the studied initial temperatures of the cold heat agent Tx_1, the effect of changes in its flow rate Lx on the final temperature Tx_2 can be neglected.

Conclusions. Analyzing the results obtained, the following conclusions can be drawn: 1) the proposed model for calculating the optimal mode of heat recovery allows preliminary calculation of changes in the consumption of the primary fuel and energy resource as a result of the reuse of heat from the exhaust process gases of power generating equipment; 2) the results of the research can be used to calculate the economic efficiency of introducing energy-saving technologies into production; 3) when calculating the saving of the primary fuel and energy resource through the introduction of the reuse of heat of exhaust process gases, it is necessary to take into account the initial temperature of the cold heat agent.

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МОДЕЛЬ РОЗРАХУНКУ ОПТИМАЛЬНОГО РЕЖИМУ РЕКУПЕРАЦІЇ ТЕПЛА НА ЕНЕРГОГЕНЕРУЮЧОМУ ОБЛАДНАННІ ПЕРЕРОБНОЇ І ХАРЧОВОЇ ПРОМИСЛОВОСТІ

Степан Балабан; Володимир Каспрук

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

Резюме. *Технічні рішення направлені на збереження енергетичних ресурсів і зменшення негативного впливу виробництва на довкілля є особливо актуальними. До таких рішень відносять рекуперацію тепла відпрацьованих технологічних газів енергогенеруючого обладнання й повторне його використання у технологічних процесах. Попередньо проведений аналіз роботи періодично працюючого енергогенеруючого обладнання на підприємствах переробної і харчової промисловості показав недостатню увагу до даної проблеми. Серед можливих причин такої ситуації на особливу увагу заслуговує відсутність адаптованої до таких умов методів розрахунку доцільності впровадження повторного використання тепла відпрацьованих технологічних газів. Мета дослідження – створення моделі розрахунку оптимального режиму повторного використання тепла відпрацьованих технологічних газів під час реалізації двоетапного процесу їх охолодження. Проаналізовано вплив заходів з рекуперації тепла відпрацьованих технологічних газів на зменшення негативного впливу виробництва на довкілля й зростання конкурентоспроможності продукції. Проаналізовано схеми повторного використання тепла на періодично працюючому енергогенеруючому обладнанні переробної і харчової промисловості. Встановлено залежності об’ємної витрати холодного теплового агента від його початкової температури до різних значень кінцевої температури. Зазначено, що наведені залежності дозволяють визначити зміну кінцевої температури попередньо підігрітих технологічних газів у результаті зміни їх початкової температури від* -30^0C *до* $+30^0C$ *і розрахувати кількість зекономленого в результаті первинного енергоносія. Запропонована модель розрахунку оптимального режиму рекуперації тепла відпрацьованих технологічних газів дозволяє розрахувати зміни витрати первинного паливно-енергетичного ресурсу і створити базу даних для ефективного впровадження у виробництво енергозберігаючих технологій шляхом повторного використання тепла відпрацьованих технологічних газів.*

Ключові слова: *рекуперація, енергогенеруюче обладнання, теплообмінник, тепловий насос, первинний паливно-енергетичний ресурс.*

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