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Synergy of secondary energy resource utilization and hydrogen technology for reducing the carbon footprint of industrial thermal units

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Abstract. The article presents research results focused on improving energy efficiency and reducing the carbon footprint during pellet burning in rotary kilns. The study includes experimental kiln production, development of its energy balance, analysis of energy loss components, assessment of renewable and non-renewable energy losses, and determination of greenhouse gas emissions. The influence of operating parameters on kiln efficiency was examined, and their optimal values were identified. The thermal potential of secondary energy resources at the pellet burning plant was evaluated. A waste-heat utilization scheme for municipal and domestic heating and hot water supply was proposed. The study also establishes dependencies demonstrating the potential for reducing CO₂ emissions when substituting natural gas with a mixture containing reducing hydrogen. Research results on lowering the carbon footprint by burning environmentally neutral biomass are presented, along with practical recommendations. The scientific and applied outcomes of the work enable the development of measures aimed at decarbonization and enhancing the efficiency of rotary kilns used for pellet burning in mining and metallurgical enterprises.

1. Introduction

Mining and metallurgical enterprises (MME) are significant consumers of fossil fuels and, accordingly, polluters of the atmosphere with harmful components of combustion products. At the same time, the technological equipment of these enterprises can potentially become a powerful source of secondary energy resources that can be used for the needs of heating, ventilation and hot water supply of industrial and municipal buildings. The energy potential of technological production processes according to the Law of Ukraine [1] refers to renewable energy sources. And the use of renewable energy sources is the basis for achieving sustainable development goals (Sustainable Development Goals/SDGs) [2].

The implementation in Ukraine of measures envisaged by the Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable energy sources [3] will contribute to the implementation of the state policy in the field of renewable energy development and will allow to significantly reduce the consumption of traditional fuel and energy resources in all sectors of the national economy of Ukraine and, accordingly, increase the level of energy security of the state. According to the Law of Ukraine “On Energy Efficiency” [4], district heating systems are considered effective if they use at least 50% of waste heat, 75% of heat from cogeneration of energy, or



50% of the totality of such energy and heat.

The need for thermal energy in the municipal sector is extremely high due to the low thermal insulation characteristics of the enclosing structures of residential and public buildings. Therefore, technological installations and units of mining and processing plant can be simultaneously considered:

- as energy consumers and as generators of secondary energy resources;
- both powerful sources of greenhouse gas emissions and installations that make it possible to reduce their emissions through the use of secondary energy resources.

In Ukraine, metallurgy accounts for 51% of all carbon dioxide (CO₂) emissions generated in the manufacturing industry and construction [5]. Energy efficiency indicators of metallurgical equipment, for heating of which natural gas is used, are 1.3-1.5 times higher than the indicators of similar equipment of enterprises of the USA, Japan, EU countries [6]. Average specific CO₂ emissions in the world metallurgy are 1.81-1.89 t/t of steel, at the same time in Ukraine they reach 2.369 t/t of steel [7], which indicates the presence of significant reserves for reducing emissions.

The beneficial use of the waste energy potential of metallurgical equipment heated by fossil fuels makes it possible to increase the efficiency of fuel use in such equipment, and the optimization of the operating parameters of its operation makes it possible to increase its efficiency, reduce specific fuel consumption, which in turn provides an additional reduction in greenhouse gas emissions. This corresponds to the main theses of Directive (EU) 2023/1791 [8], according to which energy efficiency is considered as a separate energy source.

The purpose of the study is to develop measures to increase the energy efficiency of the pellet burning plant and reduce greenhouse gas emissions into the atmosphere by improving the operating parameters of rotary kilns, using waste heat from the furnaces for heating, ventilation and hot water supply of residential and communal consumers, and partially replacing the natural gas fuel with a mixture of natural gas and renewable hydrogen.

Addressing the carbon footprint of steel plants is important for the EU's carbon border adjustment mechanism to ensure a level playing field between iron and steel producers paying for CO₂ emissions under the EU ETS and importers [9, 10]. Such regulation should also stimulate the decarbonisation of steel production in EU partner countries. The full application of carbon border adjustment and the purchase of SVAM certificates is foreseen from 1 January 2026.

2. Methods

The object of the study was selected as a rotary kiln for pellet roasting, installed at the Poltava Mining and Processing Plant (Horishni Plavni, Poltava region, Ukraine). The number of such equipment is increasing both in Ukraine and abroad as the technology for pellet production develops and environmental and energy requirements for equipment increase [11].

The basis for determining the efficiency of the installation is the methodology for compiling and studying its heat and material balances. The methodology for compiling balances was based on general thermodynamic principles, as well as the study of literary sources that address the issues of developing energy balances in pellet roasting installations [12].

To form the balance equations, experimental tests of the installation were performed to determine the main parameters of its operation and the following data were obtained:

1. Gas analysis of combustion products for the presence of CO₂, O₂, CO, NO at the following balance points:

- at the outlet of combustion products from the firing chamber to the drying chamber (stream A);
- at the outlet of combustion products from the drying chamber to the atmosphere (stream B);
- at the outlet of the air flow from the annular cooling chamber to the atmosphere (stream D);
- at the inlet of secondary heated air to the furnace.

Sampling of combustion products was carried out using water-cooled probes.

2. Pressure, flow rate, temperature and heat of combustion of fuel.
3. Composition and characteristics of raw materials and finished product.
4. Temperature of combustion products at balance points.

5. Flow rate and excess air coefficient in combustion products at balance points of the installation. The installation diagram is shown in figure 1.

The nominal thermal power of each rotary kiln is 113 MW, the nominal natural gas consumption per kiln is 10,760 m³/h.

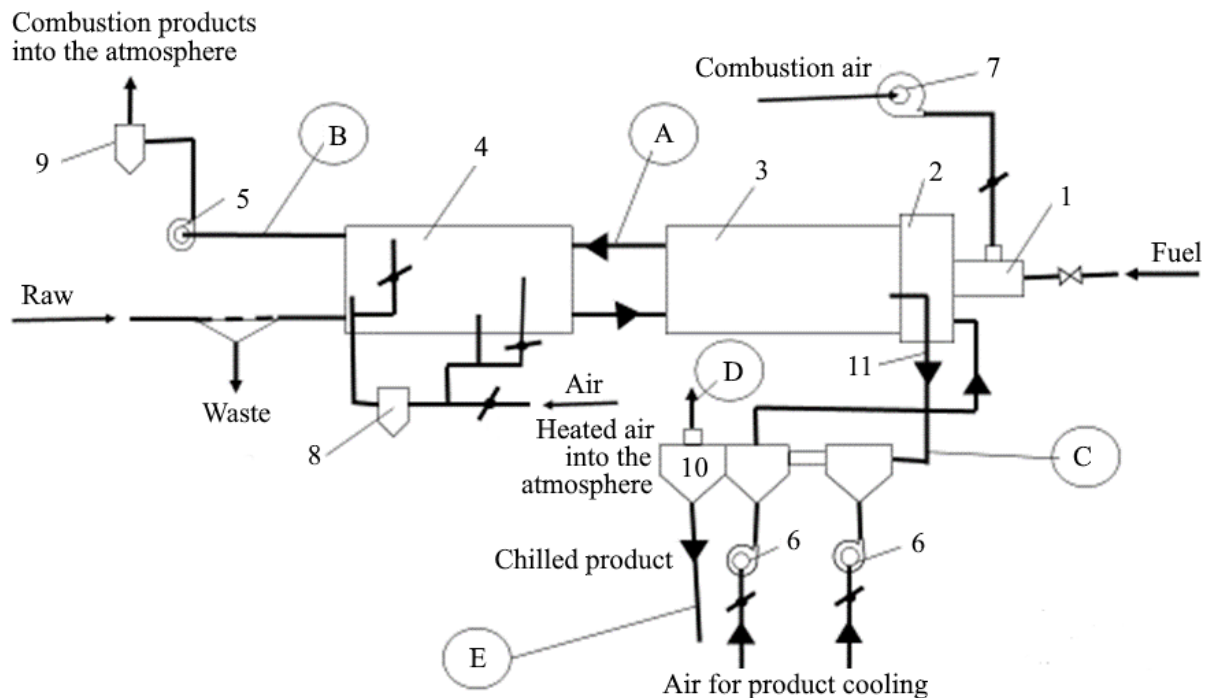


Figure 1. Schematic diagram of the pellet burning plant: 1- burner; 2- rotary kiln furnace; 3- burning chamber; 4- drying chamber; 5- smoke exhauster for removing combustion products; 6- fans for supplying air to the cooling chambers; 7- blower fan for supplying primary air for combustion; 8, 9- gas cleaning systems; 10- annular pellet coolers; 11- line for removing burnt pellets. A - flow of combustion products from the burning chamber to the drying chamber; B - fuel combustion products from the drying chamber to the gas cleaning system; C - removal of pellets to annular coolers; E - cooled product; D - removal of air into the atmosphere.

The compilation of the heat and material balances of the plant made it possible to determine the efficiency of its operation, the environmental characteristics of emissions and to assess the plant as a source of waste heat.

The heat balance equation of the plant is represented by the dependence (1):

$$Q_{\text{inc}} = Q_{\text{out}}, \quad (1)$$

where Q_{inc} and Q_{out} are respectively the incoming and outgoing heat, MW.

The useful heat used for technological needs of drying, heating and burning pellets during the surveys was determined according to dependence (2) as the difference between heat input and heat loss:

$$Q_{\text{usf}} = (Q_{\text{ch}} + Q'_{\text{ha}} + Q''_{\text{hsa}} + Q_{\text{hf}} + Q_{\text{er}} + Q_{\text{had}} + Q_{\text{hrm}}) + \\ + (Q_{\text{php}} + Q'_{\text{hl}} + Q''_{\text{hha}} + Q_{\text{hlw}} + Q_5 + Q_{\text{ohl}} + Q_{\text{hsev}} + Q_{\text{edr}}). \quad (2)$$

The determination of individual heat balance items was carried out according to the relationships given in table 1.

Table 1. Dependencies for determining the main components of the heat balance of a pellet burning furnace.

No.	Name of the heat balance component	Marking	Dependency for determination
1	Chemical heat of combustion of fuel	Q_{ch}	$Q_{ch} = B \cdot Q_f^c$
2	Physical heat of air for combustion	Q_{ha}^i	$Q_{ha}^i = C'_a \cdot V_a \cdot B \cdot t'_a \cdot \alpha$
3	Physical heat of fuel	Q_{hf}	$Q_{hsa} = B \cdot C_f \cdot t_f$
4	Heat loss with combustion products at the exit of the drying chamber	Q_{hl}^i	$Q_{hl}^i = C_{hcfg} \cdot t'_{egt} \cdot V'_{fgf}$
5	Heat of heated air leaving the ring coolers (potential heat)	Q_{hha}''	$Q_{hha}'' = C''_{hca} \cdot t''_{tha} \cdot V''_{hafr}$
6	Heat losses with technological waste	Q_{hlw}	$Q_{hlw} = M_{wmfr} \cdot C_{hcw} \cdot t_{tw}$

In equation (2) and table 1, the following notations are used: Q_{hsa}'' – physical heat of secondary air, W; Q_{er} – heat of exothermic reactions of magnetite oxidation, W; Q_{had} – physical heat of additional air, W; Q_{hrm} – physical heat of the raw material at the input, W; Q_{php} – physical heat of pellets at the exit from the firing chamber, W; Q_5 – heat loss to the environment, W; Q_{ohl} – other heat losses, W; Q_{hsev} – heat spent on evaporation of moisture from the raw material, W; Q_{edr} – endothermic dissociation reactions of fluxing additives, W; B – fuel consumption, m³/s; Q_f^c – fuel combustion heat, J/m³; t'_a – combustion air temperature, °C; C'_a – heat capacity of air, J/(m³·K); V_a – theoretical air flow rate, m³/s; α – air flow rate; C_f – fuel heat capacity, J/(m³·K); t_f – fuel temperature, °C; C_{hcfg} – heat capacity of flue gases, J/(m³·K); t'_{egt} – exhaust gas temperature, °C; V'_{fgf} – flue gas flow rate, m³/s; C''_{hca} – heat capacity of air, J/(m³·K); t''_{tha} – temperature of heated air, °C; V''_{hafr} – heated air flow rate, m³/s; M_{wmfr} – waste mass flow rate, kg/s; C_{hcw} – heat capacity of waste, J/(kg·K); t_{tw} – waste temperature, °C.

The efficiency of a heating furnace is determined according to the following relationship:

$$\eta = \frac{Q_{usf}}{Q_{ch}} \cdot 100, \% \quad (3)$$

During the research, it was taken into account that the heating of the secondary air supplied to the combustion chamber is carried out due to the heat of the pellets coming from the firing chamber. This makes it possible to partially use the heat losses that occur in the ring coolers. The efficiency of the heat utilization process was estimated by the value of the heat utilization coefficient (HUC), which was determined by the formula [13]:

$$\eta' = \frac{Q_{afr}}{Q_{hlp}^i - Q_{pex}''} \cdot 100, \% \quad (4)$$

Q_{hlp}^i – heat loss with pellets entering the cooling chamber, W; Q_{pex}'' – heat loss with pellets leaving the cooling chamber, W; Q_{afr} – physical heat of secondary air heated in cooling chambers, W.

According to the test results, a comprehensive indicator of the efficiency of the installation was determined - specific fuel consumption per 1 ton of technological product b_{fuel} according to the dependence [13]:

$$b_{fuel} = \frac{B_f \cdot Q_f^c}{M} \quad (5)$$

B_f – fuel consumption during a fixed period of installation operation (month, year, etc.); M – the amount of product obtained during a fixed period of operation of the installation in tons.

During the testing period, the following technological parameters of the installation were recorded: “raw” pellets were supplied with a moisture content of 10%; the amount of spillage was up to 8.5%; the consumption of “raw” pellets during the testing period was 445.3 t/h at an initial temperature of 21 °C.

In the drying zone, moisture evaporates and the raw material is heated to 216 °C. The temperature of the coolant in drying zone 2 reaches 391 °C. After drying, the pellets enter the preheating zone. The temperature in this zone is about 980 °C. In this zone, magnetite oxidation processes partially occur, which occur with oxygen absorption.

The temperature in the furnace firing zone is 1252 °C. Natural gas consumption during the testing period was 5071 nm³/h. Air enters the furnace in two streams:

- primary air in the amount of 14887 nm³/hour with a temperature of about 85 °C enters the burner for combustion of fuel gas;
- secondary air, heated in the cooler to a temperature of 1077 °C, enters the furnace in a parallel stream.

The amount of primary air supplied to the burner was designed so that the concentration of combustible gas in the gas-air mixture was not less than the upper limit of ignition, which is 15% by volume. The excess coefficient of primary air did not exceed 0.55 - 0.6. With a larger amount of primary air, the phenomenon of flame penetration into the burner body and disruption of the stability of the combustion process may occur.

In the ring cooler, the pellets are cooled to a temperature of no more than 120 °C. During the test period, the temperature of the pellets was 66.9 °C. The air supplied to the ring cooler is heated. In this case, one air flow with a temperature of 238.8 °C is removed through the cooler exhaust pipe into the atmosphere, and the other flow, heated to a temperature of 1077 °C, enters the rotary kiln as secondary air.

In this way, partial use of the heat of the burned pellets in the technological process is achieved, thereby increasing the efficiency of fuel use and increasing the efficiency of the installation.

The mixture of fuel combustion products and secondary air formed in the rotary kiln enters sequentially into the preheating zone and then into the drying zone. The mixture of natural gas combustion products and water vapor formed during drying, cooled to a temperature of 104 °C, is removed into the atmosphere using a smoke exhauster.

Optimization of the installation operation modes was carried out by changing the amount of primary air for combustion, as well as changing the amount of secondary air and the excess air coefficient.

During the tests, environmental performance indicators of the installation were also determined. The main results of the pollutant emission inventory are given in table 2.

Table 2. Basic information on the inventory of pollutant emissions during testing of a pellet burning plant.

No.	Indicator name	Marking	Unit of measure	Size	Method of receipt
1	Concentration of gases in combustion products:				
	- carbon monoxide	CO	% vol.	0.0014	measurement
	- oxygen	O ₂		17.7	
	- nitrogen	N ₂		80.39	
	- nitrogen oxide	NO _x		0.0015	
2	Gross emissions of pollutants in combustion products:				
	- carbon dioxide in combustion products;	CO ₂	kg/thous nm ³	1960	calculation
	- carbon monoxide	CO		1.36	
	-nitrogen oxide	NO _x		2.38	
3	Gross annual emissions of pollutants into the atmosphere:				
	- carbon dioxide in combustion products;	CO ₂	tons per year	39740	calculation
	- carbon monoxide	CO		27.58	
	-nitrogen oxide	NO _x		48.26	

3. Results and discussion

Calculations of the heat and material balances of the pellet burning plant have been performed in order to optimize its operating modes and determine the value of the efficiency coefficient when using natural gas as fuel.

The main components of the heat balance are given in table 3.

The specific heat consumption for burning 1 ton of pellets was 151.6 kWh/t; specific natural gas consumption was 14.3 m³/t; specific CO₂ emission was 28 kg/t.

Table 3. Results of tests of the pellet burning plant.

No.	Components of heat balance	Marking	Indicator value, kW	Indicator value, %
Heat input				
1	Chemical heat of combustion of fuel	Q_{ch}	55645	53.97
2	Physical heat of primary combustion air	Q_{ha}	614	0.59
3	Physical heat of fuel	Q_{hf}	39	0.040
4	Physical heat of secondary air	Q_{hsa}''	6940	6.73
5	Physical heat of the raw material at the input at $t = 21$ °C	Q_{hrm}	1872	1.82
6	Physical heat of additional air	Q_{had}	836	0.81
7	Heat of exothermic reactions of magnetite oxidation	Q_{er}	37162	36.04
Total			103108	100.00
Heat consumption				
1	Endothermic dissociation reactions of flux additives	Q_{edr}	558	0.54
2	Heat for evaporation of moisture from the raw material	Q_{hsev}	33087	32.09
3	Physical heat of exhaust gases including:			
	- at the exit of the drying chamber (stream B, figure 1);	Q_{hl}'	11829	11.47
	- at the exit of the cooling chambers (stream D, figure 1)	Q_{hha}''	18884	18.32
4	Physical heat of pellets at the exit of the firing chamber	Q_{php}	6004	5.82
5	Heat loss to the environment from heated equipment	Q_5	14691	14.25
6	Other heat losses	Q_{ohl}	17042	16.53
7	Heat loss with product waste	Q_{hlw}	1007	0.98
Total			103102	100.00

In the consumption part of the heat balance, heat losses with waste gases reached 29.8%. Of these, 11.5% are heat losses with waste gases from the drying chambers and 18.3% - losses with heated air discharged into the atmosphere from the ring cooler. Heat losses to the environment from the heated surfaces of the installation enclosures reach 14.5% of the total heat consumption. Pellets cooled in the ring cooler release up to 5.8% of heat to the environment.

The efficiency of heat use (kWh) during pellet burning is 85.6%. Thus, a significant part of the heat contained in the burned pellets is returned to the main technological cycle together with the heated air for combustion. But even under such conditions, the amount of heat removed together with the air from the ring coolers into the environment is significant - 18.9 MW, which is about 18% of the total heat consumption. This heat is a secondary energy resource of the process and can be used for municipal and household heating and hot water supply needs.

Testing the installation at different excess air coefficients showed that a significant increase in the efficiency can be obtained by reducing heat losses with the air removed from the ring cooler. Control over the amount of this air consumption was carried out by the amount of oxygen concentration at the outlet of the rotary kiln and the known amount of excess primary air entering the burner.

Studies have shown that changing the oxygen concentration in the combustion products at the outlet of the rotary kiln from 17.05 to 16.6% (vol.) leads to a significant redistribution of the heat balance items of the installation and a change in its efficiency from 40.1% to 24%. Table 4 shows the main

results of the study of the furnace operation at different oxygen concentrations in the combustion products.

Analysis of the table data shows that a decrease in the O₂ concentration in the combustion products at the outlet of the rotary kiln, 17.05 to 16.6% leads to a decrease in the efficiency of the installation from 40.1 to 24.0% due to a decrease in the efficiency of using the heat of the fired pellets in the annular cooler from 86.5% to 77% and an increase in heat losses with exhaust gases. Along with a decrease in gas consumption, carbon dioxide emissions into the atmosphere are reduced.

When conducting research, the thermal potential of secondary energy resources of the pellet firing installation was identified. Depending on the operating parameters of the installation, the amount of heat that can be used varied from 17 to 27 MW. A scheme for using waste heat for municipal and domestic needs for heating and hot water supply of a residential area located near the mining and processing plant is proposed (figure 2).

Table 4. Determination of the economic efficiency of the installation when changing operating parameters.

No.	Parameter names	Unit of measurement	Oxygen concentrations in combustion products	
			17.5%	16.6%
1	Fuel consumption	nm ³ /h	5071	5071
2	Primary air consumption	nm ³ /h	19522	19522
3	Installation performance	kg/h	367000	367000
4	Raw material moisture	%	10	10
5	Excess air coefficient at the exit of the firing chamber	-	4.87	4.38
6	Excess air ratio in exhaust gases after the drying chamber	-	5.99	5.41
7	Volumetric flow rate of secondary air at the inlet to the combustion device	nm ³ /h	237499	211810
8	Volumetric flow of combustion products at the outlet of the drying chamber (flow B)	nm ³ /h	320918	290318
9	Air volume flow rates at the outlet of the ring coolers (flow D)	nm ³ /h	197029	226925
10	Heat loss with combustion products at the outlet of the drying chamber (stream B)	kW	12186	11026
11	Heat loss with air at the outlet of the ring cooler (flow D)	kW	16922	27028
12	Heat input into the furnace with secondary heated air	kW	93733	83594
13	Total heat input	kW	64854	64919
14	Total heat loss to the installation	kW	42543	51565
15	Useful heat	kW	22311	13354
16	Furnace efficiency	%	40.1	24.0
17	Heat utilization coefficient	%	86.5	77.0
18	Reducing natural gas costs by optimizing operating conditions	nm ³ /h	625.6	-
19	Reduction of CO ₂ greenhouse gas emissions into the atmosphere	t/year	4900	-

The scheme envisages heating hot water in a heat exchanger in the recycling plant on the territory of the mining and processing plant by using the waste heat of warm air from the ring coolers of the furnace. The resulting coolant will be sent to the existing hot water boiler house of the residential area and used for heating and hot water supply. If necessary, additional heating of the coolant will be carried out in the hot water boilers of the boiler house.

Provided that the technological equipment operates for 4000 hours per year, the use of the secondary energy resources will provide an opportunity to obtain 72 GWh of heat, which will be used for heating

and hot water supply, which will ensure a reduction in natural gas consumption by 8 million m³ and, accordingly, a reduction in CO₂ emissions into the atmosphere by 16 thousand tons.

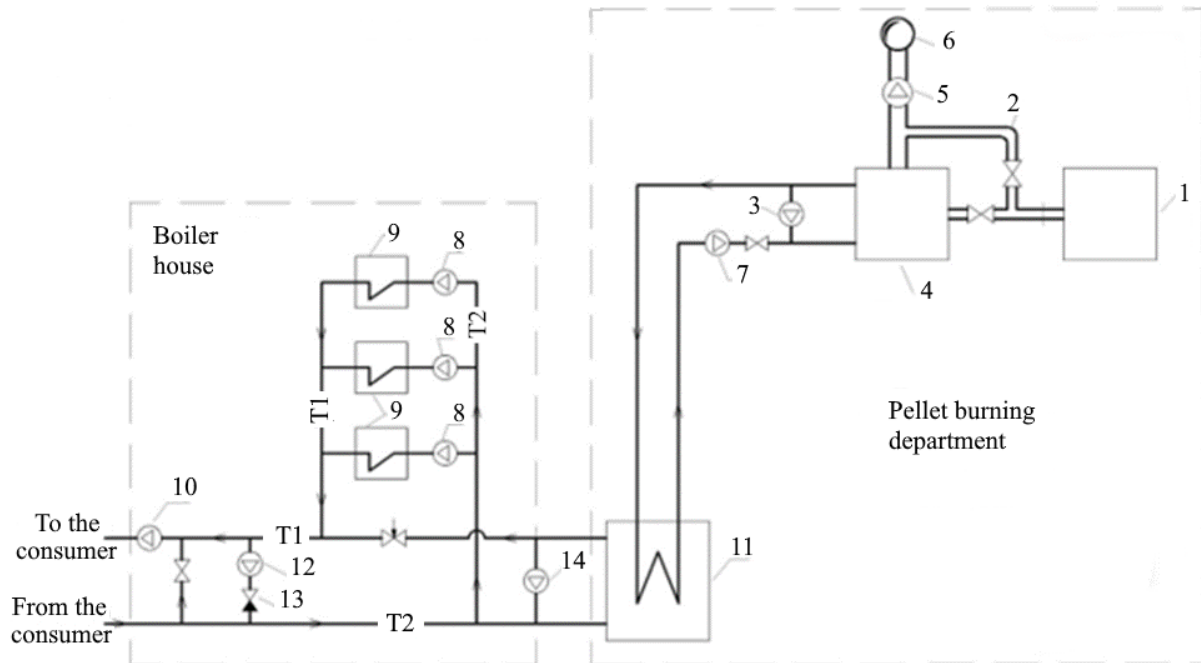


Figure 2. General scheme of waste heat utilization from the pellet burning plant: 1- pellet burning plant with a ring cooler; 2- bypass line for hot air from the ring cooler; 3- recirculation pump for regulating the water temperature at the inlet to the recycler and preventing condensation of hot air from the ring cooler; 4- heat recycler with a thermal capacity of 60 MW; 5- smoke exhauster; 6- smoke pipe for removing exhaust air into the atmosphere; 7- circulation pump for the coolant - hot water of the recycler circuit; 8- boiler pumps in the boiler room; 9- hot water boilers of the existing municipal boiler room with a total thermal capacity of about 20 MW per hour; 10- circulation pump of the heat network; 11- water heat exchanger of the recycler circuit; 12- pump for the recirculation system and regulation of the network water temperature; 13- check valve; 14- pump for the recirculation system and regulation of the water temperature after the recycler.

The use of secondary energy resources for third-party consumers of heat for municipal and domestic purposes does not directly affect the efficiency of the pellet burning plant, but it makes it possible to increase the HUC as a general energy indicator of the plant's efficiency from 40.1% to 72.9%.

As an additional source of reducing carbon dioxide emissions into the atmosphere, one can consider partial replacement of natural gas used as fuel for the rotary kiln with a mixture of natural gas and renewable hydrogen. The use of such a mixture with a hydrogen content of up to 20% (vol.) is possible without reconstruction of the furnace, burners and gas and air ducts with which the plant is equipped [14-19]. As calculations have shown, the use of such a mixture for heating a rotary kiln allows reducing CO₂ emissions from the plant by up to 2590 t/year (figure 3).

The individual impact of the considered measures on the amount of carbon dioxide emissions is shown in figure 4. The results obtained prove the high efficiency of utilization of waste heat of the installation for municipal and domestic needs for heating and hot water supply in comparison with other considered measures. Calculations show that the simultaneous implementation of the considered measures can ensure a reduction in carbon dioxide emissions of up to 23.5 thousand tons/year.

Another way to reduce the carbon footprint when operating rotary kilns for pellet burning is to use renewable and alternative fuels, such as environmentally neutral biomass. In this case, biomass is most often used as an additive to bentonite as a binder. For example, in work [20] the issue of using rice husks as such an additive was considered. The pellets obtained using this technology had greater strength and

porosity. In addition, this makes it possible to reduce the use of coke - a traditional fossil raw material with high CO₂ emissions. In [21], the experience of manufacturing "green pellets" made of fine iron ore, bentonite, fluxing additives and rice husks is highlighted. This reduces the use of fossil fuels and CO₂ emissions.

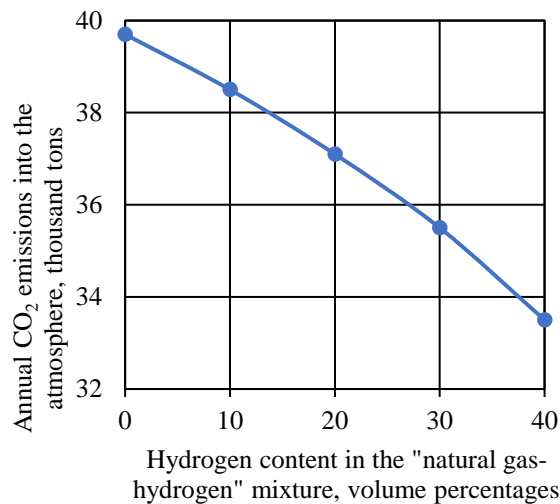


Figure 3. Gross CO₂ emissions from a pellet burning plant when replacing natural gas with its mixture with reducing hydrogen.

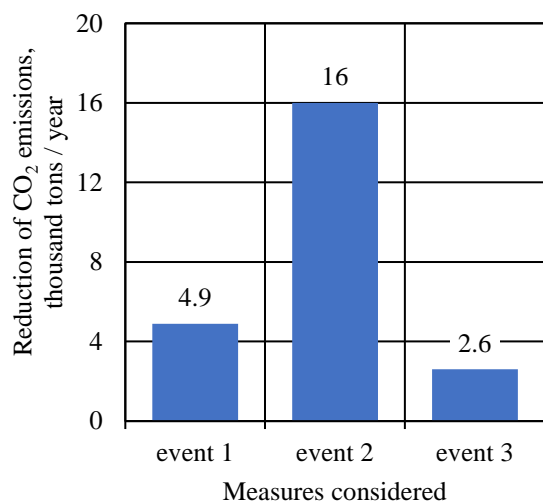


Figure 4. The impact of the considered measures on the amount of carbon dioxide emissions: 1- optimization of the operating parameters of the installation; 2- use of the installation's waste heat for municipal and domestic needs; 3- use of a mixture of natural gas and hydrogen for heating the rotary kiln with a hydrogen content of 20% in the mixture.

The authors of the work conducted a study of the possibility of using biomass as fuel in the firing furnaces of the Poltava Mining and Processing Plant. Part of the natural gas was replaced with sunflower husks with the following elemental composition per working mass in % by mass: ash content – 2.4%; S – 0.2%; C – 42.5%; H – 4.9%; N – 0.4%; O – 34.6%; humidity–15%.

The husks were fed by a pneumatic transport system with an air duct diameter of 150 mm under a pressure of about 3 atm directly into the furnace of the rotary kiln. The husk was burned in a natural gas torch, which was supplied in an amount of about 3200 m³/h through the gas burner device of the rotary kiln (figure 5).

At the maximum possible speed in the pneumatic transport system pipeline of about 25 m/s, the flow rate of the air mixture entering the furnace did not exceed 6 - 8 thousand nm³ per hour. At the maximum possible mass concentration of husk in the pneumatic transport pipelines of about 0.5 kg/kg of air, the maximum amount of husk supplied by the pneumatic transport system to the furnace was about 3-4 tons per hour (72 - 96 tons per day).

If the system operates for 330 days a year, the supply of husk can be about 24 thousand tons -

32 thousand tons, depending on the heat output of the rotary kiln.



Figure 5. Photo of the air duct for feeding husks into the rotary kiln furnace.

1 ton of husk with a combustion heat of 3800 kcal/kg replaces 390 m³ of natural gas with a combustion heat of 8250 kcal/m³. Thus, there is a possibility of diversification of 9.4 million m³ - 12.5 million m³ of natural gas per year on one furnace. The pellet burning plant has an average heat load of about 41 Gcal/h. Thus, husks can replace about 25% of the heat load of the plant. The reduction of CO₂ emissions per year can be 18.0-24.5 thousand tons of CO₂.

4. Conclusions

The authors of the article conducted a study of the operation of the pellet burning plant of the Poltava Mining and Processing Plant and proposed measures to increase energy efficiency and reduce carbon dioxide emissions into the atmosphere. These measures include:

1) Optimization of the operating parameters of the plant, namely the excess air coefficient in the exhaust gases from the rotary kiln by changing the amount of secondary air supplied from the ring coolers;

2) Utilization of the heat of the heated air (secondary energy resources) coming from the ring coolers in the municipal heat supply system by heating the coolant in the heat exchanger and supplying such coolant to the water-heating boiler house to meet the heating needs of residential buildings and the mining and processing plant's own needs;

3) Partial replacement of natural gas with a mixture of natural gas and renewable hydrogen and use of such fuel in the existing plant within the criteria for fuel interchangeability.

It was determined that the most effective is the implementation of a system for utilizing waste heat from the ring coolers of the plant. The overall energy efficiency indicator of the plant (heat utilization coefficient) increases with the implementation of the measure from 40.1% to 72.9%. Greenhouse gas emissions are reduced by 16 thousand tons/year. However, the implementation of the measure is associated with significant investments and the performance of construction and installation works, the cost estimate of which was not considered in this work.

A significant economic and environmental effect is also provided by the measure to optimize the operating parameters of the furnace. Optimization of the excess air coefficient makes it possible to increase the furnace efficiency from 24% to 40.1%, as well as reduce greenhouse gas emissions into the atmosphere by 4.9 thousand tons/year. An important advantage of such a measure is the lack of the need for significant investments.

Replacing natural gas with its mixture with renewable hydrogen and using this mixture as fuel within the requirements of the interchangeability criteria allows reducing greenhouse gas emissions by up to

2.6 thousand tons/year.

Partial replacement of natural gas with biomass obtained according to sustainability criteria also makes it possible to reduce the carbon footprint when burning pellets. For a furnace with an average thermal load of about 41 Gcal/h, the reduction in CO₂ emissions can be up to 20 thousand tons per year.

In order to obtain the maximum possible energy and environmental effect, it is proposed to implement all the proposed measures, since they do not antagonize each other. The total reduction in greenhouse gas emissions from their implementation can reach 40 thousand tons/year, and the complex indicator of fuel efficiency can be increased from the existing 24% to 72.9%.

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