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Study of the efficiency of using renewable hydrogen in heating equipment to reduce carbon dioxide emissions

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Abstract. The results of theoretical study of operation of continuous furnaces heated by natural gas, renewable hydrogen, and their mixture are presented. The furnaces have the same design, but significantly different energy efficiencies due to different heat losses and capability of recuperative fume gas heat utilization system. The measures to reduce heat losses and to increase air temperature for fuel combustion can reduce specific fuel consumption for metal heating and carbon dioxide emissions by 25.8% for natural gas furnaces. For furnaces operating on mixture of natural gas and hydrogen, a greater reduction in carbon dioxide emissions is achieved in furnaces with worse energy efficiency, but with greater fuel consumption for metal heating. The paper shows the possibility of converting a furnace with better energy efficiency indicators to be heated by mixture of natural gas (75%) and hydrogen (25%). The measure reduces the natural gas consumption and carbon dioxide emissions to 9.2% due to the use of hydrogen with specific consumption 13.81 m³ per ton of metal. To ensure the same costs for metal heating when transferring continuous furnaces from natural gas to hydrogen, or their mixture, the ratio of prices for natural gas and hydrogen should not exceed 0.301-0.312.

1. Introduction

The United Nations Climate Change Conference COP26 (November 2021, Glasgow) has declared the main task - keeping the global warming of the planet's atmosphere within 1.5 °C compared to the pre-industrial level [1]. According to the state policy of Ukraine in the field of climate change, one of the main directions for solving this problem is "reducing anthropogenic emissions and increasing the absorption of greenhouse gases and ensuring a gradual transition to low-carbon development of the state" [2]. In his speech at COP26, the President of Ukraine, Volodymyr Zelenskyi, said that Ukraine planned to reduce greenhouse gas emissions by 65% by 2030 (from the level of 1990) and to achieve climate neutrality by 2060.

Metallurgy is an important branch of the economy of most industrialized countries. In the world, the largest contributions to the carbon dioxide emission are made by the following industries: ferrous metallurgy (6%), transport (23%), heat energy (39%) from total volume of global carbon dioxide emission. In Ukraine ferrous metallurgy contributes 23% of all carbon dioxide emission [3]. If the average



specific emission of carbon dioxide in the world metallurgy according to the World Steel Association are 1.81-1.89 t/t of steel, then in Ukraine this indicator reaches 2.369 t/t of steel [4]. Such data indicate that domestic metallurgy has a significant reserve for reducing carbon dioxide emissions and energy costs for production.

Under the limited investment capacity of Ukrainian enterprises in the implementation of "metallurgical technologies of the future", the task of reducing of carbon dioxide emission can be solved in several ways:

- 1) implementation of well-known and tested technologies (Best Available Technologies), including technologies with a fairly short payback period [5], for example: decommissioning of open-hearth furnaces and transition to converter steel production; replacement of steel casting in a mold by continuous casting machine of blanks etc;
- 2) reduction of fossil fuel consumption by using metallurgical units with increased energy efficiency;
- 3) using renewable hydrogen as an alternative to fossil fuel.

Taking into account the number of scientific researches, developments and publications, the use of renewable hydrogen as a fuel is extremely relevant. Because of relative deficit and high cost of renewable hydrogen, the idea of using hydrogen in a mixture with natural gas has been the most popular in recent years. The use of the mixture is attractive because there is a possibility of using existing equipment and gas transport systems to transport a mixture with a hydrogen content of up to 20-25% [6]. However, taking into account the rapid increase in natural gas prices in 2022, the cost of renewable hydrogen at \$10-15/kg does not seem exorbitant. In addition, according to the forecasts of Bloomberg New Energy Finance (BNEF), the cost of renewable hydrogen will reach \$2/kg by 2030, and it will begin to compete with coal and natural gas as a fuel for ferrous metallurgy, and by 2050, hydrogen at a price of \$1/kg will become more profitable than gas and may become a competitor to the cheapest coal. However, there are less optimistic forecasts regarding the cost of hydrogen, for example, the International Renewable Energy Agency IRENA predicts that the price of hydrogen will be \$4-6/kg by 2025 and will reach \$2/kg only by 2040 [7].

According to [4], the largest amount of carbon dioxide emissions from metallurgical enterprises in Ukraine relates to blast-furnace production (32.1%), steel production (12.4%) and steam and power generations (36.6%). The processes of preparation of metallurgical raw materials (10.8%) and rolling (8.1%) are characterized by lower carbon dioxide emissions.

Therefore, the scientists have made efforts to reduce the emissions during the production of cast iron and steel. Rolling production uses up to 24.5% of natural gas from its total consumption by the metallurgy of Ukraine, and energy efficiency of thermal units that use natural gas for heating is 1.3-1.5 times lower than energy efficiency in similar units of the countries of the European Union, Japan and the USA [8, 9].

Rolling production is the last stage of processing iron ore raw materials on its transformation into a finished product. The specific consumption of fuel in rolling directly affects both the cost of production and the emissions of greenhouse gases into the atmosphere. This paper considers the operation of a continuous furnace designed for heating steel slabs before forming. Such furnaces belong to the most common type of heating devices used in sheet-rolling and section-rolling shops of Ukrainian enterprises.

The purpose of this paper is as follows:

- study of thermal performance of the furnace heated by mixture of natural gas and renewable hydrogen with a hydrogen content in the mixture from 0 to 100%;
- determination of carbon dioxide emission during fuel combustion;
- comparison of changes in furnace energy efficiency indicators and specific carbon dioxide emissions after the implementation of energy-saving measures and using hydrogen, or its mixture with natural gas as a fuel.

2. Methods

2.1. Technical characteristics of furnaces

The object of the study is continuous furnaces of the same design with a maximum productivity of each furnace of 100 t/h. Figure 1 shows a diagram of the operating area of the furnace, which is divided into six zones: a preheating zone and five heating zones (three upper and two lower zones). The dimensions

of the operating area of the furnaces are given in table 1.

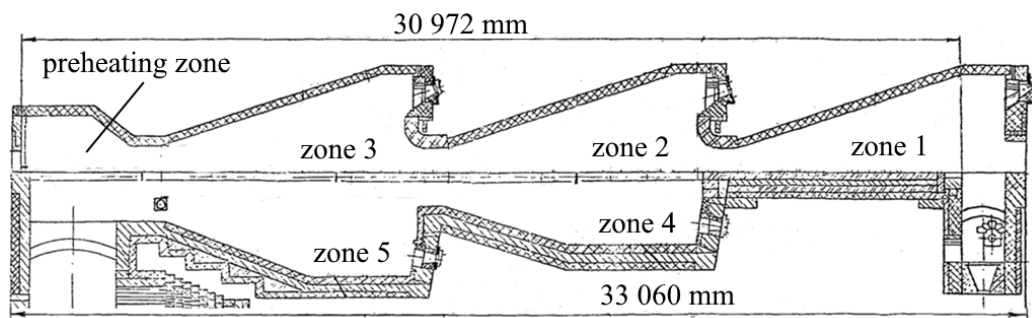


Figure 1. Furnace profile and numbers of technological zones.

Table 1. Dimensions of the operating area of furnaces.

Parameter	Value of the parameter
The length of the furnace zones, mm:	30972
preheating zone	5258
zones 3 and 5	8552
zones 2 and 4	9308
zone 1	7854
The width of operating area of the furnaces, mm	7888
Maximum height of zones from skid pipes, mm:	
zone 1 -3	3110
zone 4	2310
zone 5	2730
preheating zone	1770
The minimum height of the furnace between zones, mm	790

The metal moves along the furnace with the help of a pusher. In the preheating zone and zones 2-5, the metal is placed on heat-insulated skid pipes and heated from both sides. In zone 1, the metal moves along a monolithic hearth, where metal is heated on one side. The design of the furnace provides the cooling of pipes by technical water at the ends of metal loading and unloading and evaporative cooling of skid pipes.

The furnaces are equipped with 32 diffusion burners designed by "STALPROEKT". There are 8 burners in zone 1 and 6 burners in each other heating zone of the furnace. The maximum fuel consumption per furnace is 6200 m³/h.

The difference between the furnaces are the lining materials and the technical characteristics of the recuperators.

The vault and walls of furnace 1 are made of fireclay bricks with a thickness of 250 mm, the thickness of the side walls of the upper zones and the end wall at the metal loading windows is 580 mm and the thickness of the lower zones is 690 mm. The thickness of the end walls in which the burners are located is 690 mm. Longitudinal and transverse skid pipes and risers are insulated with fire-resistant lining based on high-aluminous cement. The monolithic hearth of the furnace consists of corundum blocks placed on fireclay bricks.

Furnace 2 has been reconstructed with the replacement of the fire-resistant lining with a lining made of fibrous fire-resistant materials (combined modular blocks, plates and mats produced by Unifrax Luyang Trading Co.). The furnace vault, side and end walls have thickness of 350-380 mm. Longitudinal and transverse skid pipes are isolated by removable IM PYROLOG modular blocks manufactured by "Morgan Advanced Materials". The monolithic hearth of zone 1 of furnace 2 is lined in the same way as furnace 1.

The furnaces are equipped with loop metal recuperators made of noncorrosive heat-resistant steel

to heat the air used for fuel combustion. The outer diameter of the recuperator tubes is 76 mm, the thickness of the tube walls is 4.5 mm. The recuperators of furnaces 1 and 2 are of the same type and consist of 8 sections, two rows of 4 sections in each row. The total heat exchange surface of the recuperator of furnace 1 is 958 m², for furnace 2 – 1290 m². The maximum air heating temperature when using natural gas as fuel is 350 °C for furnace 1 and 450 °C for furnace 2.

Thus, according to its heat engineering characteristics, furnace 1 belongs to the heating equipment, designed by the standards of the last century, has low energy efficiency indicators, and it is still actively used at metallurgical enterprises of Ukraine. The furnace 2 is an upgraded version of the furnace 1. The furnace 2 lining has been reconstructed and equipped with a recuperator with an increased heating surface, which made it possible to improve the energy efficiency without changing the design of the furnace.

2.2. Research methodology

A mathematical model of the thermal operation of the furnace has been used. The mathematical model makes it possible to calculate the processes of fuel combustion and heat exchange by radiation in the "gas-lining-metal" system, taking into account convective heat transfer.

The initial data for modeling are following: composition of natural gas; proportions of natural gas and recycling hydrogen in the fuel mixture; fuel burning conditions; geometric dimensions of the operating area of the furnace and slabs; initial temperature and final parameters of slab heating; furnace performance and its temperature regime; the temperature of the outer surface of the furnace lining; degrees of blackness of metal and lining; material and geometric dimensions of recuperator tubes and their location; areas of free cross-section for the passage of air and fume gases; the total area of the heat exchange surface of the recuperator; in the first approximation, the temperature of fume gases, the temperature of air heating in the recuperator are set; thermophysical properties of steel and gases.

According to methods [10], fuel combustion calculations are performed to determine the theoretical and actual air consumption; specific consumption of combustion products; the composition of fume gases and the dependence of their enthalpy on temperature.

For further calculations, the method of successive approximations is used. According to methods [11, 12], the metal heating has been calculated, and the following has been determined: external heat exchange parameters in the furnace zones; heat flows from fume gases to metal, changes in surface temperature and temperature distribution along the thickness of slabs during the heating process, temperature distribution of fume gases and the furnace along its operating area. Since the coefficients of heat transfer by convection are unknown in advance due to the lack of data on the speed of fume in the operating area of the furnace, in the first approximation, the convective component is not taken into account.

According to the method [11], heat losses in the operating area of the furnace zones are calculated, fuel consumption is determined for each zone and for the furnace as a whole, the thermal balance of the furnace is compiled and the technical and economic indicators of its operation are determined (total thermal power, efficiency of the furnace, specific consumption of fuel mixture and its components: natural gas and hydrogen).

Next, the temperature of air heating in the recuperator is calculated according [11].

At the next stage, the velocities of the fume gases in the furnace zones are determined, and the coefficients of heat transfer by convection for longitudinal gas flow around the plate are calculated [12].

The coefficients of heat transfer by convection, the temperature of the fume gases leaving the furnace, and the temperature of the air heating are used as initial data for calculating the thermal work of the furnace in the following approximations. A sign of the end of the calculations is the achievement of relative errors in the determination of the temperature of the fume gases leaving the furnace and the temperature of air heating in the recuperator of values smaller than the permissible error of the calculations. The calculations end when the relative errors in determining the temperature of the fume gases leaving the furnace and the temperature of air heating in the recuperator are smaller than the allowable error of the calculations.

The specific and annual mass emission of carbon dioxide are determined based on the results of calculations of the furnace thermal operation:

- mass emission of carbon dioxide ($\text{kg}_{\text{CO}_2}/\text{m}^3_{\text{fuel}}$) during the furnace operation is determined depending on the composition of the fuel:

$$B_{\text{CO}_2} = \frac{\text{CO}_2}{100} \cdot v_{\text{fumes}} \cdot \rho_{\text{CO}_2}, \quad (1)$$

where CO_2 is volume percentage of carbon dioxide in fume gases; v_{fumes} is specific fume output from fuel combustion, $\text{m}^3_{\text{fumes}}/\text{m}^3_{\text{fuel}}$; ρ_{CO_2} is density of carbon dioxide, kg/m^3 .

- specific mass emission of carbon dioxide ($\text{kg}_{\text{CO}_2}/\text{t}_{\text{metal}}$) is calculated as:

$$b_{\text{CO}_2} = B_{\text{CO}_2} \cdot b_{\text{fuel}}, \quad (2)$$

where b_{fuel} is specific fuel consumption for heating the metal, $\text{m}^3_{\text{fuel}}/\text{t}_{\text{metal}}$.

- annual mass emission of carbon dioxide ($\text{kg}_{\text{CO}_2}/\text{year}$):

$$B_{\text{CO}_2}^{\text{year}} = b_{\text{CO}_2} \cdot M, \quad (3)$$

where M is annual production, $\text{t}_{\text{metal}}/\text{year}$.

3. Initial data

Calculations of the thermal work of continuous furnaces 1 and 2 have been performed for the following initial data:

- dimensions of the heated slabs are $350 \times 1850 \times 3140$ mm;
- material of the slabs is structural steel Fe37-3FN/FU;
- number of slabs in the furnace – 34;
- furnace productivity 100 t/h;
- annual production is 700,000 tons/year;
- duration of metal heating is 5.4 h;
- initial temperature of the metal is 20 °C;
- final parameters of slab heating: surface temperature is 1220 °C; temperature difference across the thickness of the slab is 20 °C;
- temperature regime of furnaces heated with natural gas: in zones 3 and 5 the temperature is 1120-1140 °C; in zones 2 and 4 the temperature is 1280-1290 °C; in zone 1 the temperature is 1250-1260 °C;
- air heating temperature in the recuperator of furnaces that use natural gas is 350 °C for furnace 1 and 450 °C for furnace 2;
- consumption of technical water for cooling the structural elements of furnaces 1 and 2 is 240 m^3/h , water temperature at the inlet and outlet of the water cooling system is 20 and 40 °C, respectively;
- thermophysical properties of steel, gases and lining materials are recommended in the works [13, 14];
- vapor productivity of the evaporative cooling system of furnace 1 is 12.9 t/h and furnace 2 is 8.04 t/h, steam temperature is 209 °C, working pressure is 1.8 MPa, steam enthalpy at the exit from the evaporative cooling system is 2797 kJ/kg, feed water temperature is 95 °C, feed water enthalpy is 400 kJ/kg;
- emissivity factors of metal and masonry are 0.8 and 0.85, respectively;
- ambient temperature is 20 °C.
- temperatures of the outer surface of the furnace lining are given in table 2.

Calculations have been made for cases of furnace heating with natural gas, a mixture of natural gas and renewable hydrogen with a hydrogen content of 25, 50, and 75 percent by volume, and for the case of heating with pure hydrogen. The composition of natural gas is shown in table 3. The heat of combustion of natural gas and renewable hydrogen, respectively, is 36832.7 kJ/m^3 and 10760 kJ/m^3 .

Natural gas and hydrogen do not contain moisture. Dry atmospheric air with an oxygen content of 21% is supplied for fuel combustion. Air flow coefficient is 1.03.

Table 2. The temperature of the outer surface of the furnace lining.

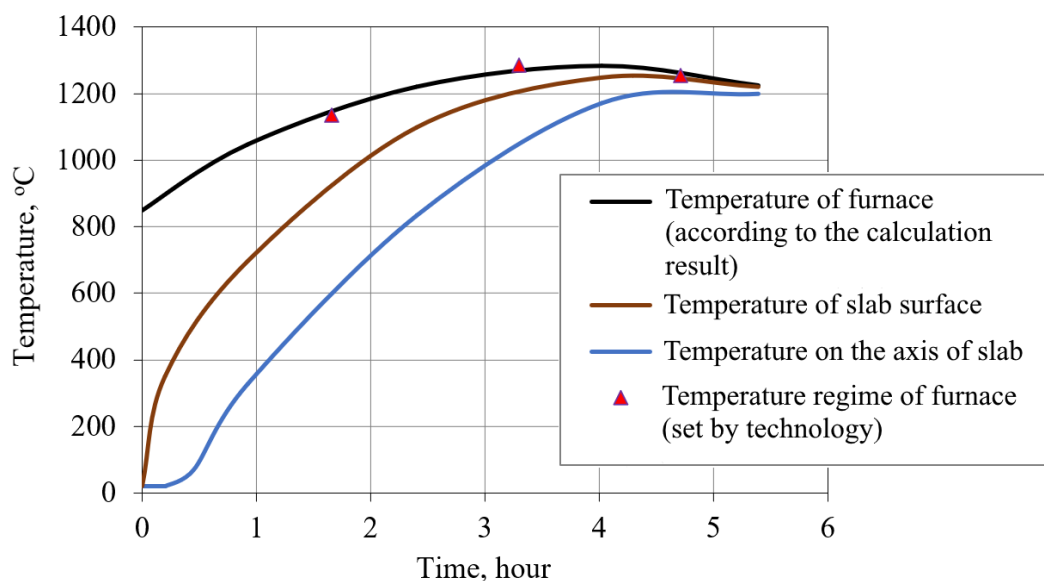
Place of temperature measurement	Temperature, °C	
	furnace 1	furnace 2
Vault of preheating zone and zone 3	250	60
Vault of zones 1 and 2	350	70
End walls of the zones 3 and 5	120	50
Side walls of zones 3, 5 and preheating zone	120	50
End walls of zones 1, 2, 4	170	60
Side walls of zones 2, 4 and 1	170	60

Table 3. Composition of natural gas, percentages by volume.

CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	C ₅ H ₁₂	C ₆ H ₁₂	CO ₂	N ₂
95.388	2.405	0.783	0.248	0.054	0.015	0.246	0.861

4. Results and discussion

Calculations of the thermal work of continuous furnaces 1 and 2, operating at the temperature regime given in the initial data, when using natural gas as fuel, have been performed. The temperature diagram of slab heating in furnace 1 is shown in figure 2. As can be seen from the figure, the calculated values of the furnace temperature correspond to the given temperature regime. Similar results have been obtained for furnace 2.

**Figure 2.** Temperature diagram of slab heating (furnace 1).

Based on the results of modeling the furnaces operation on a mixture of natural gas and hydrogen, the temperature regimes of metal heating have been developed by adjusting the furnace temperatures in zones 3 and 5 and the temperature of the outgoing fume gases. According to the results of the calculations, when the proportion of hydrogen in the fuel mixture increases from 0.25 to 1, the heating of the metal is ensured when the furnace temperature changes in the specified zones by 5-10 °C.

The obtained results of fuel combustion calculations, energy efficiency indicators of furnaces 1 and 2 are given in table 4, and heat balances of furnaces are given in tables 5, 6. The results calculations of fuel combustion, energy efficiency indicators of furnaces 1 and 2 are given in table 4. Figure 3 shows the results of calculations of fuel, air and fume gas consumption, figure 4 shows the results of calculations of specific emissions of carbon dioxide, and figure 5 shows the results of calculations of specific

consumption of natural gas and hydrogen when heating furnaces 1 and 2 with fuel of different composition. The results of calculations of annual carbon dioxide emissions are presented in table 4.

Table 4. Calculation results.

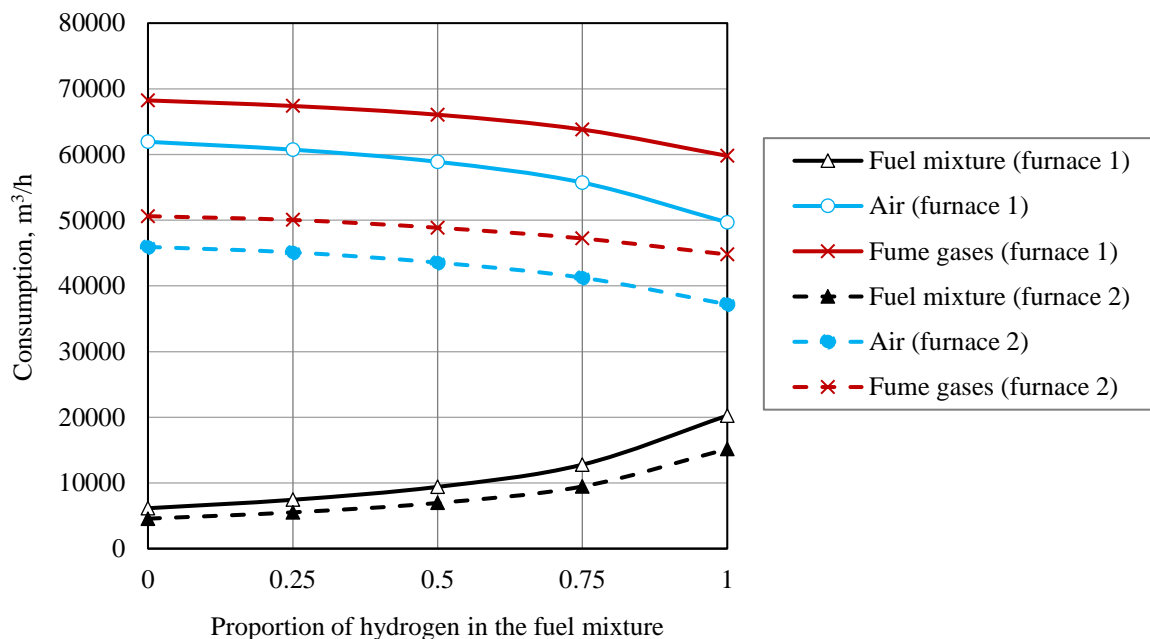
Fuel	Mixture of natural gas and hydrogen				Hydrogen
	Natural gas	0.25	0.5	0.75	
Proportion of hydrogen in the mixture	0	0.25	0.5	0.75	1
Fuel combustion heat, kJ/m ³	36832.7	30314.5	23796.4	17278.2	10760.0
Actual air consumption, m ³ /m ³	10.0692	8.1650	6.2608	4.3566	2.4524
Specific consumption of fume gases, m ³ /m ³	11.0941	9.0587	7.0233	4.9878	2.9524
Fume gases composition, volume percentages:					
CO ₂	9.3878	8.6229	7.4146	5.2202	0.0000
H ₂ O	18.2783	19.5487	21.5556	25.2005	33.8710
O ₂	0.5551	0.5513	0.5452	0.5342	0.5081
N ₂	71.7788	71.2771	70.4845	69.0451	65.6210
Furnace 1					
Temperatures of fume gases leaving the furnace, °C	915	911	900	883	880
Air heating temperature, °C	352	350	341	328	319
Fuel consumption for furnace, m ³ /year	6151	7439	9405	12790	20253
Fuel utilization rate	0.7102	0.7134	0.7187	0.7277	0.7379
Efficiency coefficient of the furnace, %	36.2	36.3	36.6	37.1	37.6
Mass emission of CO ₂ , kg/m ³ of fuel	2.046	1.534	1.023	0.511	0.000
Specific emission of CO ₂ , kg/t of metal	125.84	114.14	96.20	65.41	0.00
Annual emission of CO ₂ , thousand t/year	88.09	79.90	67.34	45.79	0
Furnace 2					
Temperatures of fume gases leaving the furnace, °C	860	856	842	825	820
Air heating temperature, °C	450	449	449	444	425
Fuel consumption for furnace, m ³ /year	4562	5523	6956	9466	15166
Fuel utilization rate	0.7752	0.778	0.7866	0.7959	0.7980
Efficiency coefficient of the furnace, %	48.8	48.9	49.5	50.1	50.2
Mass emission of CO ₂ , kg/m ³ of fuel	2.046	1.534	1.023	0.511	0.000
Specific emission of CO ₂ , kg/t of metal	93.33	84.74	71.15	48.41	0.00
Annual emission of CO ₂ , thousand t/year	65.33	59.32	49.81	33.89	0

Table 5. Heat balances of the furnace 1.

Fuel	Mixture of natural gas and hydrogen				Hydrogen
	Natural gas	0.25	0.5	0.75	
Proportion of hydrogen in the mixture	0	0.25	0.5	0.75	1
Heat gains, MW					
- chemical heat of fuel	62.931	62.638	62.169	61.385	60.534
- physical heat of air	8.006	7.805	7.366	6.696	5.799
<i>Total:</i>	70.937	70.443	69.535	68.081	66.333
Heat losses, MW					
- heat absorbed by the metal	22.761	22.761	22.761	22.761	22.761
- heat losses in operating area of furnace, including:	19.919	19.916	19.909	19.899	19.898
- heat loss by thermal conduction through the lining	4.929	4.929	4.929	4.929	4.929
- heat loss for cooling of skid pipes	8.586	8.586	8.586	8.586	8.586
- heat loss with cooling water	5.567	5.567	5.567	5.567	5.567
- heat loss by radiation through windows	0.837	0.834	0.827	0.816	0.816
- heat loss with fume gases leaving the furnace	26.246	25.757	24.856	23.414	21.667
- unaccounted heat losses	1.992	1.992	1.991	1.99	1.99
<i>Total:</i>	70.918	70.426	69.517	68.063	66.316
Imbalance, %	0.03	0.02	0.03	0.03	0.03

Table 6. Heat balances of the furnace 2.

Fuel	Natural gas	Mixture of natural gas and hydrogen			Hydrogen
Proportion of hydrogen in the mixture	0	0.25	0.5	0.75	1
Heat gains, MW					
- chemical heat of fuel	46.676	46.51	45.977	45.434	45.329
- physical heat of air	7.675	7.517	7.258	6.793	5.849
<i>Total:</i>	54.351	54.027	53.235	52.227	51.178
Heat losses, MW					
- heat absorbed by the metal	22.761	22.761	22.761	22.761	22.761
- heat losses in operating area of furnace, including:	12.191	12.189	12.181	12.172	12.171
- heat loss by thermal conduction through the lining	0.47	0.47	0.47	0.47	0.47
- heat loss for cooling of skid pipes	5.351	5.351	5.351	5.351	5.351
- heat loss with cooling water	5.567	5.567	5.567	5.567	5.567
- heat loss by radiation through windows	0.803	0.801	0.793	0.784	0.783
- heat loss with fume gases leaving the furnace	18.166	17.843	17.068	16.068	15.007
- unaccounted heat losses	1.219	1.219	1.218	1.217	1.217
<i>Total:</i>	54.337	54.012	53.228	52.218	51.156
Imbalance, %	0.03	0.03	0.01	0.02	0.04

**Figure 3.** Change in consumption of fuel, air and fume gases depending on composition of fuel mixture.

A comparison of furnaces 1 and 2 when operating on natural gas shows that the energy efficiency indicators of furnace 2 are significantly better compared to the similar indicators of furnace 1. According to the heat balances of the furnaces (tables 5, 6), the use of fibrous fire-resistant materials reduces heat losses by thermal conductivity through the lining from 4.929 to 0.47 MW, and the replacement of insulation of skid pipes with modular blocks ensures a reduction of heat losses for their cooling from 8.586 to 5.351 MW. A slight decrease in heat losses by radiation through the working windows of the furnaces from 0.837 to 0.803 MW, due to the different temperature near the loading windows, ensures a decrease in heat losses in the operating area of the furnaces from 19.919 to 12.191 MW (by 38.8%).

Increasing the temperature of the air going to burn fuel in furnace 2 by 100 °C, the amount of heat in the operating area of the furnace increases from 4.686 to 6.056 MJ/m³. A decrease in the temperature of the fume gases leaving the furnaces from 915 to 860 °C ensures a decrease in heat loss with fume gases from 15.361 to 14.336 MJ/m³. All this leads to an increase in the efficiency of the furnace from 36.2 to 48.8%, a decrease in the specific consumption of natural gas for heating metal from 61.51 to 45.62 m³/t and the specific emission of carbon dioxide from 125.84 to 93.33 kg/t (by 25.8%).

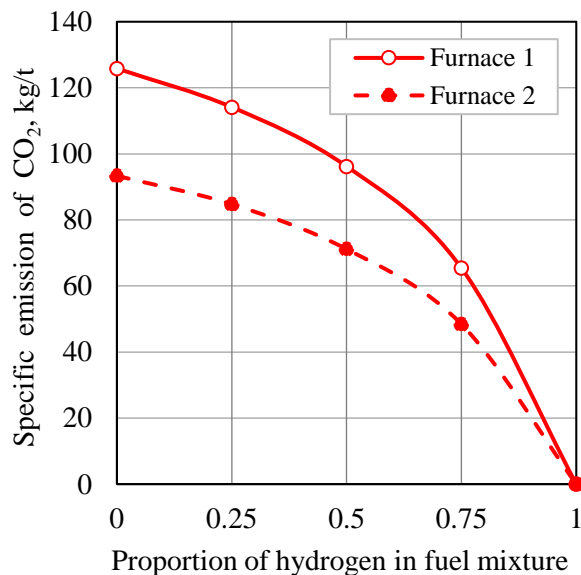


Figure 4. Specific emission of carbon dioxide depending on the composition of fuel mixture.

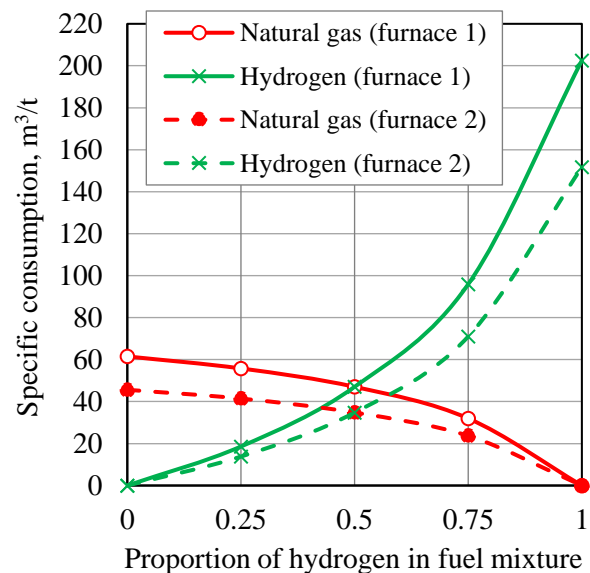


Figure 5. Specific consumption of natural gas and hydrogen depending on the composition of fuel mixture.

An increase in the proportion of hydrogen in the fuel mixture changes its composition and heat of combustion, and also affects the heat exchange in the operating area of the furnaces and leads to a decrease in the temperature of the outgoing fume gases (table 3).

A comparison of fuel, air, and fume gas consumptions in furnaces 1 and 2 using fuels of different composition is shown in figure 3. An increase in the part of hydrogen in the mixture from 0 to 1 leads to an increase in fuel consumption for furnace 1 from 6151 to 20253 m³/h and from 4562 to 15166 m³/h for furnace 2 (figure 3). The consumptions of air and fume gases decrease, respectively from 61934 to 49668 m³/h (air) and from 68238 to 59794 m³/h (fume gases) at furnace 1 and from 45936 to 37192 m³/h (air) and from 50612 to 44775 m³/h (fume gases) at furnace 2. Simulation of recuperators operations of furnaces have showed that a decrease in coolant consumption and the temperature of fume gases at the recuperator inlet leads to a decrease in the temperature of air heating in the range of 25-33 °C.

In general, an increase in the part of hydrogen in the fuel mixture has a positive effect on such indicators of furnaces as coefficients of fuel heat utilization and coefficient of efficiency. The efficiency increases from 36.2 to 37.6% when replacing natural gas with hydrogen at furnace 1 and from 48.8 to 50.2% when replacing fuel at furnace 2 (table 3).

Specific emission of carbon dioxide depending on the composition of the fuel mixture is shown in figure 4. The figure shows that increasing the proportion of hydrogen in the mixture leads to reduction of carbon dioxide emission. For example, if furnace 1 operates on fuel mixture with a 25% hydrogen content, the specific emission of carbon dioxide is reduced by 11.7 kg/t of metal, while replacing the mixture with a 75% hydrogen content with pure hydrogen provides a decrease of specific emission of carbon dioxide to 65.41 kg/t of metal. For furnace 2, the reduction of carbon dioxide emissions in these cases is smaller and amounts to 8.59 and 48.41 kg/t of metal, respectively. Thus, the use of hydrogen to reduce carbon dioxide emission looks more attractive for furnace 1. However, this result is achieved with higher specific

consumption of natural gas and hydrogen, the change of which depending on the proportion of hydrogen in the fuel mixture is shown in figure 5. The specific fuel consumption for heating metal with a mixture of any composition with a hydrogen content of less than 100% is greater in furnace 1 compared to furnace 2 (figure 5), which causes a greater reduction in carbon dioxide emission when using hydrogen.

The economic feasibility of using hydrogen in continuous furnaces, without taking into account the capital costs of implementing the measure, fines for exceeding carbon dioxide emission, or the possible benefit from the sale of a quota for carbon dioxide emission, can be estimated by fuel costs, based on the condition:

$$FC_{ng} \leq FC_m, \quad (4)$$

where $FC_{ng} = b_{ng} \cdot C_{ng}$ – specific fuel costs, under the heating the furnace with natural gas, \$/t of metal; $FC_m = b_m \cdot (X_{ng} \cdot C_{ng} + X_h \cdot C_h)$ – specific fuel costs, under the using a mixture of natural gas and hydrogen (or pure hydrogen), \$/t of metal; b_{ng} – specific fuel consumption when heating the furnace with natural gas, m^3/t of metal; b_m – specific fuel consumption under the heating the furnace with a mixture of natural gas and hydrogen, m^3/t of metal; C_{ng} and C_h – cost of natural gas and hydrogen, respectively, \$/m³; X_{ng} and X_h – proportions of natural gas and hydrogen in the fuel mixture.

As we can see from equation (4) the use of hydrogen for furnace heating does not lead to an increase the metal heating costs under the ratio of prices for hydrogen and natural gas (C_h / C_{ng}):

$$\frac{C_h}{C_{ng}} \leq \frac{b_{ng} - b_m \cdot X_{ng}}{b_m \cdot X_h}. \quad (5)$$

According to the calculations this ratio almost does not depend on the energy efficiency of the furnace and the proportion of hydrogen in the fuel mixture and is equal to $C_h / C_{ng} \leq 0.301-0.312$.

It should be noted that the conversion of the furnace to hydrogen requires its reconstruction, associated with the replacement of gas pipelines and furnace burners. In [15, 16], it is reported on the development by Toyota Motor Corporation and Jiangsu Jufeng Thermal Technology Co. Ltd. burners for hydrogen. It is also known about the development of burners for hydrogen or its mixture with natural gas by SAACKE GmbH and Selas Heat Technology Company [17, 18]. Unfortunately, the burners of these companies are not represented on the Ukrainian market now, and renewable hydrogen is produced in Ukraine in limited capacity. However, global trends in hydrogen production and use, as well as the activity of the Energy Association "Ukrainian Hydrogen Council" indicate the rapid growth of hydrogen production and use as a fuel in various industries in the near future.

For Ukrainian metallurgical enterprises, the use of hydrogen in a mixture with natural gas makes it possible not to change the existing designs of metallurgical units or to change them with minimal costs. Most researchers consider that it is possible and quite safe to use a mixture with a hydrogen content of up to 25% [6, 19] or up to 30% [20-22] in industrial units without replacing burners and metrological equipment. In the work [23], devoted to the use of a mixture of natural gas with hydrogen in household gas appliances, the upper limit of the hydrogen content is 50%.

Furnaces 1 and 2 considered in this paper, had the same designs with natural gas provided for heating the furnaces. Furnace 2 was reconstructed to increase its energy efficiency, which made it possible to reduce the specific consumption of metal heating. Therefore, the gas and air pipelines of the furnace 2 and its burners, provide the possibility to use a mixture of natural gas and hydrogen, in which the proportion of hydrogen is 0.25. However, it should be noted that in this research, the authors did not conduct mathematical modeling or experimental verification of the operation of burners designed by "STALPROEKT" on mixed gas. The operation and its safety of these burners when changing fuel require further research.

Capital investments are not necessary to convert the furnace 2 to a mixture with a hydrogen content of 25%, and the temperature regime of this furnace can be adjusted during the starting-up and adjustment period. The implementation of the measure can reduce the consumption of natural gas for heating metal from 45.62 to 41.42 m^3/t due to the use of 13.81 m^3/t of renewable hydrogen, which can reduce greenhouse gas emissions by 8.59 kg/t of metal, or 6,010 t/year. The calculation according to (5) shows that the use

of a mixture with a hydrogen content of 25% for furnace heating does not lead to an increase in metal heating costs at the ratio of prices for hydrogen and natural gas $C_h / C_{ng} = 0.304$. At the cost of natural gas \$1,000 per thousand cubic meters, the measure can be considered economically feasible at a hydrogen price of \$304 per thousand cubic meters or 3.40\$/kg.

Now, when the hydrogen is more expensive, it is advisable to focus efforts on improving the energy efficiency of existing furnaces by their reconstruction, to reduce heat loss from the operating area to the environment, increase the heating temperature of the air used for burning fuel, due to increasing the degree of heat utilization of fume gases. According to works [24-26], these measures are capable of saving fuel and reducing carbon dioxide emissions by up to 50%.

5. Conclusions

The authors of the paper have investigated the thermal performance of two continuous furnaces when heated with natural gas, renewable hydrogen, and a mixture of natural gas and hydrogen with a hydrogen content of 25, 50 and 75%. The energy efficiency indicators of furnaces and carbon dioxide emissions generated during fuel combustion have been determined. The furnaces have the same design, but differ in the materials used for their lining and the efficiency of the recuperators for heating the air used for fuel combustion. Thus, for the lining of furnace 1, mainly formed fireclays are used, and the recuperator of the furnace provides air heating temperature up to 350 °C. Furnace 2 lining is mainly made of fibrous refractories, and the recuperator of the furnace has an increased heat exchange surface and provides air heating up to 450 °C.

A comparison of furnace operations when they are heated with natural gas has showed that measures aimed at reducing heat losses in the operating area of the furnace and increasing the air heating temperature allow increasing the efficiency of the furnace from 36.2 to 48.8% and reducing specific fuel consumption by 15.89 m³/t of metal and specific emissions of carbon dioxide by 32.51 kg/t of metal.

When furnaces are heated with hydrogen or a mixture of hydrogen and natural gas, the specific fuel consumption and carbon dioxide emissions for furnace 1 are bigger than for furnace 2, because of better energy efficiency indicators of furnace 2.

Using hydrogen in a furnace with worse energy efficiency indicators (furnace 1) leads to a greater reduction in carbon dioxide emissions. However, this result is achieved with higher specific fuel consumption for metal heating.

For these furnaces, the price ratio for hydrogen and natural gas has been determined, the price ratio should not exceed 0.301-0.312 to ensure the same costs for metal heating when heating the furnaces with hydrogen or its mixture with natural gas.

It has been determined that furnace 2 can be switched to heating with a mixture with a hydrogen content of 25% without replacing auxiliary equipment, but the durability and safety of burners operation require experimental verification and is not considered in this paper. Replacing natural gas with its mixture with hydrogen of the specified composition ensures a decrease in the specific consumption of natural gas for heating metal by 4.2 m³/t and a decrease in the specific emission of carbon dioxide by 8.59 kg/t of metal (or 6,010 t/year). At the same time, the specific consumption of hydrogen for metal heating is 13.81 m³/t. The implementation of the measure does not lead to an increase in costs for heating metal at the ratio of prices for hydrogen and natural gas $C_h / C_{ng} \leq 0.304$.

References

- [1] Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021. Addendum Part two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement at its third session. (2022) Available from: https://unfccc.int/sites/default/files/resource/cma2021_10_add1_adv.pdf
- [2] Kontseptsiia realizatsii derzhavnoi polityky u sferi zminy klimatu na period do 2030 roku. Shkvaleno rozporiadzhenniam Kabinetu Ministriv Ukrainy vid 7 hrudnia 2016 r. No. 932-r. Available from: <https://zakon.rada.gov.ua/laws/show/932-2016-%D1%80#Text>

- [3] Babachenko O I, Tuboltsev L G and Merkulov O Ye 2021 Prospects for Decarbonization of Metallurgical Technologies *Fundamental and applied problems of ferrous metallurgy*, **35**, pp 4-33. DOI: 10.52150/2522-9117-2021-35-4-33
- [4] Shatokha V, Matukhno E, Belokon K and Shmatkov G 2020 Potential Means to Reduce CO₂ Emissions of Iron and Steel Industry in Ukraine Using Best Available Technologies *J. Sustain. Metall.* **6**, pp 451–462. DOI: 10.1007/s40831-020-00289-0
- [5] Shatokha V I 2015 Stalyi rozvytok chornoj metalurhii (Dnipropetrovsk: Driant) 184 p
- [6] Shkarovskiy A, Koliienko A and Turchenko V 2022 Interchangeability and Standardization of the Parameters of Combustible Gases When Using Hydrogen *Architecture and Engineering*, **7** (1), P. 33-45. DOI: 10.23968/2500-0055-2022-7-1-33-45
- [7] Babachenko O I, Nesterov O S and Garmash L I 2021 Low-carbon Technologies in Blast-furnace Production *Fundamental and applied problems of ferrous metallurgy*, **35**, pp 34-54. DOI: 10.52150/2522-9117-2021-35-34-54
- [8] Mishchenko I M 2012 *Chernaia Metallurgii i Okhrana Okruzhaiushchei Sredy* (Donetsk: GVUZ DonNTU), 446 p
- [9] Venher V V, Romanovska N I and Chyzhevskaya M B 2022 Tendentsii ta Vektory Rozvytku Metalurhiinoi Haluzi Ukrainy *Ahrosvit*, (4), pp 37-47. DOI: 10.32702/2306-6792.2022.4.37
- [10] Gubinskii V I et al 2007 *Metallurgicheskie Pechi: Teoriia i Raschety*. Vol. 1 (Minsk: Belorusskaia nauka)
- [11] Gubinskii V I et al 2007 *Metallurgicheskie Pechi: Teoriia i Raschety*. Vol. 2 (Minsk: Belorusskaia nauka)
- [12] Rumiantsev V D 2006 *Teoriia Teplo- i Masoobmena* (Dnepropetrovsk: Porogi)
- [13] Kazantsev E I 1975 *Promyshlennyye Pechi. Spravochnoe Rukovodstvo Dlia Raschetov i Proektirovaniia* (Moskva: Metallurgii)
- [14] Web-site of "Inventum" company: <https://inventum.com.ua/en/produkcija.html>
- [15] Toyota Develops World's First General-purpose Hydrogen Burner for Industrial Use. Toyota Motor Corporation Official Global Website. Available from: <https://global.toyota/en/newsroom/corporate/25260001.html>
- [16] Hydrogen Low NO_x Burner. Official Website of Jiangsu Jufeng Thermal Technology Co., Ltd. Available from: <https://www.generalflame-jf.com/low-nox-burner/gas-low-nox-burner/hydrogen-low-nox-burner.html>
- [17] Hydrogen burners for industrial decarbonization (2022). Official Website of SAACKE GmbH. Available from: <https://www.saacke.com/fileadmin/saacke/pdf/hydrogen-burners-industrial-decarbonization-whitepaper.pdf>
- [18] Selas ISGAD™ Low NO_x Hydrogen Burner. Official Website of Selas Heat Technology Company Available from: <https://www.selas.com/product/industrial-burners/nozzle-mix-burners/chemical-process-burners/selas-iscad-low-nox-hydrogen-burner/>
- [19] Stetsenko A A, Nedzelsky S D and Naumenko V A 2019 The Effect of Hydrogen on the Physical Properties of Natural Gas and the Metrological Characteristics of Its Metering Systems *Metrolohiia ta Prylady*, (6), pp 45-50. DOI: 10/33955/2307-2180(6)2019.45-50
- [20] Glanville Paul et al 2022 Impact of Hydrogen/ Natural Gas Blends on Partially Premixed Combustion Equipment: NO_x Emission and Operational Performance *Energies*, **15** (5), 1706. DOI: 10.3390/en15051706
- [21] Zanusso U, Fabro J, Luzzo I and Cirilli F 2021 Development and testing of flameless burner fed by NG/H₂mix *Materiaux et Techniques*, 109 (3-4), 304. DOI: 10.1051/mattech/2022004
- [22] Luzzo I et al 2021 Feasibility Study for the Utilization of Natural Gas and Hydrogen Blends on Industrial Furnaces *Materiaux et Techniques*, 109 (3-4), 306. DOI: 10.1051/mattech/2022006
- [23] Soroka B S et al 2020 Enerhetychni i Ekolohichni Kharakterystyky Pobutovykh Hazovykh Pryladiv pry Vykorystanni Metano-vodnevoi Sumishi Yak Palyvnoho Hazu *Naftohazova Haluz Ukrainy*, (6), pp 3-14
- [24] Yeromin O and Gupalo O 2015 Snizhenie Kolichestva Vrednykh Vybrosov pri Obieemnom

- sposobe Szhiganiia Topliva *Ekologiia i Promyshlennost*, (1), pp 40-45
- [25] Radchenko Y et al 2021 Reconstruction of Chamber Furnace Lining *Metallurgical and Ore Mining Industry*, (3), pp 74-82
- [26] Iasnogor V I, Yeromin O O, Gupalo O V and Matukhno O V 2017 Konstruirovanie Nagrevatelnykh Pechei Novogo Pokoleniia *Energetické procesy 2017 : Zborník vedeckých prác.(Košice)*, p. 153–160