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FLAME TEMPERATURE AS A FUNCTION OF THE COMBUSTION CONDITIONS OF GASEOUS FUELS

TEMPERATURA PLAMENA V ODVISNOSTI OD POGOJEV ZGOREVANJA PLINASTIH GORIV

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Analysis of the influence of preheating and of enriching the combustion air on the flame temperature as a parameter of the steel-heating process. The results, given in graphical form, were obtained with calculations of the combustion for two gaseous fuel types (natural gas and a mixture of gases) in industrial conditions. Analysing the different curves has made it possible to compare the combustion conditions for two gaseous fuels of different heating values and to describe the influence of changes in excess air ratio values, air preheated temperature and oxygen content of the combustion air on the flame temperature.

Key words: steel, heating process, flame temperature, combustion, air preheating, enriching of air

Analiziran je vpliv predgrevanja in obogatitve zgorevnega zraka na temperaturo plamena kot parametra ogrevanja jekla. Rezultati, ki so predstavljeni, so bili pridobljeni z analitičnim izračunom procesa zgorevanja za dve vrsti plinastega goriva (naravni plin in mešanica plinov) v industrijskih razmerah. Analiza odvisnosti je omogočila primerjavo pogojev zgorevanja dveh plinastih goriv z različno kalorično vrednostjo in vpliv prebitka zraka, temperature predgrevanja zraka in vsebnosti kisika v zraku na temperaturo plamena.

Ključne besede: jekla, ogrevanje, temperatura plamena, zgorevanje, predgrevanje zraka, obogatitev zraka

1 INTRODUCTION

Fuel contributes significantly to manufacturing costs, and in some industries represents one of the largest expenses. Improvements in the overall energy efficiency of an industrial plant, reflected in increased values of the output/input ratio, are primarily achieved by reducing the energy input values and also the energy losses on the output side of a process step [1-3]. Due to the increasing shortage of primary energy, especially of fuels, and environmental pollution through wastes in the use of energy, efficient energy recovery becomes very necessary. With nearly all industrial processes consuming primary energy, a considerable part of the heat is lost as waste gas. The major energy loss from industrial furnaces is via the sensible heat of the waste gas, the temperature of which is generally in the interval 600–1400 °C. The recuperative utilization of waste gas heat for processing is one of the most effective methods of energy recovery. Due to the reduction of the fuel quantity, less waste gas reaches the atmosphere, and as a result the efficiency is increased. By installing a recuperator in the waste-gas flue to preheat the combustion air the flame temperature is increased, the heat-transfer efficiency is improved and the overall fuel consumption is reduced [4-8].

The total loss of heat in the waste flue gases can be minimized by providing the proper amount of air for combustion. The amount of waste flue gases can be minimized and the heating rate of the unit can be increased by the oxygen enrichment of combustion air. With the same fuel input, enriched air for combustion raises the flame temperature of a given fuel, thereby improving the heat-transfer rate and increasing the production. Alternatively, the fuel input can be decreased when enriched air is used to maintain the same production rate as obtained with fuel using ordinary air. Increased production rates almost always reduce the heat losses per unit of product in any high-temperature furnace [5, 8-10].

Studies of the fuel-combustion process can provide new insights into the temperature structure of flames and allow better modelling of the radiation flux for the design of radiation zones and the physics of fire spread in many industrial furnaces, especially those operating at high temperatures.

2 RESULTS AND DISCUSSION

The composition and the heating values of the used fuels are given in **Table 1**. The conditions of the combustion process are defined by:

- changes in excess air ratio values, λ = 1.00–1.20;
- temperature of preheated air, T_{ca} = 50–500 °C;
- oxygen content in combustion air, $v(O_2)$ = 21–30 %.

The results obtained using an analytical method of the combustion process calculation, combined with some experimental results (analysis of gases chemical composition), are shown in **Figures 1-6**. The amount of

Table 1: Chemical composition(in volume fraction φ) and heating values of fuels
Tabela 1: Kemična sestava (v masnih deležih φ) in kalorična vrednost goriv

Analysis, φ/%										
H_2	CH_4	CO	C_2H_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2	O_2	H_2O	N_2
Natural gas										
–	84.16	–	–	0.63	0.55	0.54	–	–	8.22	5.90
Mixed gas										
27.47	10.19	15.44	1.15	–	–	–	3.99	2.48	1.65	37.63
Heating values [10^{-3} MJ/m^3]										
Natural gas: 31883.059 *Mixed gas:* 9263.894										

combustion air and the amount of combustion products can be defined as a function of the fuel quality, the air's oxygen content and the air ratio values. Changes of the amount of combustion air (V_{ca}) and combustion product, i.e., the waste gas amount values (V_{cp}), including the influence of the air's oxygen content and the excess air ratio values, were given in **Figures 1** and **2**. These changes significantly affect the main heating parameters. The curves describe the dependence of the variation in oxygen-content values on the changes of the amount of combustion air (**Figure 1**) and on the amount of combustion products (**Figure 2**). These graphs are extended to include the influence of the excess air ratio values (λ =1.0; 1.08; 1.16).

According to **Figure 1** it can be seen that the amount of air, supplied for the natural-gas combustion, was considerable larger than the air consumption when the mixed gas was used as a working fuel, for the total range of content of oxygen in the combustion air. For fuel combustion with higher values of $v(O_2)$, and with lower values of λ, less combustion air was needed.

The amount of waste flue gases can be minimised (amount of combustion products can be decreased), by the oxygen enrichment of the combustion air. By increasing the content of oxygen in this air (**Figure 2**), the amount of air per unit of fuel is decreased, as a result of which the amount of produced flue gases (waste gases) also decreases. According to the data in **Figure 2**, it can be concluded that with the increase of the excess air ratio, the values of the amount of combustion products also increase. The amount of combustion products increases for the total range of the oxygen content in the combustion air.

The equation used for the calculations of the flame temperature (T_f) is

$$T_f = \frac{Q_{h(f)} + Q_{ph(ca)}}{V_{cp} c_p} \qquad (1)$$

where:
$Q_{h(f)}$ - heating value of fuel; J/m^3
$Q_{ph(ca)}$ - enthalpy of preheated combustion air, J/m^3
V_{cp} – combustion products amount (volume) per unit of fuel, m^3/m^3
c_p – specific heat of combustion products, J/m^{3}K

The results of the flame temperature calculations are presented in **Figures 3-6** for the air preheating temperature in the interval 100–500 °C, for two values of excess air ratio (1.10; 1.20), and two values of oxygen content in the combustion air (21 %; 24 %), respectively. Two families of curves with different flows were obtained for the two used types of metallurgical fuels

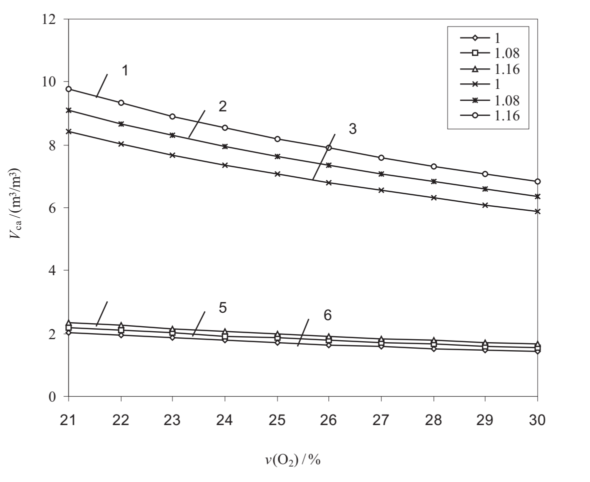

Figure 1: Effect of oxygen content in the combustion air on the amount of air (λ = 1.10; 1.08; 1.16); 1, 2, 3 – Natural gas; 4, 5, 6 – Mixed gas
Slika 1: Vpliv vsebnosti kisika v zgorevalnem zraku na količino zraka (λ = 1,10; 1,08; 1,16); 1, 2, 3 – naravni plin; 4, 5, 6 – zmes plinov

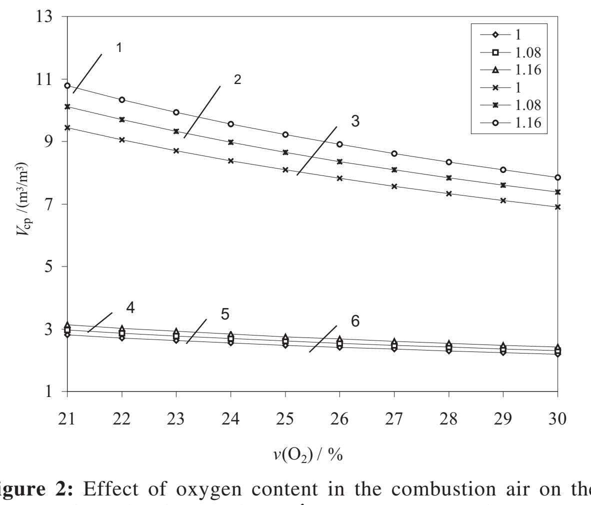

Figure 2: Effect of oxygen content in the combustion air on the amount of combustion products (λ = 1.10; 1.08; 1.16); 1, 2, 3 – Natural gas; 4, 5, 6 – Mixed gas
Slika 2: Vpliv vsebnosti zgorevalnega zraka na količino proizvodov zgorevanja (λ = 1,10; 1,08; 1,16); 1, 2, 3 – naravni plin; 4, 5, 6 – zmes plinov

(**Table 1**) and for the different conditions of combustion with different values of air preheating temperature, content of oxygen in the combustion air, waste gas temperature and ratio of air excess.

According to the obtained results, the flame temperature can be considered to be a function of fuel quality and to be dependent on the parameters of the conditions of the fuel-combustion process.

The curves in **Figure 3 and 4** describe the flame temperature as a function of the air preheating temperature for the two types of fuels used. **Figure 3** presents the changes in the flame-temperature values with the increase of the air preheating temperature, for two values of oxygen content and excess air ratio. The influence of air preheating, for a constant value of excess air ratio (λ = 1.10) and for the contents of oxygen in the combustion air of 21 %, 24 % and 27 %, respectively, is shown in **Figure 4**.

The curves 1, 2, 5 and 6 in **Figure 3** show the conditions of natural gas combustion, while curves 3, 4, 7 and 8 describe the changes of the fuel temperature when the mixed gas is used as a working fuel. The influence of the excess air ratio on the flame temperature can be described by two values of the coefficient λ (1.10; 1.20). Curves 1, 2, 3, 4 are related to λ = 1.10, while curves 5, 6, 7, 8 describe the conditions of the fuel combustion for λ = 1.20. The values of the oxygen content in the combustion air (v(O_2)), were used as follows: curves 1, 3, 5, 7, $v(O_2)$ = 21 % and curves 2, 4, 6, 8, $v(O_2)$ = 24 %.

The six lines in **Figure 4** can be classified as follows: the family of lines 1, 3, 5 describes the combustion of natural gas, while the lines 2, 4, 6 are related to the combustion of mixed gas. The values of the air-preheating temperature are 0–500 °C, while the values of the oxygen content are:
- line 1, 2, $v(O_2)$ = 21 %;
- line 3, 4, $v(O_2)$ = 24 %;

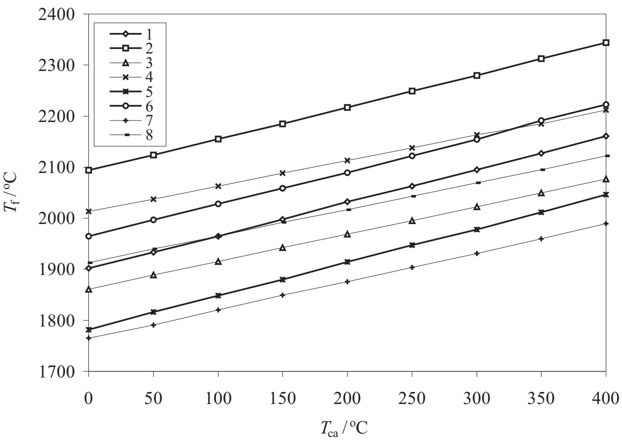

Figure 3: Changes in flame-temperature values with air preheat temperature 1, 2, 5, 6 – Natural gas; 3, 4, 7, 8 – Mixed gas; 1, 3 (λ =1.10, $v(O_2)$ = 21 %); 2, 4 (λ =1.10, $v(O_2)$ = 24 %); 5, 7 (λ =1.20, $v(O_2)$ = 21 %); 6, 8 (λ = 1.20, $v(O_2)$ = 24 %)

Slika 3: Sprememba temperature plamena v odvisnosti od temperature predgrevanja zraka. 1, 2, 5, 6 – naravni plin; 3, 4, 7, 8 – zmes plinov

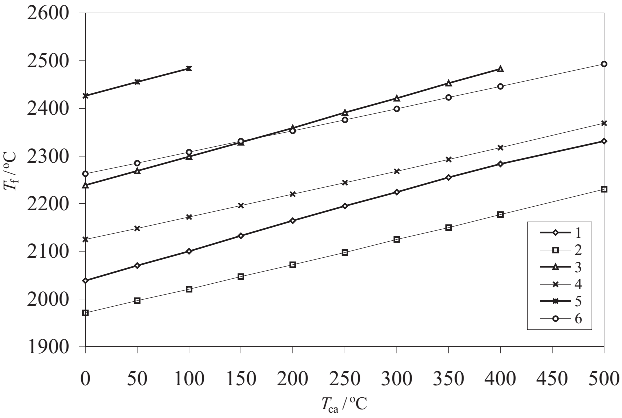

Figure 4: Influence of air preheating on flame temperature (l =1.10); 1, 3, 5 – Natural gas; 2, 4, 6 – Mixed gas; 1, 2 ($v(O_2)$ = 21 %); 4, 6 ($v(O_2)$ = 24 %); 3, 5 ($v(O_2)$ = 27 %)

Slika 4: Vpliv temperature predgrevanja na temperaturo plamena (λ = 1,10); 1, 3, 5 – naravni plin; 2, 4, 6 – zmes plinov

- line 5, 6, $v(O_2)$ = 27 %.

Figure 5 describes the flame temperature as a function of oxygen content in the combustion air. The two families of curves represent:
- curves 1, 2, 3, natural gas combustion;
- curves 4, 5, 6, mixed gas combustion.

The values of the air-preheating temperature used for the calculations were:
- curves 1, 4, T_{ca} = 100 °C;
- curves 2, 5, T_{ca} = 300 °C;
- curves 3, 6, T_{ca} = 500 °C.

The excess air ratio, in the case of combustion process presented in **Figures 4** and **5,** had a constant value of λ = 1.10.

On the basis of the shape and flow of these curves it can be concluded that he quality of the fuel, i.e., the heating value of the fuel is directly proportional to the increase in the flame temperature. The analysis of the

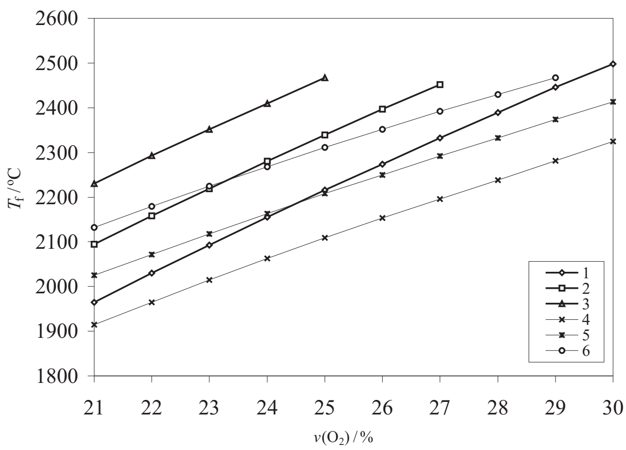

Figure 5: Influence of air oxygen content on flame temperature (λ = 1.10); 1, 2, 3 – Natural gas; 4, 5, 6 – Mixed gas; 1, 4 (T_{ca} =100 °C); 2, 5 (T_{ca} = 300 °C); 3, 6 (T_{ca} = 500 °C)

Slika 5: Vpliv vsebnosti kisika v zraku na temperaturo plamena (λ = 1,10); 1, 2, 3 – naravni plin; 2, 4, 6 – zmes plinov

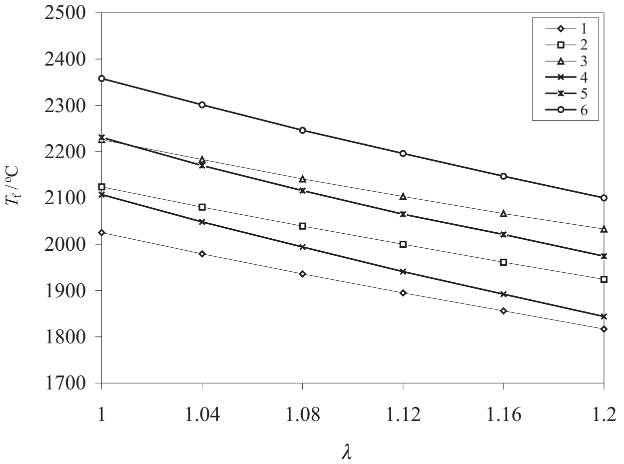

Figure 6: Influence of excess air ratio on flame temperature ($v(O_2)$ = 21 %); 1, 2, 3 – Mixed gas; 4, 5, 6 – Natural gas; 1, 4 (T_{ca} = 0 °C); 2, 5 (T_{ca} = 200 °C); 3, 6 (T_{ca} = 400 °C)

Slika 6: Vpliv prebitka zraka na temperaturo plamena; 1, 2, 3 – zmes plinov; 4, 5, 6 – naravni plin

flow of curves in **Figures 3, 4 and 5** shows that the increasing of the flame temperature is slightly faster for the natural gas than for the mixed gas combustion. Also, for the combustion process with the preheating of the combustion air, the flame temperature is increased for all the values of oxygen content in the combustion air. With the increase of the rate of enrichment air (content of oxygen in the combustion air), the values of the flame temperature also increase across the whole investigated range of air preheating temperature (**Figure 4**), as well as for all of the used values of the air temperature (**Figure 5**), while the value of the air excess ratio was constant. The results presented in **Figure 6** describe the flame temperature as a function of air excess ratio, for the range of λ = 1.0–1.20. The curves can be classified in the following groups:

– curves 1, 2, 3, combustion of mixed gas;
– curves 4, 5, 6, combustion of natural gas.

The values of the air-preheating temperature, for a constant value of air oxygen content, considered in the calculations, were:

– curves 1, 4, T_{ca} = 0 °C;
– curves 2, 5, T_{ca} = 200 °C;
– curves 3, 6, T_{ca} = 400 °C.

It is clear that the flame temperature decreased substantially with increasing values of air excess ratio for the total range of air-preheating temperature values and for all the values of the oxygen content in the combustion air. This can be explained according to equation 1, and the statement that during fuel combustion with higher values of λ, a smaller amount of air for combustion is needed. Therefore, the amount of heat transferred to the combustion air and combustion products is also reduced. As a result of this, the flame temperature decreases.

3 CONCLUSIONS

Calculations of fuel combustion are necessary to determine the quantity of combustion air, the amount and chemical composition of combustion products, the flame temperature and the fuel economy.

The fuel-combustion process is significantly affected by the heating value of fuel, the amount of combustion air, the air-preheating temperature, the oxygen enrichment in the air and the waste gas temperature.

The examined parameters of the fuel combustion have a great influence on the variation in the flame temperature values for both of the used fuels.

A high temperature for the combustion air is recommended for a fuel with a low heating value, because the flame temperature is raised, the heat-transfer efficiency improved and the overall fuel consumption reduced.

The amount of waste flue gases can be minimized and the heating rate of the unit can be increased by increasing the content of oxygen in the combustion air. With the same fuel input for the enriched combustion air the flame temperature of a given fuel increases, thereby improving the heat-transfer rate and increasing the production. Alternatively, the fuel input can be decreased.

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