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ANALYSIS OF COMBUSTION CHARACTERISTICS IN A ALUMINIUM MELTING FURNACE

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The composition of gaseous combustion product leaving the chamber of aluminium melting furnace in TLM Šibenik was investigated by measurements and numerical analysis in order to reduce the fuel consumption and increase the capacity of the existing furnace. Investigations were motivated by the fact that the actual specific fuel consumption was considerably higher and the actual furnace production was considerably lower than the design values according to the furnace technical documentation and the previous reached values in practice.

Key words: *aluminium melting fuce, combustion characteristics, measurements, numerical analysis*

Analiza procesa izgaranja u peći za taljenje aluminija. Sastav plinovitih produkata izgaranja koji napuštaju radni prostor peći za taljenje aluminija u TLM Šibenik je istraživan mjerenjima i numeričkom analizom u cilju da se smanji potrošnja goriva i poveća kapacitet postojeće peći. Istraživanja su bila motivirana činjenicom da je stvarna specifična potrošnja goriva znatno veća, a kapacitet peći znatno manji od projektiranih vrijednosti prema tehničkoj dokumentaciji peći i prethodno u praksi postignutih vrijednosti.

Ključne riječi: *peć za taljenje aluminija, karakteristike izgaranja, mjerenja, numerička analiza*

INTRODUCTION AND OBJECTIVES

Metallurgy industries have been driven by the requirements of maintaining or improving product quality and minimization of product costs. Within these requirements the overall energy management and energy efficiency play important roles. Minimization of energy consumption per unit of product is one of the key factors.

Until recent years fuel economy in furnaces was often of secondary importance since heating costs were frequently only a small fraction of total manufacturing cost. Designers and manufacturers were primarily concerned with increasing furnace output. However, much more attention is now paid to efficient operation of furnaces and recent advances in technology have led to major improvements in thermal efficiency [1, 2]. Whilst furnace efficiency and fuel consumption is obviously an important factor in the selection of heating equipment the paramount consideration is the production of melted material at cheapest cost [3].

The objective of the paper is to establish conditions under which the aluminium-melting furnace in TLM Šibenik should be operated in order to maximize the furnace production and the thermal efficiency and minimize the fuel consumption. Investigations were motivated by the fact that the actual specific fuel consumption was considerably higher and the actual furnace production was considerably lower than the design values according to the furnace technical documentation and the previously reached values in practice.

Aluminium melting furnace GAUTSCHI TP-100, type SVE 25, is placed in the Cast belt plant. The furnace operates with two cold air burners fired by light fuel oil. The unit has the design melting capacity of 25 t of molten aluminium, the nominal melting rate of 4,5 t/h and the nominal temperature of melt of 720 °C. The maximum temperature of molten aluminium is 850 °C. The furnace may be charged by liquid and solid charge.

However in reality, for the same time now, the furnace had a maximum discharge capacity of 11 t of molten aluminium before recharging. The furnace was charged with 4 to 5 t of molten aluminium from the induction melting furnaces, located in the melting plant Foundry TLM, and 6 t of solid charge. The furnace productivity was three casting cycles daily. Consequently, the melting process of 6 t of solid charge took nearly 8 hours, which was a much longer time in relation to the design melting rate. Further-

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more, the liquid charge had to be added because the required technological process of melting only solid charge could not be carried out. Namely, the combustion process was not in working order so that the needed furnace temperature could not be achieved.

At the same time, the fuel oil consumption was also significantly increased. As a relative measure of the efficiencies of furnaces may serve the unit fuel consumption, i.e. the amount of energy needed to heat a unit mass of the charge to the required specification.

The design unit fuel consumption of light oil for melting 25 t, 50 % solid and 50 % liquid, aluminium to the temperature of 720 °C is 90 kg/t and for 100 % solid charge, under the same conditions, it is 105 kg/t. Because of the melt cooling during its transportation from the melting furnace to the casting furnace, the melt must be superheated up to 770 °C. At the continuous furnace work of 700 t aluminium per months, the unit fuel consumption is 140 kg/t [4]. Since this production has not been achieved, the unit fuel consumption could be about 155 t/h. However, the actual unit fuel consumption was 180 to 200 kg/t at average discharge temperature of 780 °C.

According to the information's of the technical staff the new furnace by putting into working had realized the design operating characteristics, i.e. capacity and unit fuel consumption. However, during the time a gradual diminishing of capacity and increase of unit fuel consumption had occurred.

In order to decrease the fuel consumption and increase the furnace capacity it is necessary to discover and then eliminate the cause of non adequate working of heating equipment, i.e. to improve the combustion process. The most effective way of achieving the goal is to establish the temperature and the composition of product gases leaving the furnace chamber. In this paper the results achieved by measurements were compared with those obtained by calculation of the equilibrium compositions and the adiabatic flame temperature of the combustion products related to the amount of supplied combustion air.

MEASURING RESULTS

The temperatures of the flue gases were measured by means of thermocouple NiCr-Ni and the major gas-phase species concentrations were detected by two flue gas analysers from Testo in one point at the end of the furnace chamber where the waste gases enter the flue, i.e., at the inlet of flue gas duct which is placed in the opposite direction of the charging door. Combustion product samples were taken using a stainless steel probe.

Table 1. **Results obtained by first measurements of flue gases**

Tablica 1. **Rezultati dobiveni prvim mjerenjima dimnih plinova**

Temperature of flue gases / °C	920
Oxygen / %	7,9
Carbon oxide / ppm	1500
Carbon dioxide / %	8,4
Excess air (*n*)	1,60

The first measurements were done by electronic flue gas analysers Testo 32 with the inserted chemical measuring cells. Flue gas parameters such as O_2 and CO are directly measured by the measuring system while CO_2 is calculated from O_2 and CO_{2max} of a specific fuel. The results are shown in Table 1.

The measurements were repeated by the new-purchased flue gas analysers Testo 350 XL after a certain increase of the cross-section of flue gas duct inlet. With this measuring system the additional flue gas parameters such as NO, NO_2, H_2, SO_2 and unburnt hydrocarbons C_xH_y can be measured. The results are shown in Table 2. The excess air value was calculated from the measured value of O_2

Table 2. **Results obtained by second measurements of flue gases**

Tablica 2. **Rezultati dobiveni drugim mjerenjima dimnih plinova**

Temperature of flue gases / °C	1093
O_2 / %	7,3
CO / ppm	13
CO_2 / %	10,1
NO /ppm	89
NO_2 /ppm	0
H_2 / ppm	14
SO_2 /ppm	100
C_xH_y /ppm	150
Excess air (*n*)	1,53

$$n = \frac{21\%\,O_2}{21\%\,O_2 - \%\,O_2} \tag{1}$$

In both cases the measurements were done at the maximum burner thermal power.

NUMERICAL RESULTS

For the comparison of the measurement results with theoretical data, there was a need to calculate the adiabatic temperature and the composition of a mixture at a given temperature, pressure and stoichiometry in order to find out the variation of temperature and combustion product mixture composition with equivalence ratio.

For a combustion process that takes place adiabatically and with no work or changes in kinetic or potential energy, the temperature of the products is referred to as the adiabatic flame temperature. This is the maximum temperature that can be achieved for the given reactants, because any heat transfer from the reacting substances and any incomplete combustion would tend to lower the temperature of the products. The adiabatic temperature can be controlled with the amount of excess air that is used. This case of combustion in the aluminium melting furnace may be considered as a constant-pressure system. If a fuel-air mixture burns adiabatically at constant pressure, the absolute enthalpy of the reactants at the initial state (T_i = 298 K, p = 101325 Pa) equals the absolute enthalpy of the products at the final state ($T_i = T_{ad}$, p = 101325 Pa), i.e., application of the first-law statement results in:

$$H_{reac}(T_i, p) = H_{prod}(T_{ad}, p) \tag{2}$$

Equation (1) defines the constant-pressure adiabatic flame temperature.

The condition for equilibrium may be stated in terms of any of several thermodynamics functions, for example, the minimization of the Gibbs free energy or Helmholtz free energy, or the maximization of the entropy. If the temperature and pressure are used to characterize a thermodynamic state, the Gibbs free energy is the most easily minimized, because of the fact that temperature and pressure are its natural variables. In this consideration of chemical equilibrium the Gibbs function was introduced in calculating the equilibrium composition of ideal-gas mixtures using equilibrium-constants together with element conservation [5].

The combustion of light fuel oil ($C_{10,8}H_{18,7}$) in air at initial temperature of 298,15 K and at constant pressure of 101325 Pa was considered. The Fortran program HPFLAME, which incorporates the Olikara & Borman equilibrium routines [6], to carry out the thermochemical calculations for the equilibrium compositions and the constant-pressure adiabatic flame temperature for equivalence rations, Φ, of 0,6 to 1,4 (increment $\Delta\Phi$ = 0,1) is used. The input file for the program requires the definition of the fuel by providing the number of carbon, hydrogen, oxygen, and nitrogen atoms constituting the fuel molecule, the equivalence ratio, a guess for the adiabatic flame temperature, the pressure, and the reactants enthalpy.

The equivalence ratio, used in this paper, indicates quantitatively whether a fuel-air mixture is rich, lean or stoichiometric is defined as

$$\Phi = \frac{(A/F)_{stoic}}{(A/F)} \tag{3}$$

where

(A/F) is mass air-fuel ratio (kg/kg).

According to this definition for fuel-rich mixtures, Φ > 1, and for fuel-lean mixtures, Φ < 1. Another parameter frequently used to define relative stoichiometry representing the ratio of supplied air to the theoretical air requirement is known as excess air or air-fuel-ratio, n, which relates to the equivalence ratio as $n = 1/\Phi$.

The calculated equilibrium compositions and the flame temperature of the combustion products for the combustion of light fuel oil ($C_{10,8}H_{18,7}$) in air, at initial temperature of 298,15 K and at constant pressure of 101325 Pa, are given against equivalence ratio in the Table 3.-4. and also plotted in Figure 1.-2., respectively.

Table 3. **The calculated equilibrium compositions of the combus-tion products of light fuel oil given against equivalence ratio, Φ, and air-fuel-ratio, n**

Tablica 3. **Izračunat ravnotežni sastav produkata izgaranja lakog loživog ulja u ovisnosti o ekvivalentnom odnosu, Φ, i pretičku zraka, n**

Φ	0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4
n	1,6	1,43	1,25	1,11	1,0	0,9	0,83	0,77	0,715
O_2 / %	7,9	5,85	3,80	2,01	0,73	0,146	0,019	0,0027	0,0
CO / %	0,0	0,026	0,14	0,58	1,65	3,66	6,17	8,56	10,67
H_2 / %	0,0	0,0053	0,03	0,097	0,282	0,705	1,44	2,44	3,6
CO_2 / %	8,47	9,79	10,99	11,85	11,97	11,07	9,54	8,063	6,82
H_2O / %	7,32	8,45	9,52	10,49	11,32	11,88	12,05	11,88	11,46
N_2 / %	75,98	75,43	74,58	74,18	73,3	72,06	70,51	68,89	67,31

Table 4. **The adiabatic flame temperature given against equivalence ratio, Φ, and air-fuel-ratio, n, for light fuel oil**

Tablica 4. **Adijabatska temperatura plamena u ovisnosti o ekvivalentnom odnosu, Φ, i pretičku zraka, n, za lako loživo ulje**

Φ	0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4
n	1,6	1,43	1,25	1,11	1,0	0,9	0,83	0,77	0,715
T/K	1734	1919	2086	2222	2305	2315	2263	2192	2117

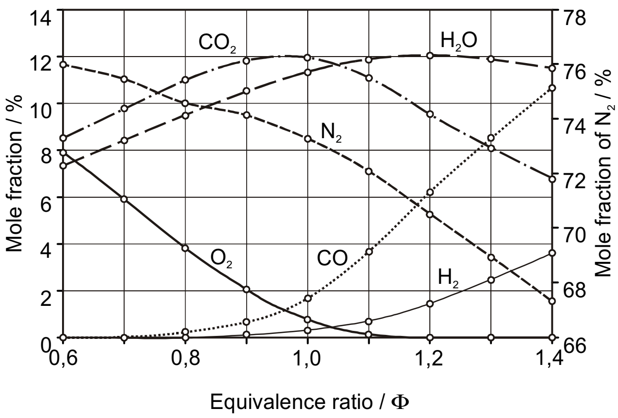

Figure 1. **The major species of equilibrium compositions of the combustion products of light fuel oil as functions of equivalence ratio**

Slika 1. **Glavne komponente ravnotežnog sastava produkata izgaranja lakog loživog ulja u ovisnosti o ekvivalentnom odnosu**

The proportion of either carbon dioxide or oxygen in the furnace gases can be related to the amount of combustion air, which is supplied. Thus measurement of the proportions of these gaseous constitutes can be used to ensure that the fuel is burnt with the optimum amount of excess air. This is illustrated in Figure 1., which shows schematically how the theoretical composition of the furnace gases varies with the amount of combustion air. Basically, the proportion of CO_2 is a maximum under stoichiometric conditions and can decrease due to dilution by excess air or incomplete combustion.

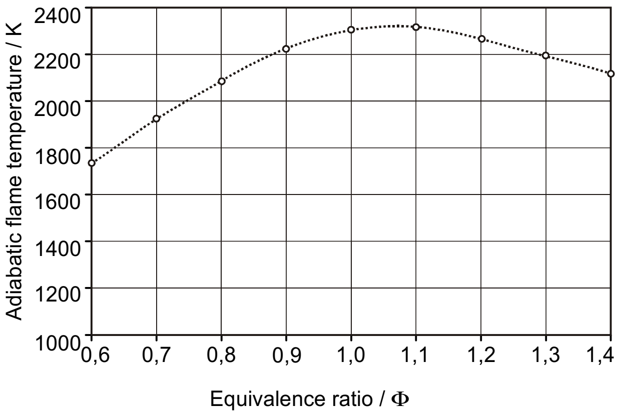

Figure 2. **Effect of equivalence ratio on equilibrium adiabatic flame temperature for light fuel oil**

Slika 2. **Utjecaj ekvivalentnog odnosa na ravnotežnu adijabatsku temperaturu plamena za lako loživo ulje**

As it can be seen from the Figure 2., the adiabatic flame temperature reaches a peak very close to the stoichiometric condition, $\Phi = 1$, slightly on the fuel-rich side. This is due to the fact that when the system is slightly under oxidized, the specific heat of the products is reduced and thus the flame temperature is increased.

DISCUSSION OF RESULTS

According to the first measurements (Table 1.) the presence of carbon monoxide in the flue gases indicates incomplete combustion. The energy losses due to incomplete combustion of the fuel can be avoided by remedying any defect in the burner, by improving by fuel/air mixing and by increasing the amount of excess air. But at the same time in the flue gases was also the significant percentage of oxygen content. On the basis of that fact it was found out that the incomplete combustion could be a consequence of non-adequate exit flue gas velocity under full load operating conditions, i.e., at the maximum burner thermal power. Decreasing the cross-section of flue opening in the furnace structure, for removal of flue gases from the furnace chamber, was resulted in unacceptably high velocities and pressure drops of waste gases. Namely, about seven years ego the flue-opening cross-section had been decreased by about 50 % to minimise the thermal losses with waste gases and radiation through flue opening from the high-temperature furnace chamber. However, it was discovered that during the time the slag from the furnace had been decreasing the flue-opening cross-section by about 80 %.

To ensure the complete combustion process within the furnace chamber, it was necessary to enlarge the flue-opening cross-section so that the natural draught of the furnace chimney overcomes the flow resistant of the furnace-chimney system and can pull the hot combustion gases through the furnace. In principle, the required flue cross-sectional area to achieve a particular velocity must be large enough so that the mass flow rate of the exhaust gases is equal to the sum of the mass flow rates of the fuel and combustion air.

For that reasons the flue-opening cross-section was given back to 50 % of the design cross-section. The results of the second measurements confirmed the rightness of the carried out doings. By extension of the flue opening the temperature of waste gases leaving the furnace was increased by about 170 °C. The higher temperature of combustion products in the furnace chamber decreased the fuel consumption and increased the furnace capacity but the design values have not been achieved.

In order to optimize the furnace efficiency, it is necessary additionally to improve the fuel/air mixing and maintain the correct furnace pressure.

To ensure that all the fuel is burnt in the furnace chamber, it is necessary to supply more air than theoretically required for combustion. The percentage of fuel excess depends upon variables such as the type of fuel and the burner design. Typically, in an industrial furnace an oil fuel can be burnt with 15 to 30 % excess air [7]. Adding more air than enough to complete the combustion process in practice can markedly reduce the maximum obtainable flame temperature. Figure 2. shows the effect of excess air on the theoretical flame temperature for light oil firing. A change in excess air level from 20 to 30 % can result in a reduction of at least 100 °C. This fall in flame temperature can result in a 20 % reduction of radiative heat transfer. Furthermore, adding excess air increases the volume and mass flow rate of the combustion products leaving the furnace chamber so that the energy carried out in the waste gases is thus increased. These are two main factors in reducing the furnace efficiency.

Extra added air also reduces the proportion of carbon dioxide. For that reason, the proportion of either carbon dioxide or oxygen in the flue gases can be related to the amount of combustion air which is supplied. Thus measurement of these species can ensure that the fuel is burnt with the optimum amount of excess air. This is illustrated in Figure 1., which shows schematically how the theoretical composition of the combustion products varies with the amount of combustion air. The proportion of CO_2 is a maximum under stoichiometric conditions and decreases due to dilution by excess air or incomplete combustion. Therefore, for maximum efficiency CO_2 should be as high as possible and CO should be very low within safe limits (max. 0,05 %), i.e. no more than a very slight trace in combustion products that gives complete combustion.

In the furnace equipment there is no monitoring and maintenance of correct furnace pressure at all firing rates which has an influence on increased fuel consumption. However, if the pressure differential between the furnace chamber and surroundings is not correct a great leakage of hot gases from the furnace or infiltration of cold air into the chamber can occur. Monitoring the furnace pressure is usually at heart level. A slightly positive pressure of 2 mm water gauge should be maintained since the leakage effect on furnace performance is usually less serious than that of air ingress. That correct furnace pressure can be achieved by the adjustment of a mechanical damper embedded in the flue system.

CONCLUSION

The productivity and the fuel consumption of furnaces are essential characteristics of their operation, since it reflects all the positive and negative aspects of the design and thermal condition of a furnace. In melting furnace, the productivity depends substantially on the temperature of combustion gases in the furnace chamber. In this paper the effective way how to achieve an essential increase in the temperature of combustion gases of the existing aluminium melting furnace is shown. Applying measuring technique and numerical analysis the combustion process was significantly improved and an increase in the furnace capacity as well as a decrease in the fuel consumption was achieved. At the end it is designated that in order to optimize the furnace efficiency it is necessary additionally to improve the fuel/air mixing and maintain the correct furnace pressure.

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