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E. KOLCZYK*[#], Z. MICZKOWSKI*, J. CZERNECKI*

# NUMERICAL INVESTIGATION OF HEAT EXCHANGE IN ROTARY FURNACE

Process of heat exchange in a rotary furnace during converter slag reduction was modelled.Temperature distribution in the furnace and temperature of the charge (slag) only were examined. Influence of modification of the process gas supply method by changing the number of nozzles on the course of the reduction process was analyzed. It has been found out that application of a nozzle as a submerged flame burner provides possibilities to reach higher charge temperature. Application of more nozzles in the process of converter slag reduction can increase temperature of reduced slag and provide better uniformity of charge heating.

*Keywords:* numerical simulation, heat exchange, rotary furnace, slag reduction process

## 1. Introduction

The innovations in numerical methods resulting from dynamic development of computing equipment and progress in computing technology itself are becoming applied in all fields of engineering. Studying the impact of changes of selected factors on the process characteristics in the CFD (Computational Fluid Dynamics) method makes optimization of the process possible and then, in the result, improvement of efficiency, accuracy and cost savings in materials and energy [1,2].

The technology of oxygen supply into a furnace through nozzles is used in many metallurgical processes. In the literature there are many studies of modeling of flow dynamics in converters. Valencia [3,4] studied movement of a slag layer and bath oscillation. Almaraz [5] analyzed influence of bath height and depth of nozzle immersion. Cui [6,7], Shui [8], Dong [9] presented benefits of this technology in copper production. The main advantages include intense heating in the area of the nozzles and stirring of the charge inside the furnace. It was found out that the required stirring time can be reduced by increase of gas flow velocity and the height of the bath. On the other hand, a longer stirring time is needed as the distance from the nozzle zone increases.

The presented study addressed numerical simulations of heat exchange which occurs during reduction of converter slag in a rotary kiln. The process was conducted in the Hoboken type converter.

Coke, fuel oil or natural gas used interchangeably are the main reducing agents in the converter slag reduction. Coke reduces metal oxides in the slag and covers the slag surface, protecting it from secondary oxidation. The second reducing agents is supplied through the nozzles from the bottom of the charge. In that way, it induces the movement of bath stirring, which increases the rate of occurring reactions. In addition, it supplies energy to the process.

The currently used converter slag reduction process, conducted in the presence of coke and fuel oil supplied through the nozzles along with the air, has been altered to replace the fuel oil with natural gas.

Accordingly, a model comprising a heat exchange process taking under consideration combustion of gas in a nozzle and a reduction reaction at the slag-coke interface was developed. Additionally, influence of modification of the gas supply method by changing the number of nozzles was examined.

## 2. Numerical model of heat exchange in rotary furnace

The numerical model of rotary furnace was developed with application of PHOENICS software.

The model takes under consideration issues of combustion, heat exchange by radiation between the charge of the furnace and the lining as well as between the charged slag and the gas burned in the nozzle and in the burner. The numerical model was solved for a steady state.

The analysed domain had dimensions 9.07 × 4.5 × 4.5 m. The numerical model of rotary furnace contained the following components:

– steel jacket,
– layers of lining,
– lag,
– coke breeze,

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* INSTITUTE OF NON FERROUS METALS, 5 SOWIŃSKIEGO STR., 44-100 GLIWICE, POLAND

[#] Corresponding author: ewa.kolczyk@imn.gliwice.pl

- gas burner inlet and outlet,
- closing bottoms for steel jacket, 2 layers of lining, respectively,
- 3 gas nozzles (Fig. 1).

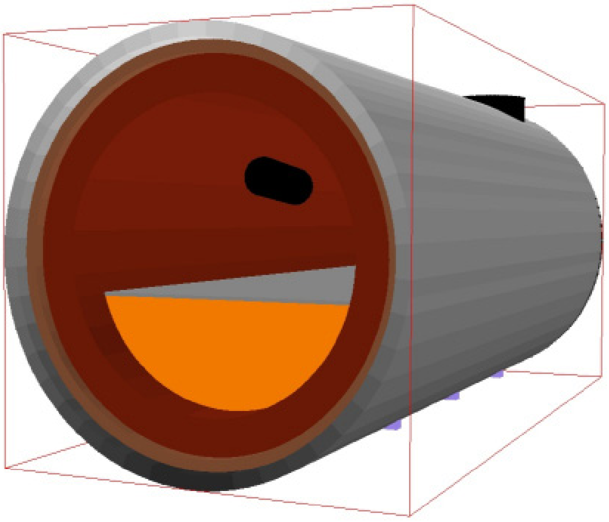

Fig. 1. Model of converter furnace – inside view

The PHOENICS software was used to generate structural grid. The analyzed space in the model of heat exchange in the converter furnace with three nozzles was divided into about 67 thousand differential elements. The number of components along the X, Y and Z axes was 32, 52 and 40, respectively.

The calculations required proper definition of the boundary and material conditions which were introduced into the PHOENICS software along with the initial values of some of the parameters.

The following assumptions were made in the calculations:

- outer jacket of the furnace of constant temperature 200°C, made of steel of the following properties:
  - density 7800 kg/m$^3$,
  - thermal conductivity coefficient 43 W/m deg,
  - specific heat capacity 473 J/kg deg,
- I layer of lining made of chamotte brick of the following properties:
  - density 1800 kg/m$^3$,
  - thermal conductivity coefficient 1.86 W/m deg,
  - specific heat capacity 880 J/kg deg,
- II layer of lining made of magnesia-chrome brick of the following properties:
  - density 2750 kg/m$^3$,
  - thermal conductivity coefficient 0.84 W/m deg,
  - specific heat capacity 800 J/kg deg,
  - emissivity of a surface 0.8,
- liquid slag of the following properties:
  - density 6500 kg/m$^3$,
  - thermal conductivity coefficient 0.15 W/m deg,
  - kinetic viscosity 1.54 m$^2$/s,
  - specific heat capacity 565 J/kg deg,
  - emissivity of a surface 0.6,
- coke breeze of the following properties:
  - bulk density 475 kg/m$^3$,
  - thermal conductivity coefficient 0.8 W/m deg,
  - specific heat capacity 850 J/kg deg,
  - emissivity 0.8 [10,11],
- nitrogen-rich natural gas of the following properties:
  - density 0.84 kg/m$^3$,
  - temperature 20°C,
  - thermal conductivity coefficient 0.02 W/m deg,
  - kinetic viscosity 3.75 × 10$^{-5}$ m$^2$/s,
  - specific heat capacity 1902 J/kg deg,
  - calorific value 37 MJ/kg.

The furnace was fired with nitrogen-rich natural gas GZ 41.5 of chemical composition: 81.88 vol %. $CH_4$; 0.76 vol %. $C_2H_6$; 0.03 vol %. $C_3H_8$; 0.63 vol %. $CO_2$; 16.7 vol %. $N_2$. The combustion occurred at the coefficient of air excess $\lambda = 1$ in the burner and $\lambda = 0.5$ in nozzles.

The gas was supplied to the furnace through the burner located in the bottom and through three nozzles immersed in the liquid slag layer. Natural gas consumption in burner and the nozzles in an amount of 72 + 24 + 24 + 24 Nm$^3$/h, respectively, were considered in the calculations. The ratio of air stream to the stream of the gas supplied to the burner was 8, and it was two times lower for the nozzle.

In the calculations of gas flow above the bath the k-e turbulence model was used. The rate of combustion reaction was assumed according to the Eddy Breakup model (from PHOENICS package), as described by the equation (1):

$$P = -a * \min\left(\frac{m_{fu}, m_{ox}}{s}\right) * \frac{EP}{KE} \tag{1}$$

where:

$s$ – ratio of oxidizer to fuel mass,
$a$ – constant in the equation of rate of reaction, value of 5 was assumed,
$m_{fu}$ – mass fraction of fuel in the mixture of fuel + air + combustion products,
$m_{ox}$ – mass fraction of air in the mixture of fuel + air + combustion products,
$KE$ – kinetic energy of turbulence,
$EP$ – kinetic energy dissipation [12].

The assumed coefficient of emissivity of the gases in heat exchange by radiation was 0.15 [1/m].

While examining the influence of modification of the process gas supply method by changing the number of nozzles three additional numerical models covering the interior of the furnace only were developed.

In all case, the model of the converter furnace was divided into theoretical symmetrical parts depending on the number of nozzles so that each part contained one nozzle. Thus separated parts were used in the numerical calculations. The numerical model of the converter equipped with three nozzles covered 1/3 of the inside length of the furnace and one nozzle located in a central position. The next two models were developed in the same way.

In the model with three nozzles the analyzed domain had dimensions 2.54 × 3.19 × 1.17 m. The numerical model consisted of:

- liquid slag,
- one nozzle – natural gas inlet,
- gas outlet – top layer of slag surface.

The generated in the PHOENICS software structural grid contained about 20.000 differential elements. The numbers of components along the X, Y and Z axes were 19, 50, 21, respectively.

The following heat fluxes were taken under consideration in numerical calculations of heat exchange in a coke-slag-gas system:

- the heat emitted in the result of reduction reaction at the slag – breeze coke interface (350 kW),
- the heat generated in the result of natural gas combustion in a nozzle (150 kW),
- the heat emitted by the furnace charge (slag) to the surroundings through the layers of lining and jacket (178 kW),
- the heat transferred from the charge through one of the closing bottoms, located in the beginning of the domain (9 kW).

## 3. Results of model calculations

When conducting the slag reduction process in a converter a burner is used to heat the charge and the furnace interior, and the nozzles are applied through which the reducer – nitrogen-rich natural gas is supplied.

Fig. 2 presents temperature distribution in the furnace as reached with the gas stream supplied by the burner in an amount of 72 Nm$^3$/h and in each of the three nozzles of 24 Nm$^3$/h. Close to the burner the flue gas temperature is at the level of 1500-1600°C. The heat generated from the fuel combustion in the nozzles is transmitted to the charge but also penetrates into the upper part of the furnace (Fig. 3). Between the charge and the lining and between the flue gas and the lining the heat exchange occurs by radiation. Between the charge and the lining the heat is transferred also by conduction.

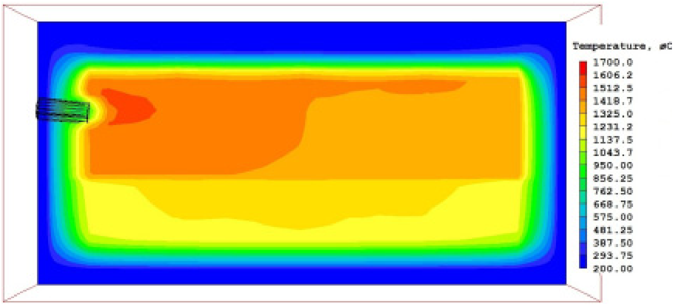

Fig. 2. Temperature distribution in furnace fired by burner and nozzles

The temperature distribution in the charge is shown in Fig. 4-5. Initial slag temperature of 1100°C increases with the time of the reduction reaching in the final stage the temperature in the range1176-1222°C. The highest temperatures is in the area of nozzles and in the upper layer, where the reduction reactions occur. Lower slag temperatures are observed at the edges of slag charge due to heat dissipation by conduction from the slag to the layers of lining and steel jacket. The lowest temperatures are observed in the bottom area.

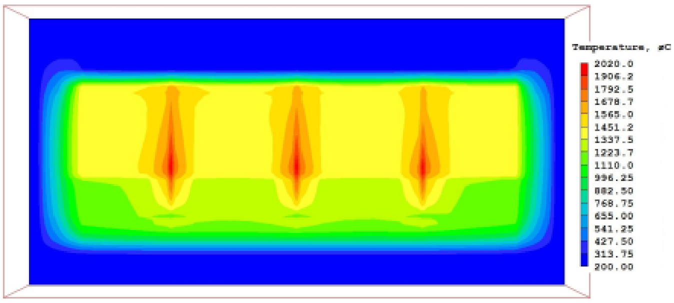

Fig. 3. Temperature distribution in furnace in the area of nozzles

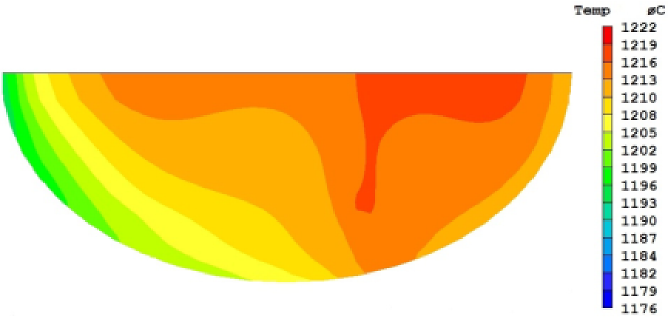

Fig. 4. Slag temperature distribution in the middle of a domain in the system of 3 nozzles in the cross-section

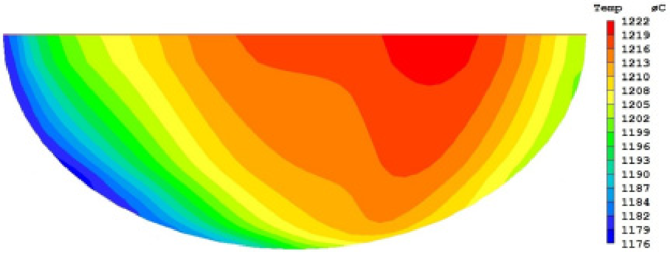

Fig. 5. Slag temperature distribution in the beginning of a domain in the system of 3 nozzles in the cross-section

In order to estimate the average temperature in the charge and to compare its values in various variants of the furnace firing, it was analyzed in vertical planes XZ and in selected heights - coordinate Z (Fig. 6).

Fig. 7 shows changes of the slag temperature along the central plane of Y = 1.59. The highest temperatures of 1219°C at a height of 1.13 m is reached in the distance of 2.5 m from the bottom, and the lowest 1210°C on the border of slag and the lining at a height of 0.2 m.

The temperature distribution in the plane Y = 0.88 (Fig. 8) is similar. The highest temperature 1221°C is observed at a height

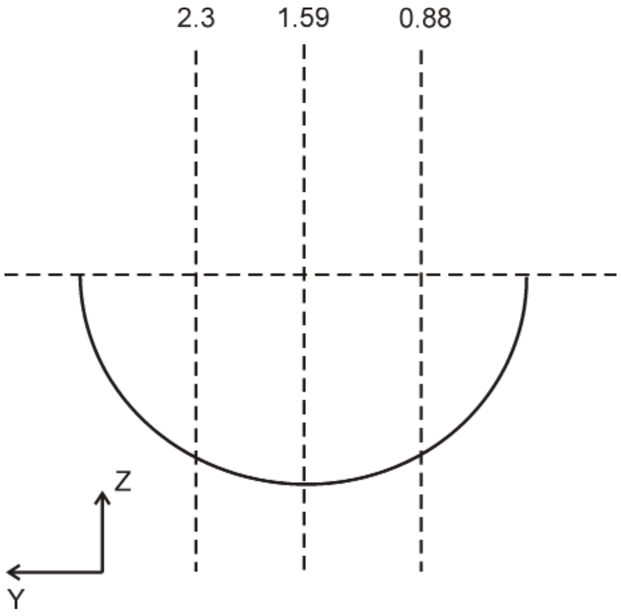

Fig. 6. Planes of cross-section

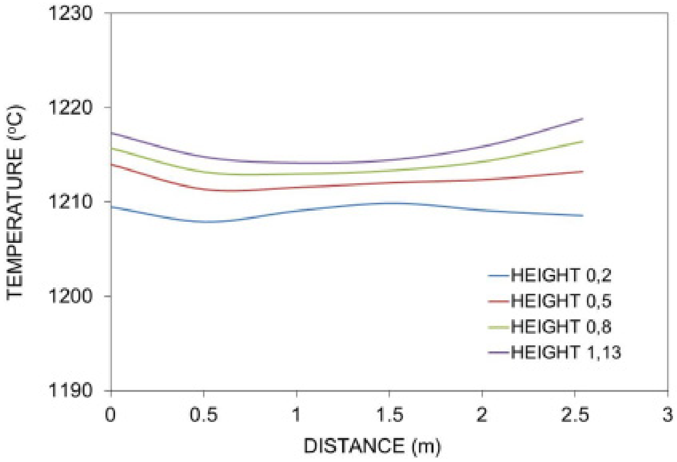

Fig. 7. Course of slag temperature in the system of 3 nozzles in the plane Y=1,59

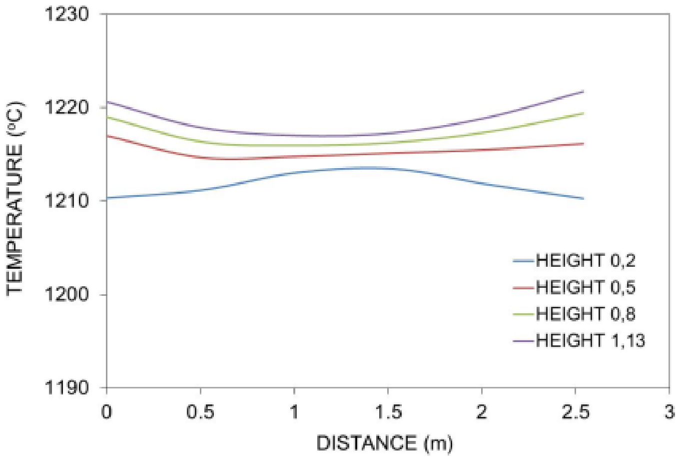

Fig. 8. Course of slag temperature in the system of 3 nozzles in the plane Y = 0,88

of 1.13 m, i.e. where the reduction process occurs at the slag-coke breeze interface, resulting in generation of heat which is then transferred to the charge interior.

In the case of extremely distant from the nozzle plane Y = 2.3 the slag temperature reaches lower values when compared to the previous ones (Fig. 9), at the level of 1185-1216°C. The graph clearly shows influence of the heat supplied through the nozzle, as the temperature increases rapidly reaching maximum values in the range 1204-1216°C and then drops, which is precisely illustrated by isotherms (Fig. 5).

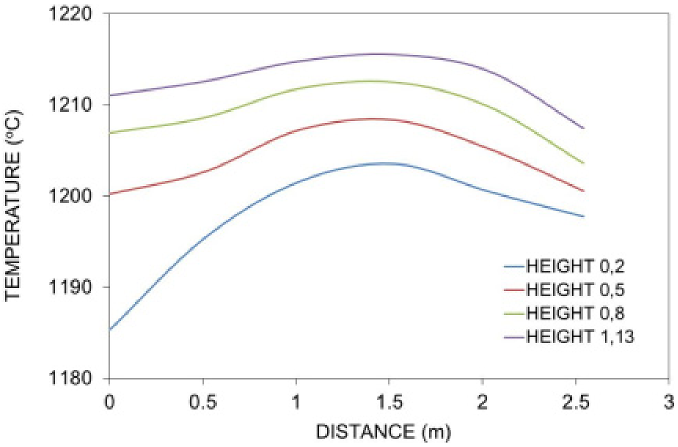

Fig. 9. Course of slag temperature in the system of 3 nozzles in the plane Y=2,3

In the same way analyses of the models with two and four nozzles were made.

On the basis of the produced temperature distribution curves the average temperature of the slag, depending on the furnace firing method, were determined (Fig. 10).

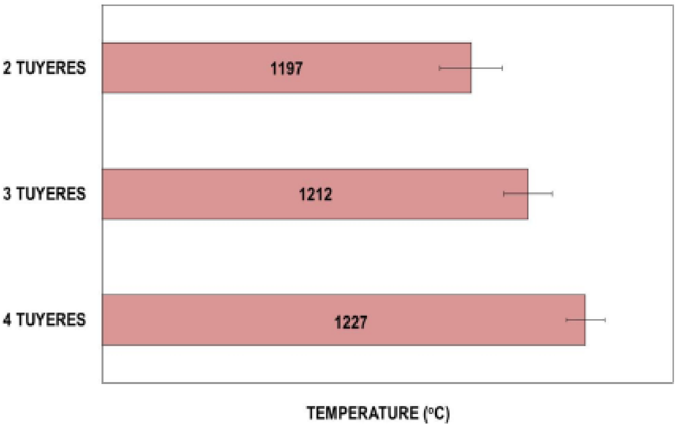

Fig. 10. Average slag temperature dependence on the furnace firing method

In the analyzed above numerical models of converter slag reduction process the initial slag temperature of 1100°C was assumed. After 2 hours of the reduction process the temperature of the slag increased in each of the analyzed situations to the required temperature – at the level of 1200°C.

In order to ensure proper coagulation and sedimentation of process products when natural gas is used the process temperature needs to be increased. It is therefore important to introduce a mixture of natural gas and air into the nozzles so that the nozzle acts as a submerged flame burner and generates additional heat flux, thereby increasing the final temperature of the slag.

The highest average slag temperature of 1227°C with a standard deviation of 4.99 was reached when the furnace was fired with four nozzles. When firing the kiln with two nozzles the slag temperature was the lowest – 1197°C with a standard deviation of 8.25.

Slag becomes more intensely heated when more nozzles are used for furnace firing. Larger number of nozzles operating during the reduction process provides also better uniformity of charge heating. This is confirmed by calculations of the standard deviation for each of the discussed cases.

## 4. Conclusions

The study presents results of numerical calculations of heat exchange in a rotary kiln during the process of converter slag reduction. The modeling was used in calculations to examine the distribution of temperature in the entire furnace space and in the slag only. The influence of modification of the gas supply method by changing the number of nozzles on the course of the reduction process was also analyzed.

The performed calculations and analyses made drawing of the following conclusions possible:

When running the process of converter slag reduction with application of three nozzles operating as submerged flame burners, and when each of them is supplied with 24 [Nm$^3$/h] of natural gas with air, the reached temperature of the slag was in the range of 1176-1222°C (1212°C on average).

In the analysis of the influence of modification of the gas supply method by changing the number of nozzles it was found out that the highest average slag temperature of 1227°C with a standard deviation of 4.99 was reached in the furnace equipped with four nozzles, while the lowest – 1197°C with a standard deviation of 8.25 when the furnace was equipped with two nozzles.

Application of a larger number of nozzles taking part in the furnace firing during the converter slag reduction process results in a higher temperature of the reduced slag and more uniform charge heating.

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