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# AN EXPERIMENTAL GASODYNAMIC STUDY OF A MODEL OF FURNACE FOR FERROALLOY PRODUCTION

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A gasodynamic study of a model of hood space was performed based on measurements of velocity and concentration distributions of gases. The experiments have shown that the absolute values of gas velocities in the hood and the outlet channel as well as their profiles do not depend on the negative pressure value in the channel. Location of ceiling nozzle outlets does not significantly affect the gasodynamic parameters of the hood space. Moreover, uniform distribution of the air, delivered through the ceiling nozzles, has been observed in the whole hood space, which creates conditions for afterburning of gaseous reaction products in this space.

*Key words:* ferroalloy/silicon, furnace, model, velocity of gases, distribution of gases

## INTRODUCTION

Ferrosilicon smelting is one the most energy-consuming electrothermal processes. In submerged-arc furnaces utilised in our country (furnaces meant for production of high silicon and silicon metal alloys in particular), significant amounts of energy (about 50 % of the energy delivered to the process, i.e. electrical energy and chemical energy of carbon reducers) are lost when gases leave the working space of the furnace [1].

Leakiness of these furnaces leads to atmospheric air being sucked in the amounts that markedly exceed the stoichiometric demand for complete combustion of waste gases that are generated during the technological process (mainly CO and SiO) in the working space of the furnace. As a result, the temperature of gases in exhaust collectors is low (about 350 °C), which hampers effective recovery of their waste energy. Energy balance of the industrial furnace has shown that sealing the furnace leaks and delivering the air in a controlled way to the hood space, where conditions for complete combustion of burnable components with the optimal amount of excessive air are created, will ensure higher temperatures of exhaust gases: even about 850 °C [1-5]. Such high-temperature exhaust gases can be utilised for heating compressed air in recuperators up to above 700 °C and, thus, a high-temperature operating medium for electrical energy production in a system combined with a gas turbine can be obtained [2].

The aim of this experimental study was a search for optimal methods of air delivery to the furnace to ensure the best conditions for post-reactive gas combustion in the hood space. In the experimental study on the effects of design characteristics, the most important parameters regarding gasodynamics in the hood space were considered: a gas stream delivered through technological windows, gas velocity distribution at the ceiling nozzle outlets, pressure distribution in the hood, effectiveness of gas blending in the hood space. In order to verify the accuracy of performed calculations, the extent to which results of the study on an isothermal, physical model can be reproduced by its corresponding, simulated model through mathematical modelling has been examined.

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## MEASUREMENT STATION

In a modernised furnace hood design, it has been assumed that combustion air will be forced through 6 ceiling nozzles, 3 nozzles around the electrodes and 4 nozzles in charges in amounts that ensure the air excess value of $\lambda_l$ = 1,2. The remaining air will be sucked by the technological windows and, as a result, gas generated during the technological process will be combusted, with the total air excess value of $\lambda_c$ = 3,0, within the hood space. A stream of gases generated during the technological process (the technological gas), $\dot{V}_t$, was calculated based on the experimental data obtained from a real object [1]. Consistently with the physical modelling principles, calculations were performed and the measurement station was designed whose main section is a cylindrical, Plexiglas, 1 : 9 model of the furnace hood (750 mm in diameter and the height of $H$ = 310 mm) with components that simulate devices fixed in a real object: electrodes, charges, ceiling nozzles and technological windows. The measurement station is presented in Figure 1. Regarding the hood, the gas delivery and exhaust systems were coupled with necessary equipment for gas stream measurement and control devices.

Gas streams for specific nozzle systems in the model, presented in Table 1, were calculated based on a cri-

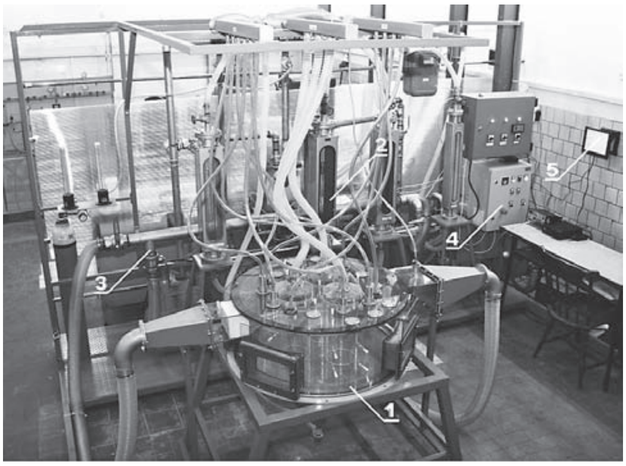


**Figure 1** The measurement station: 1 – the model of furnace hood, 2 – the gas delivery system, 3 – the gas exhaust system, 4 – the control devices, 5 – the system of data collecting and processing

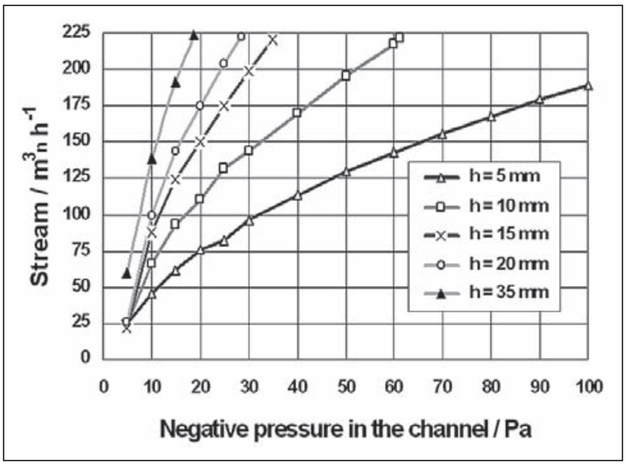


**Figure 2** The stream of sucked air, $\dot{V}_{m}$, versus the negative pressure in the channel

Table 1 **Gas streams in the model**

| Gas delivery place | Type of gas | Designation | Gas stream / $m_n^3$ $h^{-1}$ |
|---|---|---|---|
| Ceiling nozzles | Air + CO | $\dot{V}_{str}$ | 73,4 |
| Nozzles around electrodes | Air + CO | $\dot{V}_{e}$ | 49,7 |
| Nozzles in charges | Air + CO | $\dot{V}_{zas}$ | 14,2 |
| Process gas | Air + CO | $\dot{V}_{t}$ | 32,7 |
| Technological windows | Air | $\dot{V}_{m}$ | 206,0 |

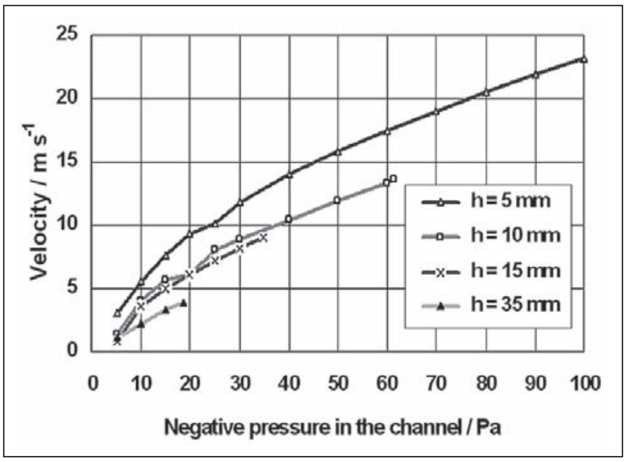


**Figure 3** Air velocities in the technological windows versus the negative pressure in the outlet channel

terion of similarity to correspondent streams in the real object. The pipe system in the air installation ensures that clean air or air with additives can be delivered to the collectors of any nozzle types. Through the ceiling nozzles, nozzles around the electrodes and nozzles in charges, air with small amounts of carbon monoxide was delivered, while the technological gas was simulated also with small amounts of carbon monoxide. In both cases, CO or $NO_2$ concentrations in the mixtures were several hundred ppm.

## A STREAM OF SUCKED AIR

A technological process with controlled amounts of excess air is only possible if the amount of air delivered to the working space of the furnace is known. Therefore, determination of the relationship between the stream of sucked air and the negative pressure in the outlet channel is important when the algorithm of automatically controlled opening of the window apertures, meant for charge material stirring, is developed.

In Figure 2, results of the investigations of relationship between the stream of sucked air, $\dot{V}_{m}$, and the negative pressure measured in the measuring point placed in the outlet channel of the hood, while in Figure 3, corresponding air velocities in the technological window openings are presented. The tests were performed for various heights of the technological window openings: from $h$ = 5 mm (3,8 % of the window total surface area) to $h$ = 35 mm (26,9 % of the total surface area). The nominal value of the stream of sucked air, $\dot{V}_{m}$ =206 $m_n^3$/h, is achieved when the negative pressure in the channel is $p_{kan}$ = 56 Pa and the aperture height is $h$ = 10 mm as well as when $p_{kan}$ = 17 Pa and $h$ = 35 mm. Air velocities change from 5 m/s, when the negative pressure in the outlet channel is about 5 Pa, to 23 m/s for 90 Pa.

## VELOCITY DISTRIBUTIONS AT THE OUTLETS OF CEILING NOZZLES

The total stream of gases sucked out of the hood space is 376 $m_n^3$/h; it is a sum of gas streams delivered to the hood (Table 1). In order to determine the media stream parameters in the model of the furnace hood, a similarity criterion for the pressure values in the technological windows (equality of Euler's numbers) [6] in the real object $Eu_r$ and the research station $Eu_m$ was applied, so for the technological windows:

$$\left(\frac{\Delta p}{\rho \cdot w^2}\right)_{\mathrm{r}} = \left(\frac{\Delta p}{\rho \cdot w^2}\right)_{\mathrm{m}} . \qquad (1)$$

For technical reasons, it was assumed that $\Delta p_r = \Delta p_m$ and $\rho_r \cong \rho_m$ (which is due to the fact that, in both cases, cold air is sucked through the technological windows);

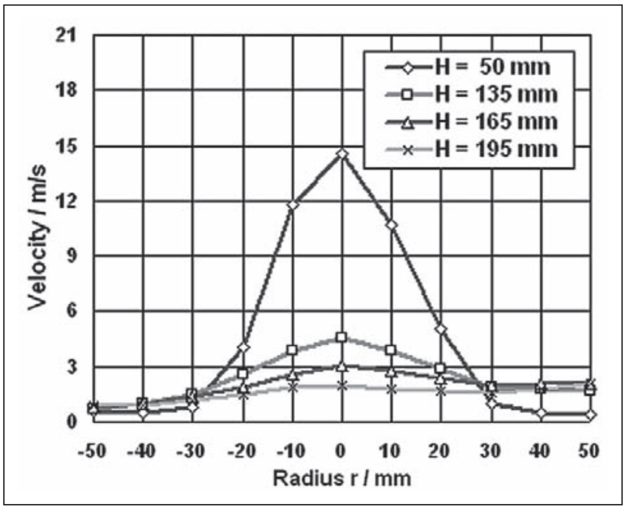


**Figure 4** Air velocity distribution at the ceiling nozzle outlet

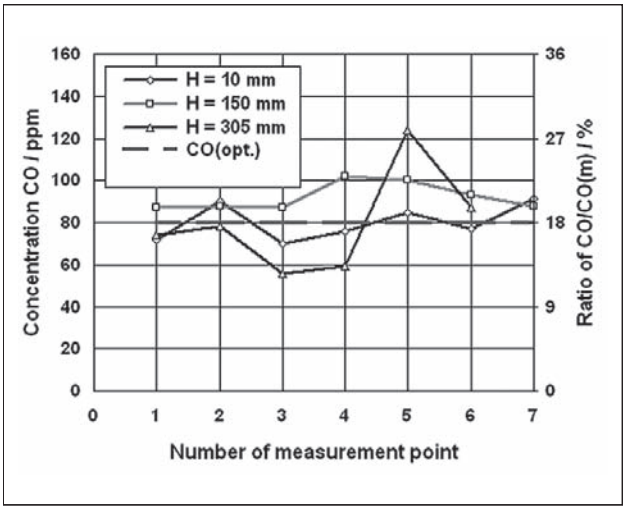


**Figure 5** A distribution of CO concentrations in the hood when a mixture of CO and air is delivered at $w_{str}$ = 15 m/s through the ceiling nozzles located at the ceiling surface ($H$ = 0)

therefore, the $Eu_r = Eu_m$ condition means equal velocities in the real object and the model of the furnace, $w_r = w_m$. In the real object (furnace) meant for production of ferroalloys, air of the ambient temperature flows into the furnace space where the temperature is about 1000 °C. In the model of furnace, cold air flows into the space where gases are also of the ambient temperature. This qualitative difference can be corrected by proper adjustment of nozzle diameters with the use of the Thring-Newby parameter [7] according to the equation:

$$d_{rz} = d_m \cdot \left(\frac{\rho_m}{\rho_{rz}}\right)^{1/2}. \quad (2)$$

The investigations of radial and axial velocities of the air at the ceiling nozzle outlets, using ceiling nozzles of various diameters, were performed with nominal streams of gases delivered to the nozzles of specific types and stable, nominal air stream, $\dot{V}_m$ = 206 $m^3_n$/h, sucked through the technological windows. The investigations of velocity distributions were performed for various technological window openings and three diameters of the ceiling nozzle. A sample velocity distribution is presented in Figure 4. Radial velocity profiles are symmetric with the outlet axis. The investigated ceiling nozzle was placed not far from the technological window meant for sucking the outside air. Thus, it may be assumed that location and design of the ceiling nozzles ensure generation of the air stream of properly high velocity, which allows for a symmetrical velocity distribution.

## INVESTIGATIONS OF GAS BLENDING IN THE HOOD SPACE

The investigations of gas blending were performed based on analyses of chemical compositions in various points of the hood space when a mixture of gases was delivered to the hood through nozzles of specific types or a system that simulated the technological gas. The analysis was performed when air with CO addition was delivered to the investigated nozzle type, while the other nozzles were supplied with clean air. CO(m) values, presented in the figures, correspond to carbon monoxide concentrations measured in a pipe delivering a mixture of the air and CO to the analysed nozzle type. These concentrations are only slightly different from the values that were calculated based on measured streams of mixed gases. The CO/CO(m) ratio shows a percentage of gas, delivered through the nozzles of analysed type, that reaches a given point in the hood space. In the figures, CO(opt) indicates a carbon monoxide concentration that was calculated as a ratio of pure CO delivered to the system to the total amount of air delivered to the hood (also through the technological windows) with the assumption of optimal blending of these two components.

The investigations of effectiveness of the air (delivered through the ceiling nozzles) blending were presented for two nozzle outlet locations:

- at the surface of the hood ceiling ($H$ = 0) for: $\dot{V}_{str}$ = 73.4 $m^3_n$/h, $\dot{V}_{CO}$ = 0,030 $m^3_n$/h (CO(m) = 440 ppm) – the results are presented in Figure 5;
- at the distance of $H$ = 50 mm from the ceiling surface for: $\dot{V}_{str}$ = 73,4 $m^3_n$/h, $\dot{V}_{CO}$ = 0,03 $m^3_n$ /h (CO(m) = 440 ppm) – the results are presented in Figure 6.

A distribution of measurement points in the hood of the furnace was presented in paper [8]. In both cases, a $D$ = 16 mm diam. nozzle was utilised, which resulted in the nozzle outlet velocity of $w_{str}$ = 15 m/s with the nominal air stream of $\dot{V}_{str}$ = 73,4 $m^3_n$/h. The largest air stream is delivered to the hood from forced draught fans and, then, through the ceiling nozzles, and its average fraction in the hood gases is 18 %. The investigations have revealed that location of the ceiling nozzle outlets has no effect on the pattern of CO concentration distributions, which can be observed by comparing the line patterns in the presented figures. In Table 2, CO concentra-

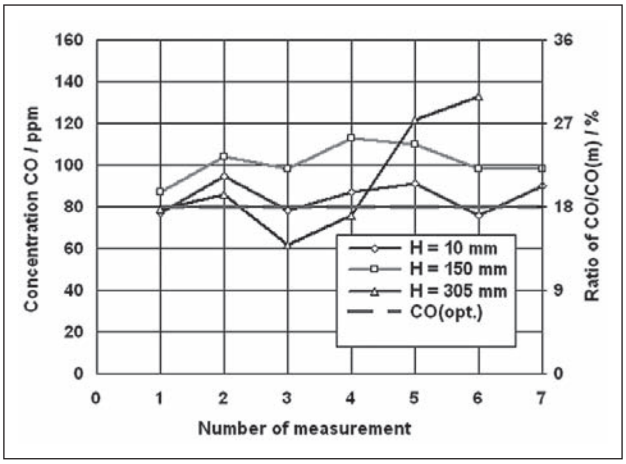


**Figure 6** A distribution of CO concentrations in the hood when a mixture of CO and air is delivered at $w_{str}$ = 15 m/s through the ceiling nozzles located at $H$ = 50 mm from the ceiling

tions, calculated as the arithmetic averages of values obtained from all measurement points and measured at a constant distance from the ceiling surface as well as an average value of the concentration in the outlet channel are presented.

Table 2 **Average CO values (ppm) for the planes within 10, 150 and 305 mm distance from the ceiling as well as in the outlet channel**

| Distance from the ceiling | Location of ceiling nozzles | |
|---|---|---|
| | *H* = 0 mm | *H* = 50 mm |
| 10 mm | 78,3 ppm | 82,3 ppm |
| 150 mm | 95,0 ppm | 101,8 ppm |
| 305 mm | 81,3 ppm | 93,0 ppm |
| Outlet channel | 89,6 ppm | 94,4 ppm |

## CONCLUSIONS

- The air sucked by the technological windows has a negligible effect on the profile and values of measured velocities of air delivered through the ceiling nozzles.
- The absolute values of gas velocities in the technological windows and their profiles do not depend on the negative pressure values in the channel.
- Location of ceiling nozzle outlets does not significantly affect the gasodynamic parameters of the hood space.
- The study has shown that suggested location of the ceiling nozzles ensures uniform distribution of the delivered air in the whole hood space, which creates conditions for nearly complete afterburning of the reaction products.

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**Note:** The responsible translator: Olga Rachowska-Siwiec, Katowice, Poland