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A Model of Gas Injection into a Blast Furnace Tuyere

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ABSTRACT

One way to further utilize produced gases in an integrated metallurgical plant is to replace oil or coal with gas as a reducing agent in a blast furnace. Therefore, it is of great interest to study the injection of reducing gas into the blast furnace. A fundamental three-dimensional mathematical model has been developed where the injection of the gas by lances into the tuyere is simulated. The model includes the coupled solution of the flow field and the combustion reactions of the gases inside the tuyere. The combustion reactions are modeled using a simple reaction scheme with three possible reactions that can occur. Two different types of fuel gas have been modeled, namely coke oven gas (COG) and basic oxygen furnace gas (BOF). The influence of the following parameters on the predicted velocities, temperatures and composition of the gas at the tuyere outlet are examined in this study: i) comparison between the two types of gases using one injection lance, ii) injection amount of coke oven gas, iii) the use of one or two injection lances, and iv) the influence of the injection angles when using two injection lances. The modeling technique is presented and discussed as well as the implied results.
The results show that the coke oven gas is combusted more completely than the BOF gas, which leads to higher flame temperature of the blast. Furthermore, the combustion conditions are better when using two injection lances compared to when using one injection lance and the predicted results are not affected to a large degree when the injection angles are changed. The modeling of the raceway is so far not included in the model, hence the influence of the outlet boundary condition at the tuyere is not reflected in the presented results.

Keywords: Blast furnace, tuyere, modeling, gas injection, CFD.

INTRODUCTION

One way to further develop the utilization of available gases, for example coke oven gas and basic oxygen furnace gas, in an integrated metallurgical plant would be to study the injection of these gases into the blast furnace. The flexibility of the gas utilization will be enhanced as gas can be moved between the blast furnace and some other user of the available gas, depending on the need at the moment. Thus, the gas injected into the blast furnace substitutes alternative reducing agents that have to be purchased from external sources [1].
Trials with gas injection into the blast furnace were done in the USA in the middle of the 1990s. In a paper by D.H Wakelin et al. [2] and J. Agarwal et al. [3] the possibility for high natural gas injection was investigated. This was done in order to meet the demands for higher hot metal productivity. Also, F.L Maddalena et al. [4] described one trial in USA where natural gas injection was replaced with coke oven gas injection.

Model Development

To increase the knowledge concerning the injection of reducing gas into the blast furnace a fundamental mathematical model of the tuyere system has been developed. The model has been used to study the influence of injection of different gases, COG and BOF gas, into the blast furnace tuyere. The model predicts the velocity, temperature and composition of the hot gas leaving the tuyere.
Focusing on coke oven gas as the reducing agent, the mathematical model has also been used to study different injection amounts of the coke oven gas. The gas amount has varied between 5 000 to 20 000 nm^3, which lies within the range of desired reducing gas amount for a production blast furnace that produces 1 500 to 2 000 tones per day. The effect of injecting the gas using one and two injection lances respectively was reported. Furthermore, the effect of changing the injection angle of the lances on the predicted velocity, temperature and composition data of the blast is also studied.

MODEL DESCRIPTION

An outline of a typical tuyere lance system is shown in **figure 1**. It includes one or two injection lances which are inserted into the blast pipe, a blast pipe and a copper tuyere.

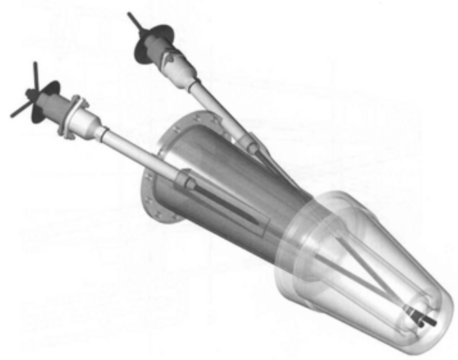
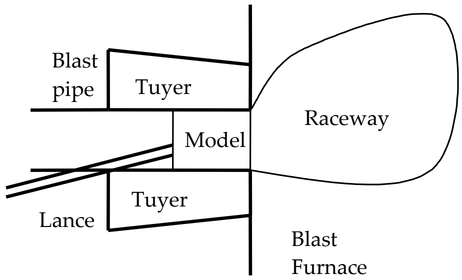


Figure 1 An overview of the tuyere lance system with injection lances. [5]

The model includes the coupled solution of the flow field and of the chemical reactions of the reducing gas in the tuyere. The tuyere and the injection lance are modeled using a body-fitted coordinate system (BFC) in three dimensions and the model is independent of time, i.e. steady state. The following assumptions have been made in the statement of the model:

- The thermal radiation in the tuyere has not been taken into account.
- The studied system is adiabatic, i.e. there is no heat losses included in the model.
- Only the inside of the tuyere behind the lance is modeled, i.e. the conditions in the raceway do not influence the results, beside the blast furnace pressure.

Based on the above mentioned assumptions for modeling the chemical reaction of the reducing gas in the tuyere, the governing transport equations have been stated. The governing equations are conservation of mass, momentum and thermal energy. The turbulence is described in three dimensions by the standard k-ε turbulence model [6, 7].



A principal sketch of the modeled region in the tuyere with one injection lance is shown in **figure 2**.

Figure 2 A two dimensional sketch of the modeled region in the tuyere.

The boundary conditions of the mathematical model include the region of integration, which is shown in **figure 3**. The figure shows the region in three dimensions and it consists of an inlet for the blast, inlets for the reducing gas, a tuyere wall region, and a tuyere outlet into the blast furnace.

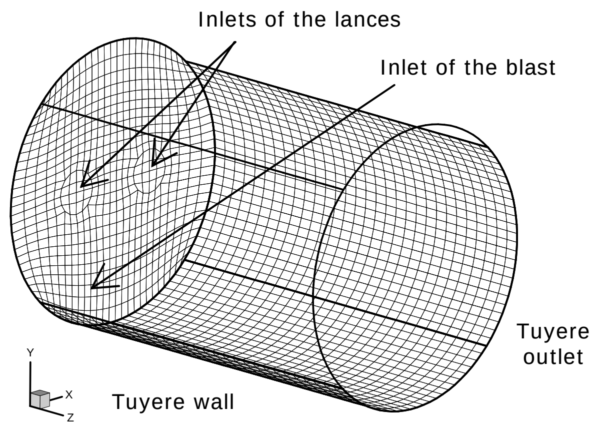


Figure 3 The region of integration

The geometry of the model is:

- The lance inlet has a diameter of 0.022 m.
- The inlet for the blast has a diameter of 0.14 m.
- The total length of the model is 0.20 m.

The reducing gas used in the simulation is gas from the basic oxygen furnace (BOF) and from the coke oven plant (COG). The composition of the BOF gas, the coke oven gas, and the blast is shown in **table 1**.

Table 1 Gas compositions

Component	BOF gas [Vol %]	COG gas [Vol %]	Blast [Vol %]
Nitrogen, N_2	27.9	3.9	76.2
Carbon dioxide, CO_2	14.7	1.3	-
Carbon monoxide, CO	55.3	6.3	-
Methane, CH_4	0.6	24.1	-
Hydrogen, H_2	1.0	62.9	-
Oxygen, O_2	-	-	23.8
Steam, H_2O	0.5	0.5	-

As can be seen in **table 1** additional oxygen is added to the blast. The thermodynamic and physical properties of the gas mixture are calculated using data from Robert J.Kee, at al. [8]. The properties for different temperatures are calculated using coefficients in an arbitrary-order polynomial for each element

Combustion Modeling

The chemical reactions were modeled using the Extended Simple Chemically Reaction System (ESCRS). It is a combustion model for gases available within the CFD software PHOENICS [9]. The chemical reactions are modeled by a finite-rate chemistry model using the eddy-break-up model [10] (EBU model) for calculating the rate of the reactions. The data to the combustion model are read from the thermodynamic database CHEMKIN [8]. The two-step reaction scheme used in the finite-rate model, were assumed to be:

- $2CH_4\ (g) + O_2\ (g) \rightarrow 2CO\ (g) + 4H_2\ (g)$ (1)
- $2CO\ (g) + O_2\ (g) \rightarrow 2CO_2\ (g)$ (2)
- $4H_2\ (g) + 2O_2\ (g) \rightarrow 4H_2O\ (g)$ (3)

The reactions are preceded in one direction. The primary reaction, equation (1), is the combustion of CH_4 with H_2 and CO as intermediate products. Equation (2) and (3) are the two secondary reactions, i.e. the combustion of the intermediate products to the final products CO_2 and H_2O. The reaction rate can be described in several ways within the frame of the EBU model, depending on the used reaction scheme. In this research, where there are two competing reactions for the same oxidizer, the reaction rate is described as:

$$R = C_1 \cdot \min\left[\frac{M_f}{s}, \frac{M_f \cdot M_o}{(M_f \cdot s + M_{f2} \cdot s_2)}\right] \cdot \rho \cdot Vol \cdot \frac{\varepsilon}{k} \qquad (4)$$

where C_1 is the EBU constant which has a default value of 4.0. The variables M_f, and M_o are the mass fractions of ‘fuel’ and ‘oxidizer’, s is the stoichiometric requirements.

The min argument, in equation 4, implies that the reaction rate is dependent on the species in the shortest supply. The variable s_2 is the stoichiometric requirement for the second reaction involving the fuel species M_{f2}. The data for the reaction enthalpy of the reactions are listed in **table 2**.

Table 2 Thermodynamic data used in the mathematical model

Reactions	**Reaction enthalpy at 298 K**, [MJ/kmol]
$2CH_4$ (g) + O_2 (g) → 2CO (g) + $4H_2$ (g)	- 71.3
2CO (g) + O_2 (g) → $2CO_2$ (g)	- 564.9
$2H_2$ (g) + O_2 (g) → $2H_2O$ (g)	- 483.6

RESULTS AND DISCUSSION

The main focus in this study is to model the effect of different parameters concerning the injection of reducing gas into a blast furnace. First, two different types of reducing gas, COG and BOF gas, have been modeled using one injection lance. Thereafter, the effects of varying the amount of the injected gas, coke oven gas, on the conditions at the tuyere outlet have been studied. Injection using one or two injection lances has been studied. Also, the influence of varying the injection angle of the lances, when using two injection lances, on the predicted results has been studied. The predicted result is presented as blast properties such as temperature, velocity, and composition of the blast, at the end of the tuyere.

BOF and Coke Oven Gas

A comparison of injecting BOF gas and coke oven gas into the tuyere has been done. The BOF gas mainly consists of CO, CO_2 and N_2 as **table 1** shows. The compound CO_2 is the final product in the reaction scheme, so the reaction most frequently occurring is the combustion of CO to CO_2, equation (2). Compared to coke oven gas, which consists of CH_4, CO and H_2, all of the reactions in the reaction scheme, equation (1) - (3) are included. The coke oven gas has a higher heating value (a larger negative reaction enthalpy) and will thus react faster than the BOF gas. **Figure 4** shows the mean temperature rise in the tuyere pipe for both BOF gas and coke oven gas.

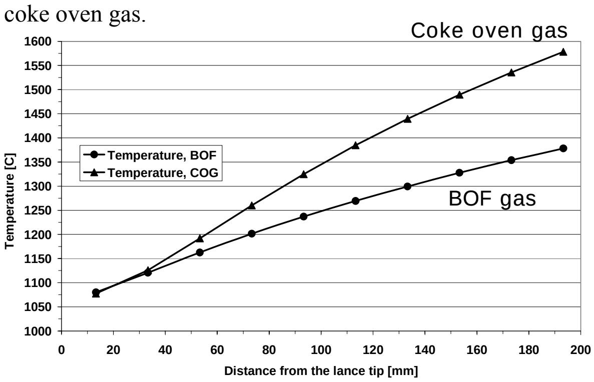


Figure 4 Mean temperature as a function of distance inside the tuyere pipe for BOF gas and coke oven gas

As the figure shows, the mean temperature rise is higher for coke oven gas than for BOF gas at the end of the tuyere, 1578 °C to 1378 °C. The mean velocity is shown in figure 5.

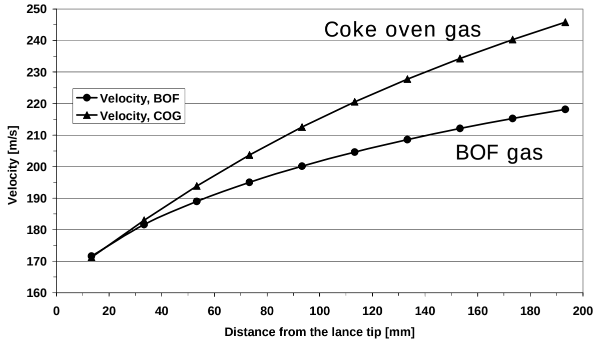


Figure 5 Mean velocity as a function of distance inside the tuyere for BOF gas and coke oven gas

As can be seen in **figure 5**, the mean velocity in the tuyere is higher for the coke oven gas than for the BOF gas, 246 m/s and 218 m/s, respectively. Note, that the mass flow for the BOF gas is higher than for the COG, since the BOF gas density is higher.

One or Two Injection Lances

The injection of coke oven gas has been modeled when using one and two injection lances. The injection rate of the reducing gas flow was varied between 5 000 to 20 000 nm^3/h in seven steps. The minimum volume flow, 5 000 nm^3/h, corresponds to a mass flow of 0.032 kg/s of coke oven gas and an inlet gas velocity of 64.5 m/s in the lance. The maximum volume flow, 20 000 nm^3/h, corresponds to a mass flow of 0.128 kg/s and a gas velocity of 257.8 m/s in the lance.

The mean temperature of the blast <u>at the end of the tuyere</u> for one injection lance is plotted versus the coke oven gas flow in **figure 6**. It can be seen under the simulated conditions that the mean temperature of the blast has a peak when injecting 10 000 nm^3/h of coke oven gas. Injection of more gas than 10 000 nm^3/h will result in a lower mean temperature, due to insufficient combustion.

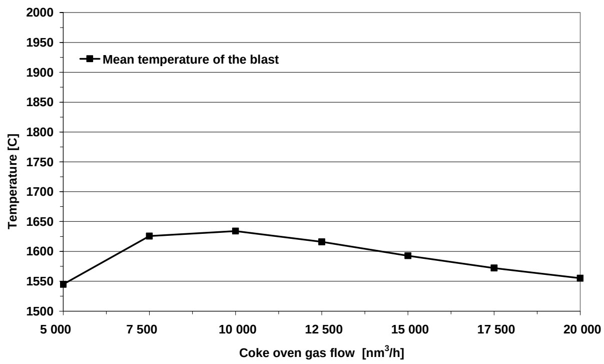


Figure 6 Mean temperature of the blast versus coke oven gas flow at the end of the tuyere pipe for a system with one injection lance

The mean temperature in the blast is plotted versus the coke oven gas flow in **figure 7**.

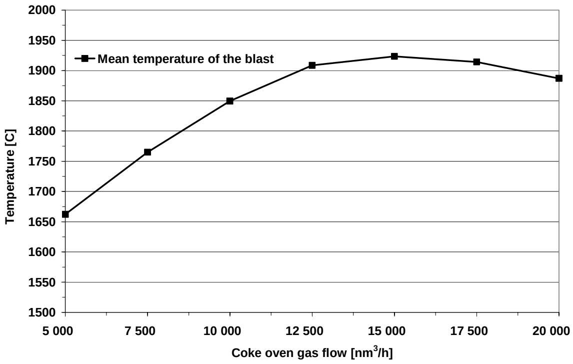


Figure 7 Mean temperature of the blast versus coke oven gas flow at the end of the tuyere pipe for a system with two injection lances

As shown in **figure 7**, the mean temperature of the blast has a peak when injecting 15 000 nm^3/h of coke oven gas using two injection lances. Injection of more coke oven gas in the tuyere will also reduce the mean temperature of the blast. By comparing **figure 6** and **figure 7** it can be seen that there are big differences in the temperature levels for the two cases. More specifically, it differs about 270 °C for the maximum blast temperature. **Figure 8** shows the velocity profile for a velocity of 200 m/s in the blast for both cases.

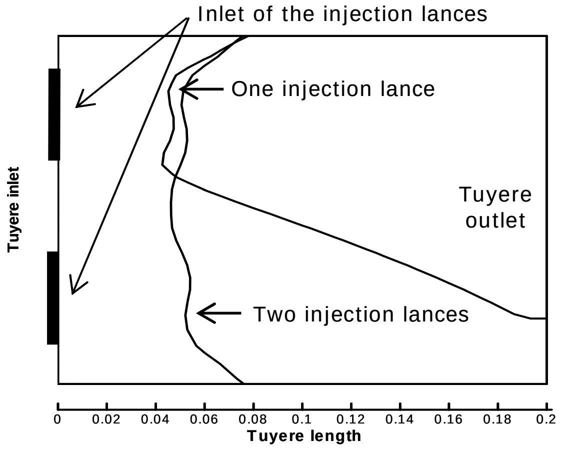


Figure 8 Comparison of the velocity profile for one and two lances at 200 m/s in the blast (Coke oven gas flow, 5 000 nm^3/h)

As can be seen in the figure, the velocity profile is much more uniform when using a two-lance configuration compared to a single-lance configuration.

Injection Angle

The effect of the injection angle of the lance, in relation to the tuyere axis, on the predicted gas conditions at the tuyere outlet has also been studied. A series of simulations have been performed where the angles of the lances were changed partly based on practical experience. An illustration of the different lance angles which have been modeled is shown in **figure 9**.

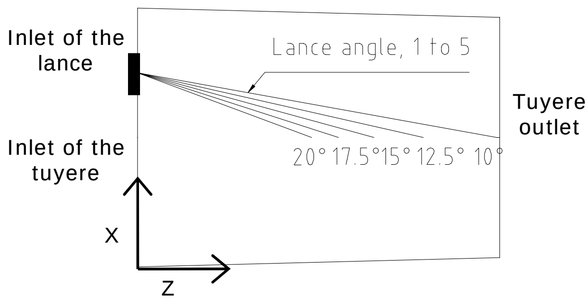


Figure 9 The different injection angles of the lance used in the model for two injection lances.

More specifically, angles between 10° to 20° degrees relative to the tuyere pipe axis have been studied. The coke oven gas injection amount in this parameter study corresponds to 12 500 nm^3/h for all simulations. A contour plot of the velocity profile at 250 m/s in the blast is shown in **figure 10.**

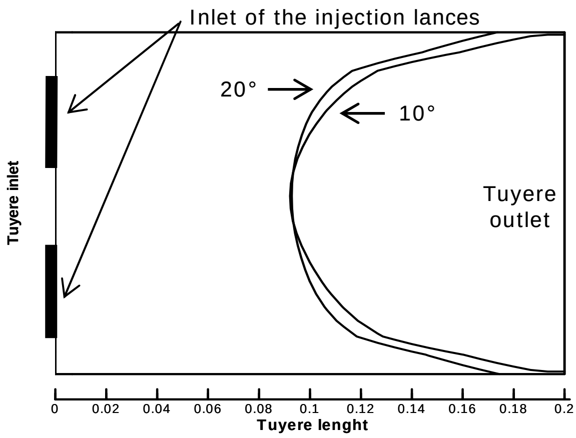


Figure 10 Contour plot of the velocity profile at 250 m/s in the blast, when comparing 10 and 20 degree angle of the injection lances

The change in the velocity profile for lance angles between 10° and 20° is very small. The profile for 250 m/s for the 20° angle are close to the profile for the 10° angle. In order to determine the relation between the oxidant and the fuel at different positions along the tuyere, a non-dimension variable *f*, called the mixture fraction may be defined, in terms of unit mass, *m*, as:

$$f = \frac{m - m_o}{m_l - m_o} \tag{6}$$

where the suffix *o* denotes the oxidant stream and *l* denote the fuel stream. The value of *f* equals 0 if the mixture at a specific position contains only oxidant and equals 1 if it contains only fuel. In **figure 11**, contour plots corresponding to a value of 0.1 for the mixture fraction, *f*, has been plotted for lance angles of 10° and 20°, respectively.

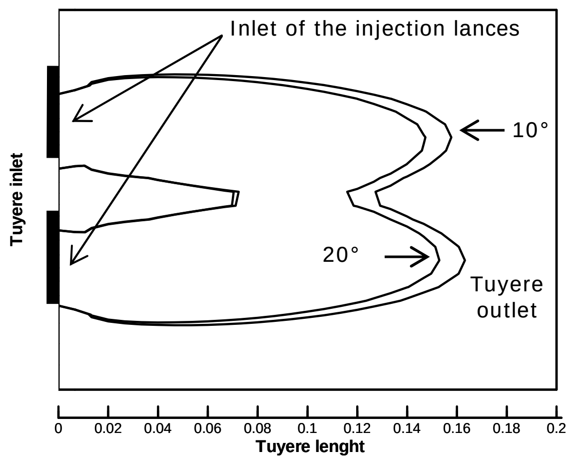


Figure 11 Contour plot of the non-dimensional variable *f* for a certain value of 0.1 in the blast, when comparing a 10° and a 20° degree angle of the injection lances

The flame is slightly longer for the case with a 10° lance angle. This indicates that the combustion is occurring earlier than for the case with a 20° lance angle, but it should be noted that the differences are quite small.

CONCLUSION

A mathematical model has been developed for an injection tuyere in a blast furnace to simulate the combustion, when injecting reducing gas. The fluid flow is solved based on fundamental transport equations in combination with the standard k-ε turbulence model. The chemical reactions are modeled using a two-step reaction scheme with three possible reactions that can occur. Furthermore, an EBU model is used to describe the rate of the reactions. The model has been used to predict velocity, temperature and composition data of the blast inside the tuyere. Based on the conditions in the study, the specific conclusions can be summarized as follows:

- The mean temperature of both the BOF gas and the coke oven gas increases with the distance from the lance tip. The temperature increase is higher for the coke oven gas due to a more complete combustion and the higher heating value of the gas.
- When using one injection lance, the maximum injecting amount is 10 000 nm^3/h. If the injection amount is higher, part of the gas will not combust in the tuyere but will enter into the blast furnace unburned.
- For two injection lances, the maximum injecting amount is increased to 15 000 nm^3/h, due to better combustion conditions. The conditions are better as the inlet velocity of the gas is lower, the turbulence in the tuyere pipe is enhanced, and also more of the coke oven gas is in contact with the blast, i.e. the reacting area is bigger.
- The effect of varying the injection angles of the lances on the predicted results is not obvious.

Finally, it should be pointed out that the conditions in the raceway are very complex and also influence the conditions in the tuyere and hence the combustion of the reducing gases.

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