**New Concept of the Auxiliary Fuel Injection Tuyeres of Blast Furnaces Developed by Numerical Simulations**

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## INTRODUCTION

The injection of pulverized materials through the tuyeres of blast furnaces has been of great differential for the steel industry. Currently, the pulverized coal has become a very important supplementary fuel for generating heat and reducing the replacement of expensive metallurgical coke to reduce operating costs, stabilize blast furnace operation and reduce the emission of carbon dioxide.
However, as the increased rate of pulverized coal injection (PCI), also increases the percentage of unburned coal. This material is not burned crosses the boundary of the combustion zone and is transported into the furnace, reducing the permeability of the surrounding coke and can even affect blast furnace stability.
In this scenario, the desirability of a maximum amount of coal burned in combustion zone, since most blast furnace tuyeres currently inject the coal. The development and technology expansion of pulverized coal injection (PCI) has occurred extensively throughout the world. Currently, more than 400 furnaces in the world and more than 30 furnaces in Brazil use pulverized coal injection.
In pursuit of higher injection rates without the furnace stability be compromised, several mechanisms are tested continuously since mixture of coals, coal injection combined with new materials such as tires, rice husks, bagasse cane sugar, even injection projects with spears double co-axial gas injection and fuel.

## GOALS

This contribution presents a technical survey of the physical and numerical comparison of four different types fuel pulverized injection in blast furnaces. We also emphasize the advantages of using a rotation system in air tuyeres injection to promote a greater air mixture with pulverized coal in combustion zone. The aim is through the physical model and computational model reproduce graphically the results obtained with different concepts and present the main characteristics of the systems studied.

## MATHEMATICAL MODEL

The fluid is treated as a continuous always in terms of macroscopic properties such as velocity, pressure, density and temperature, and its derivatives in space and time. Properties such as microscopic structure and molecular motions are ignored. Variables in the governing equations solved to the gas phase include mass, momentum, energy, chemical species, turbulence and to the particle phase include momentum and energy, as summarized in
Table 1.

Table 1. Governing Equations for the gas and particle phasis.

| | | |
|---|---|---|
| Gas Phase | Mass | $\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{U}\right) = S_m$ |
| | Momentum | $\frac{\partial}{\partial t}(\rho U) + \nabla.\left(\rho \vec{U}\vec{U}\right) = -\nabla p + \nabla.\left(\overline{\overline{\tau}}\right) + \rho \vec{g} + \vec{F}$ |
| | Energy | $\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla.(\rho U h_{tot}) - \nabla.(k\nabla T) + \nabla.(U.\tau) + U.S_M + S_E$ |
| | Gas Species i | $\frac{\partial}{\partial t}(\rho Y_i) + \nabla.\left(\rho \vec{U} Y_i\right) = -\nabla.\vec{J}_i + R_i + S_i$ |
| | Turbulent Kinetic Energy | $\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon + P_{kb}$ |
| | Turbulent Dissipation Rate | $\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\rho\varepsilon + C_{\varepsilon 1}P_{\varepsilon b}\right)$ |
| Particle Phase | Momentum | $m_p \frac{dv_p}{dt} = F_D + F_B + F_R + F_{VM} + F_P$ |
| | Energy | $\sum (m_C C_P)\frac{dT}{dt} = Q_C + Q_M + Q_R$ |

For the carbon reaction particles, it must be reactive, but the products can be found in the particulate or gas phase. Coal burning is calculated from the equations of carbon transport particles combined with turbulent dissipation calculation for volatiles combustion in gas phase.
The coal combustion can be divided into four stages: heating, raw coal combustion devolatilization, gaseous combustion and oxidation for volatile materials, gasification of carbonized material by residual gas phase turbulent. The devolatilization and carbon oxidation

process can occur in milliseconds, that time is much smaller than the typical residence time of particles in the combustion zone. Large variations in time scale equations can result in large numbers, causing problems on results accuracy.
The devolatilization can be modeled by one or more reaction steps using the generic capacity multiphase Arrhenius reaction, where the process is usually represented by one or two reaction steps. Shen et al. in their work using the model of two competing reactions, where a couple with different constants of reactions (Z1, Z2) and the actual yield of volatiles (y1 and y2), as:

$$RawCoal \begin{array}{l} \xrightarrow{Z_1} y_1 VM + (1-y_1) C_{h1} \\ \xrightarrow{Z_2} y_2 VM + (1-y_2) C_{h2} \end{array} \quad (1)$$

Where VM is the mass fraction of volatile material and $C_h$ is the residual coal burned. Often volatile yield of materials from one type of coal is known only after immediate analysis in the laboratory, where the heating rate is low and volatiles that escape may undergo secondary reactions including breakage and deposition of carbon on solid surfaces.
For devolatilization coal, the model considers **that** particle diameter changes in proportion to the particle release and the increase of fraction volatile changes in average particle coal diameter, after devolatilization must be specified as model input as:

$$\frac{d}{dt} d_p = C_s d_{0,p} \frac{\dot{m}_{ref}}{m_{ref,0}} \quad (2)$$

Where $d_p$ is the diameter of the particle current, Cs is the coefficient of increase, $d_0$, p is the particle diameter in the early devolatilization, $\dot{m}_{ref}$ is the rate of change of mass of reference material and $m_{ref}$ is the mass of reference material early devolatilization.
Two models are proposed for carbonized material oxidation: the Fild model and Gibb model. Shen et al. compares the two models and found that model proposed by Fild when used in their experiments for ~~the~~ carbon oxidation was considered only the external diffusion of reactive gases to particle surface. Thus, burned material was overestimated, and the authors recommended a model that considers more detailed mechanisms. In their studies, authors used model proposed by Gibb, where internal gaseous species diffusion within particles pores for carbonized material is also considered. By rate diffusion and chemical reaction equating, the reaction rate for a global carbon particle is shown by the equation:

$$\frac{dm_c}{dt} = \left(k_d^{-1} + k_c^{-1}\right)^{-1} X_g 4\pi R_p^2 \frac{P}{P_A} \quad (3)$$

Where reactions are being controlled by the lower difusion rates $k_d$ and $k_c$. The EDM is based on the rapid chemical reaction in relation to transport process in the flow, assuming that when the reactants are mixed, they form products instantly. The model chosen by Shen et al. in their work assumes that reaction rate is directly related to time required for mixing reagents at molecular levels.
For turbulent flows the mixing time is based on the properties of recirculation, and its rate then defined by turbulent kinetic energy k and turbulent dissipation ε, as shown in equation:

$$taxa \propto \frac{\varepsilon}{k} \quad (4)$$

The model dissipation by borders is constantly used in industrial problems, instances where reaction rate is fast compared with the rate of mixing of reagents. The boundary of a given reaction is determined by reactants, equation (5), or products, equation (6), and prioritized whichever comes first:

$$R_k = A \frac{\varepsilon}{k} \min\left(\frac{[I_m]}{v'_{KI}}\right) \quad (5)$$

$$R_k = AB \frac{\varepsilon}{k} \left(\frac{\sum_p (I_m) W_{I_m}}{\sum_p v''_{KI} W_{I_m}}\right) \quad (6)$$

The rotational flows have been study-intensive. These mechanisms are characterized by spiral flow application, which can be achieved when transmitting tangential velocities in perfectly axial flows, and twist degree applied has a significant impact on flow results. The flow characterization is done by measuring velocity profile and twist degree is measured by a dimensionless number, S, which represents axial flow torque, $G_\theta$ divided by moment axial flow product, $G_z$, radius $R_t$ equivalent as,

$$S = \frac{G_\theta}{G_z R_t} \quad (7)$$

$$G_\theta = \int_0^R \left(\rho v_z v_\theta + \rho \overline{U'_z U'_\theta}\right) r^2 dr \quad (8)$$

$$G_z = \int_0^R \left(\rho U'^2_z + \rho \overline{U^2_z} + (p - p_\infty)\right) r dr \quad (9)$$

The fluid rotation has been widely used in industry, its principal application of heat and mass exchangers, turbines, burners, particle separators, and also applied to control the pneumatic conveying line pressure drop.

## NUMERICAL MODELING

To study the behavior of pulverized fuel in tuyeres, considering conditions of spreading and spraying, as well as chemical reactions and combustion efficiency, we adopted a line study of fuel injection spray where sequenced steps were organized in: (1) physical test in reduced scale (1:4,8) using cold-compressor with maximum flow of approximately 189Nm$^3$/h available in LaSiP (Laboratory for Process Simulation) School of Engineering, Federal University of Minas Gerais, changing the types of tuyeres, with CFD simulation validating the results of physical cold simulation and (2), CFD simulation of fine coal injected combustion into tuyeres in a blast furnace that produce 700 tons Hot Metal (HM)/day in scale 1:1.

The tests were carried out using cold air at ambient temperature representing the air through tuyeres and the fuel will be represented by cornstarch sprayed with grain sizes ranging from 30 to 100 microns. This step is not considered combustion. The set used in cold tests has dimensions of small-scale 1:4,8 for 700 tons blast furnace, and 150 kg injection rate of pulverized coal per ton, as shown Table 2.

Table 2. Cold phisical simulation conditions

| | **Reduced scale** [1:4,8] |
|---|---|
| Air Injection Velocity | 100m/s |
| Coal Mass Flow | 0,014 kg/ton.HM |
| Conveying Gas Velocity | 15m/s |
| Air Temperature | 25$^o$C |

To avoid interference from the walls over flow field, the experiment was conducted in an open environment, where two white stripes, 300 mm distant from each other, were used to delineate the catchment area of images. To breathe air through tuyeres, a 22.5 kW compressor was used to produce 7.87 x105Pa pressure and a maximum flow of approximately 189Nm$^3$/h. Flow meters and pressure were used to control and monitor air conditions before tuyeres entrance, to ensure specified achievement of experiment conditions. To assess particles dispersion degree, were used a high definition camera (full HD) capable of capturing up to 60 frames per seconds.

To meet the proposed objectives, the experiments will be performed varying bill settings, all other parameters being held constant. The goal is to check the influence of the particle injection behavior into the raceway.

Concepts involved in supersonic jets have origin in equations of energy conservation, mass conservation and state equations applied in the stationary state. To simplified the calculations, the air will be consider like ideal gas. The equation of energy conservation allows relation between fluid velocity, pressure, potential energy and work made for the fluid. The computational geometry that represents the physical cold model chosen is based on a scale 1:4,8 tuyere furnace with a daily production of 700 tons of hot metal, with a diameter of 25mm and 3mm for gas injection and pulverized material. This system has mechanism of pulverized coal injection lance with simple, which was compared with injection systems for dual launches, S = 0.12 and S = 0.24, as shows the Figure 1.

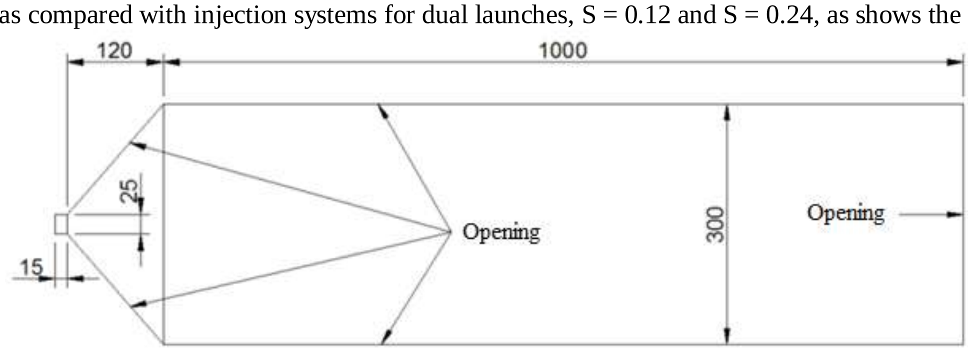


Figure 1. Computational geometry, in millimeters, of the cold phisical model.

To work with data close actual data from 700 tons daily blast furnace studied in this work, **were** used the dimensions shown in Figure 2. The region bounded by domain is restricted to data obtained from scaling the combustion zone, considering 5m diameter from furnace. At this stage, domain-scale 1:1 was chosen to represent in greater detail the operation of real equipment with various injection techniques tested.

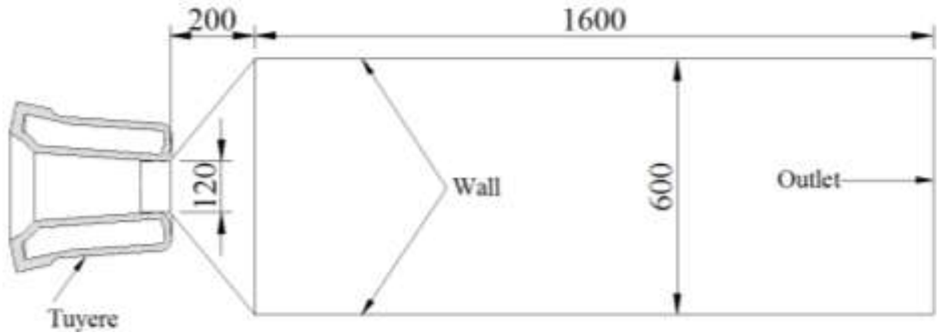

Figure 2. Computational geometry, in millimeters, of the numerical coal combustion.

To represent real boundary conditions of 700 tons blast furnace in study, the input parameters were adjusted as operational data, presented in Table 3.

Table 3. Coal combustion data.

| *Description* | *Unit* | *Present Work* | *Shen et al.* |
|---|---|---|---|
| Blast Velocity | m/s | 140 | 137 |
| Blast Temperature | K | 1273 | 1473 |
| Particles | kg/tHM | 150 | 80-190 |
| C | [%] | 74.05 | 89.1 |
| H | [%] | 5.31 | 4.7 |
| N | [%] | 1.6 | 1.7 |
| S | [%] | 0.35 | 0.37 |
| O | [%] | 11.99 | 4.1 |

In tuyeres region, although mesh vary due to geometry of each configuration, the total number of nodes in all geometries was approximately 450.000, reducing variations in accuracy due to mesh. In regions near the tuyeres received more detailed mesh to allow better capture with precision initial spread, soon after pulverized fuel injection, and air injected influence into trajectory prediction of particles throughout domain. Figure 3 represents different configurations mesh of powdered material injection with statistics mesh.

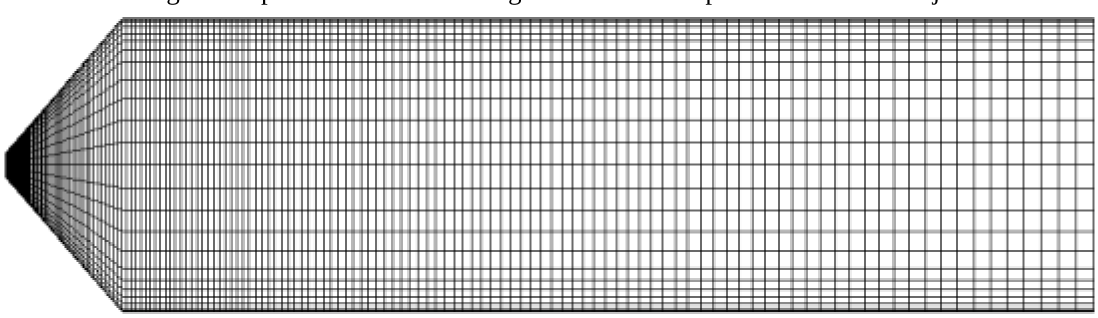
Figure 3. Mesh of the raceway zone.

Due tuyeres complexity geometry, loop control factors were monitored to ensure only hexahedron elements.

## RESULTS AND DISCUSSIONS

When comparing the settings of simple lance and double lance with new settings S = 0.12 and S = 0.24, one can observe that turbulence effect generated by incoming air provides greater scattering and increases S factor. This is because the speed centrifugal promoted on particle causes scattering increases, the greater effect is being near tuyeres exit.

Figure 4 shows relationship of injection type with scattering obtained in combustion region. The results presented in Figure 4 (a) and (b) show that for single lance, the scattering angle obtained is 12 and for double lance, scattering is almost 30% higher. The greater spread of fuel provided by dual lance allows a wider range launches this in combustion zone, when compared with simple lance, which allows increased combustion efficiency, as already stated by Maki et al. The increased efficiency allows higher rates of injection, since lower likelihood of bird's nest formation for not coal burned.

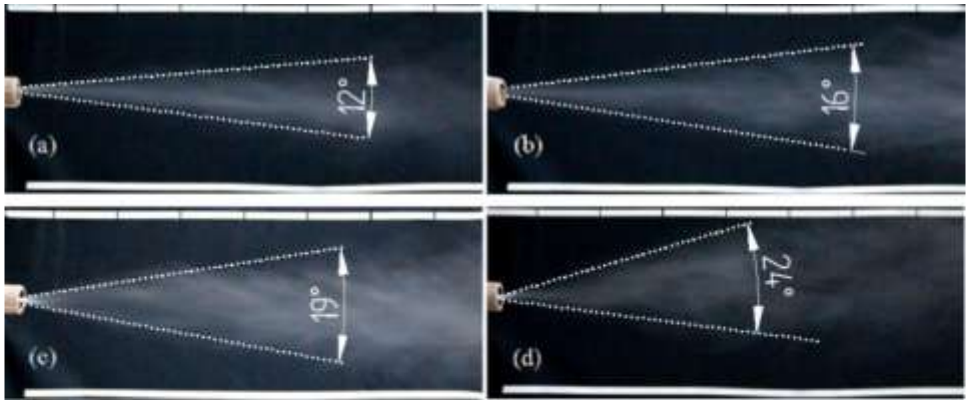


Figure 4. Effect of spreading of the material injected into the tuyeres (a) LS, (b) DL (c) S=0.12 and (d) S=0.24.

Whereas length of combustion zone, which has a strong relationship with input speed by heated air, was not altered significantly by different settings evaluated tuyeres, the second step is to evaluate particulate phase injected behavior into computational domain. To assess behavior and accuracy of models chosen, the simulation results were compared with results obtained in physical tests, as shown in Figura 5.

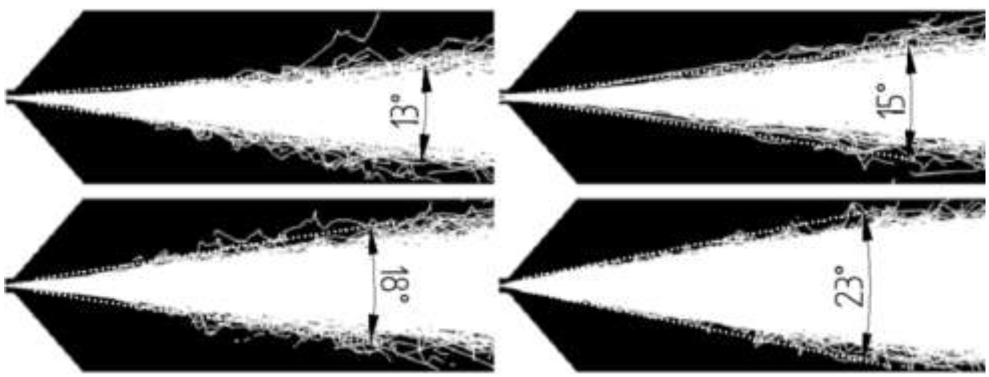


Figure 5. Scattering predicted by the model numbers of employees.

To quantify physical simulations results and compare them with numerical results, the area bounded by scattering for all injection systems studied were calculated to evaluate the availability of combustion surface area, which is presented in Table 4.

Table 4. Surface spread area of pulverized coal

| | ***Phisical Simulation*** | | ***Numerical Simulation*** | | ***Diference*** |
|---|---|---|---|---|---|
| | ***Angle*** | ***Area*** | ***Angle*** | ***Area*** | ***%*** |
| Lance Simple | 12$^o$ | 0,071[m$^2$] | 13$^o$ | 0,074[m$^2$] | 4,22 |
| Double Lance | 16$^o$ | 0,091[m$^2$] | 15$^o$ | 0,090[m$^2$] | 1,1 |
| S=0.12 | 19$^o$ | 0,106[m$^2$] | 18$^o$ | 0.105[m$^2$] | 0,94 |
| S=0.24 | 24$^o$ | 0,132[m$^2$] | 23$^o$ | 0,131[m$^2$] | 0,75 |

Thus, there is strong influence of continuous field in particles because of size. It can be seen in Figure 6 that finer particles are more scattered as they move away from the surface. Since, particles are larger and heavier, are crowded during a big chunk in the runoff, dispersing farther from tuyeres exit. It can still point out the particle size distribution at .domain exit, wherelance simple, shown in Figure 6 (a) hashighest concentration of large particles injet center and other systems providing greater spread. The system shown in Figure 6 (d), which has a twist factor, S = 0.24, in addition to providing highest scattering also has highest dispersion of larger particles

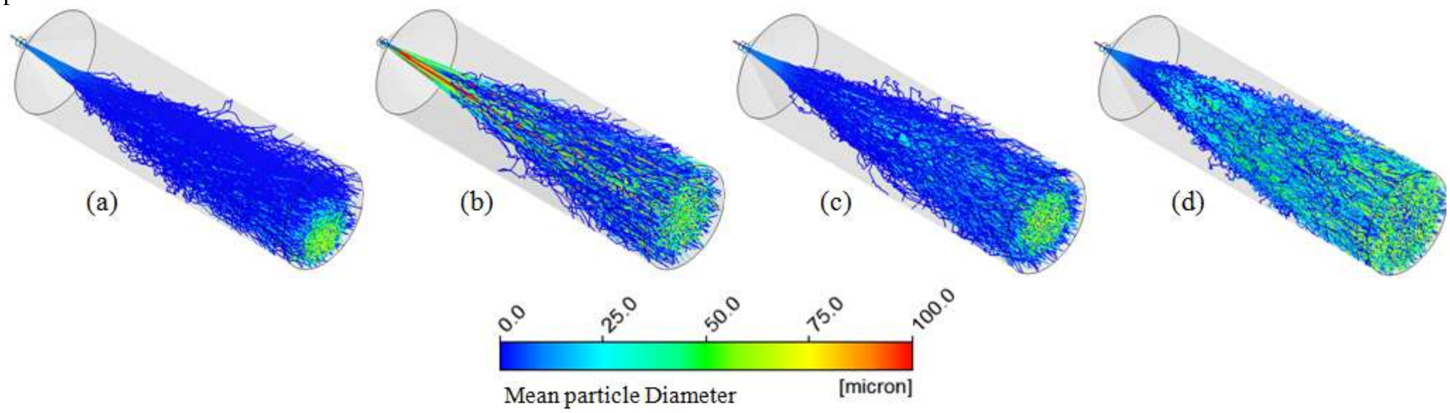


Figure 6. Size distribution of particles in the injection systems (a) LS, (b) DL, (c) S=0.12 and (d) S=0.24.

When comparingdifferent type's results of injection in this work. It is possible to see different behavior of flame in combustion zone. Figure 7 shows temperature profile for different injection methods. Note in these images that a higher heat input is provided by spear LD compared with LS launches. However, when comparing sets of twist S = 0.12 and S = 0.24, shows an increase in heat input, especially latter, which provides a superior firing power over the other.

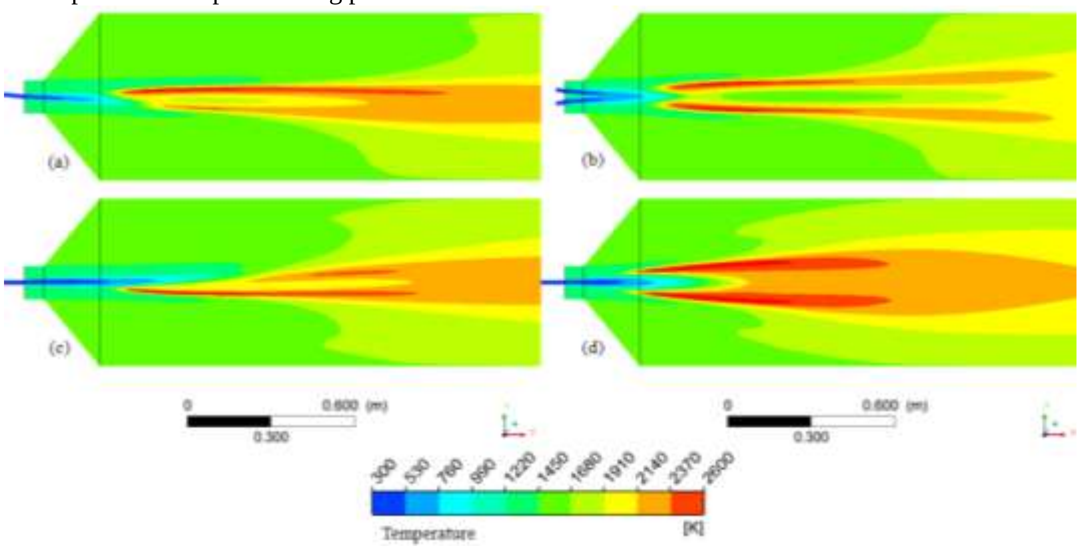


Figure 7. Temperature profile for the types of injection (a) LS, (b) LD, (c) S = 0.12 and (d) S = 0.24.

Increasing twist factor, the burning of pulverized coal is near of tuyeres exit. The largest scattering promoted by S = 0.24 system allows larger particles to spread closer to tuyeres exit, providing a greater mix of gas and particles in the combustion zone. The radiation of heat by metal loading and heated air promotes rapid combustion, reducing residence time, releasing volatile and burning almost instantly. This condition is very evident in Figure 8, when comparing maximum temperature in four different types of injection.

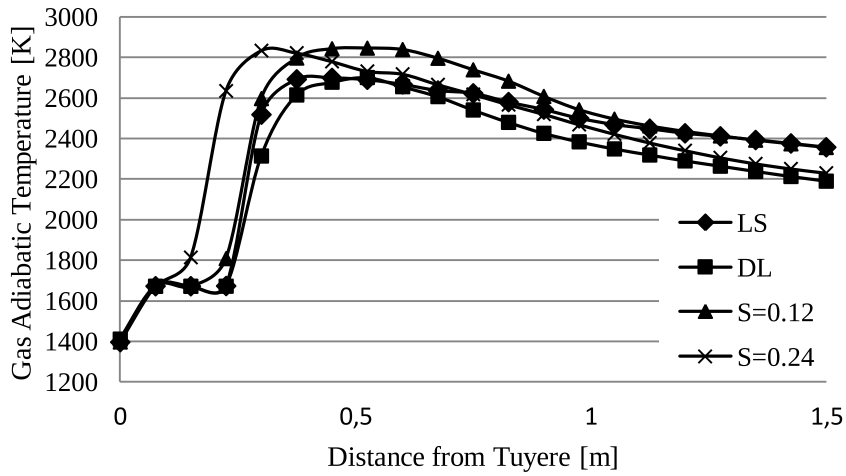


Figure 8. Comparison of gas temperature in the combustion zone of the different injection methods studied.

It is also observed (Figure 9) the increase in efficiency of burning coal, using S = 0.24, where average temperature of combustion zone rises rapidly near bellows due to increased spreading and mixing of pulverized fuel, subsequently decreasing temperature at end of combustion zone. This behavior is observed only in this configuration, and other injection systems (LS, DL and S = 0.12) have a lower temperature near tuyeres, and evolving as coal is burned.

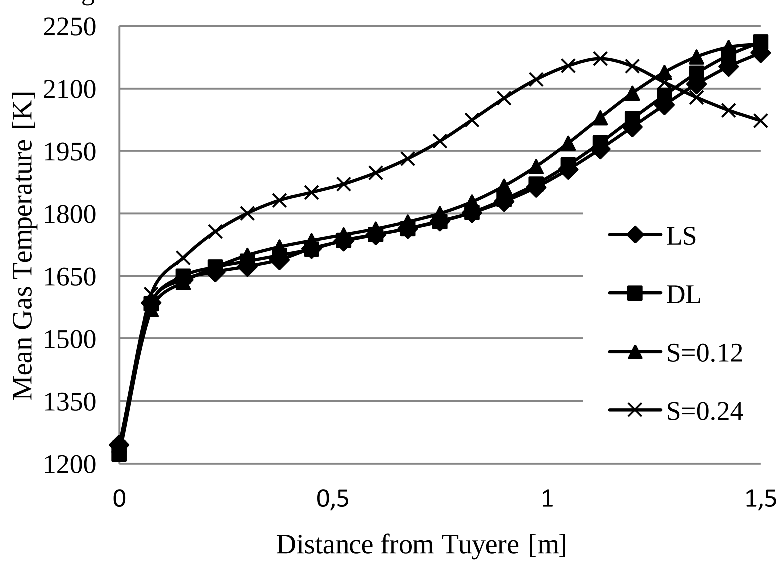


Figure 9. Average temperature of the combustion zone for the different injection methods studied.

The curves behavior obtained in Figure 9 presents a possibility of increasing injection rate of using S = 0.24, whereas with highest fuel efficiency, it is expected to burn fuel without deposition of raw coal. When compared with Shen's model et al. (Figure 10) with the torsion model S = 0.24, one can observe that mean gas temperature in combustion zone is very similar, even if inlet temperature of heated air from 1200 $^oC$ to 1000$^oC$ be the model this work.

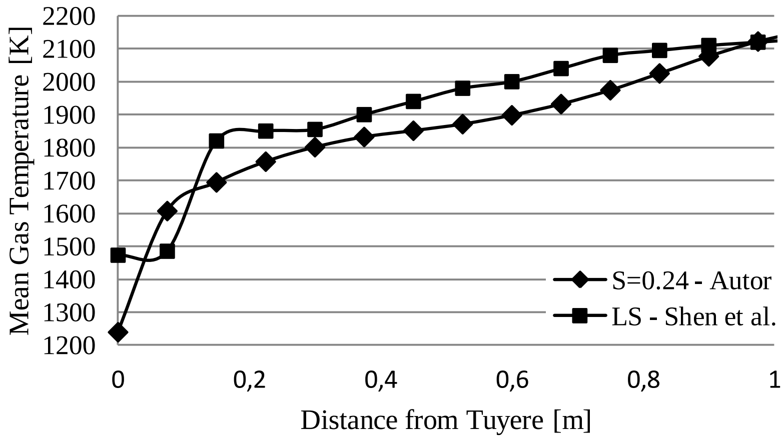


Figure 10. Comparison between the simple model launches tested by Shen et al. and injection system S=0.24 this work.

For the injection system S=0.12, one can see in Figure 11(c) that, despite the formation of a dense core of small particles, there is also a greater spread of particles that are in the periphery of the nucleus and were influenced by the vectors of rotation of the injected air. This phenomenon is more evident when a stronger twist factor S=0.24 is used (Figure 11(d)). It is observed in this configuration there is no longer a core particles, which are distributed with greater uniformity in the combustion zone, which promotes a more efficient burning.

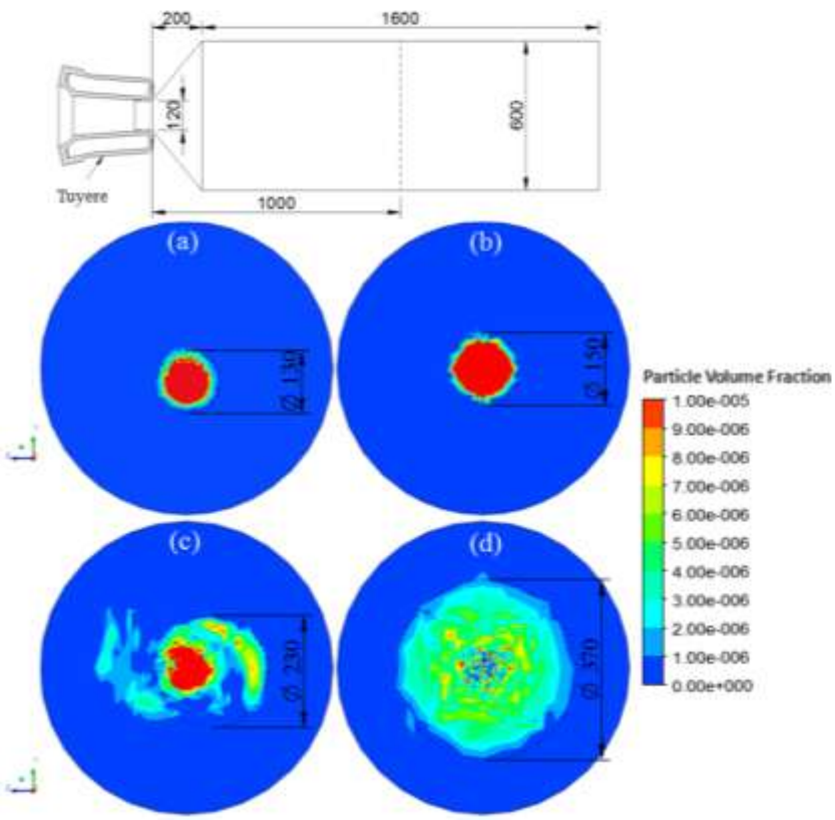


Figure 11. Volumetric fraction of fuel (a) LS, (b) DL, (c) S = 0.12 and (d) S = 0.24. Cross section 1 meter from the exit of the tuyere. Measured in millimeters.

The methods of fuel injection sprayed through single and double releases, commonly used in industry, have a slow-spreading behavior a particle moves away from tuyeres exit. Already in the injection systems with a twist, this scattering grows stronger as it move away from the tuyere. Figure 12 illustrates effect provided by twist method compared with LS and DL methods.

The particle traveling through combustion zone suffers continuous phase effects, represented by incoming air. Thus, when particle is carried by a continuous phase with twist effect, this is launched by flow that spreads more and more as it travels through area.

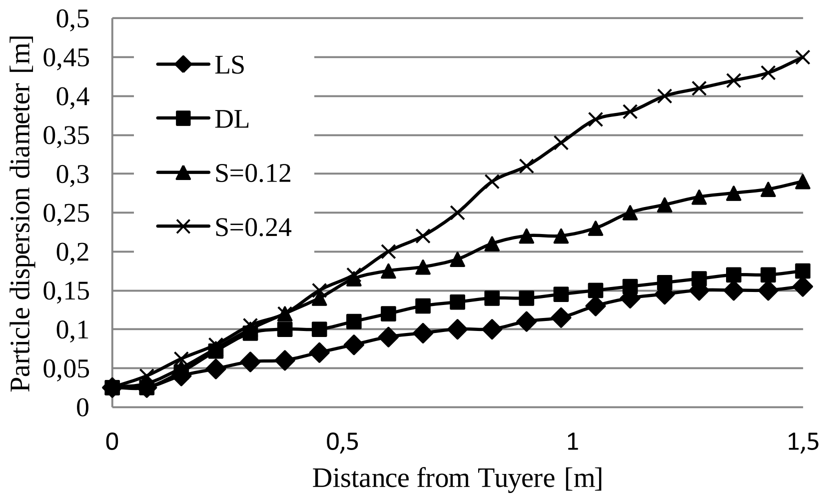


Figure 12. Evolution of the scattering distance of tuyeres.

In case of injection systems LS and LD, who suffers the first effects of flow are the particles of smaller diameter, and then those of larger diameter, and therefore a greater distance is required for the particles to center spread. On systems with torsion factors S = 0.12 and S = 0.24 the effect is felt also by heavier particles, and the trend is spreading further increase the output of the next tuyeres with more factors twisting.

## CONCLUSIONS

Discussed in this paper the effect of different methods of injecting pulverized fuel in blast furnace tuyeres, where physical tests and numerical tools were used to validate theoretical assumptions raised in the literature review.

Initial results indicated that particles behavior captured during physical simulation performed very similar to those obtained with numerical simulation. The scattering of pulverized coal showed significant differences with injection systems variation. Comparing results up to 1 meter away from exit tuyeres, the LD injection systems, S = 0.12 and S = 0.24 showed average increases of approximately 26%, 75% and 111% respectively.

Compare results of temperature average of combustion zone for fuel injection systems with LD and LS, it is possible observed similar values, with average growth of about 1% higher for LD system. However, when compared to conventional systems, LS and LD, and systems proposed by the author, S = 0.12 and 0.24, it is possible observed large increase in average temperature of combustion zone, with average increases of 2% and 7% respectively.

However, when comparing injection system used with LS authors cited, injection system S = 0.24 in this work had a higher initial scattering of pulverized fuel and rapid rise in temperature of combustion zone, even at temperatures below 200$^{o}$C blowing this author.

The results showed that evolution of average temperature in combustion zone to fuel injection system with S = 0.24 blowing temperature 1000$^{o}$C can be compared to a simple boom system with a temperature of 1200 $^{o}$C breath, where it is believed that higher rates injection can be used in blast furnaces using charcoal and plants that have Glendons as air heaters.

In all parameters, injection system S = 0.24 was more efficient, and factor S = 0.12 showed similar results to system LD and LS, simpler, had the poorest results.

The comparison results in this work, compared with results obtained by authors in the literature showed that the injection method S = 0.24 showed to be more efficient in scattering of particles, mixing and burning. The combustion model must still be validated in laboratory and industrial practice. Several important variables were not evaluated in study and should be studied in greater depth before the physical tests practical.

## ACKONWLEDGMENTS

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