COMPUTER SIMULATION OF THE FLOW AND BURNING OF FUELS INJECTED INTO THE BLAST FURNACES' RACEWAY *

Leonardo Camilo dos Reis[1]
Walter Hernan Martinez[2]
Beatriz Fausta Gandra[3]

Abstract

The injection of pulverized coal through the tuyeres, combined with adjustments to the blast furnace's operating parameters, aims to reduce the hot metal producing cost, as well as improving the energy efficiency of the steelmaking process. Auxiliary fuel injection was adopted as a method of reducing the total amount of coke needed to operate the reactor. However, the variations in blast furnace raceway conditions and the fuel combustion characteristics, due to the method and conditions of injection into the reactor, are still not fully understood. In this study, thermos-fluid dynamic models were developed to simulate the flow of gases and the combustion reactions that take place inside the raceway region of Usiminas' Blast Furnace #3. The results showed that co-injection of pulverized coal with natural gas or coke oven gas is beneficial in terms of combustion phenomena when compared to the injection of solid fuel alone. The model can be used to define the minimum and maximum volume of gases to achieve optimized burning during injection and combustion in blast furnaces.

Keywords: Blast Furnace; Thermo-fluid dynamic Model; Combustion; Co-injection.

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[1] *Mechanical Engineer, M.Sc., Specialist Researcher, Research and Development Center, Usiminas, Ipatinga, Minas Gerais, Brazil.*

[2] *Chemical Engineer, M.Sc., Specialist Researcher, Research and Development Center, Usiminas, Ipatinga, Minas Gerais, Brazil.*

[3] *Metallurgical Engineer, M.Sc., Specialist Researcher, Research and Development Center, Usiminas, Ipatinga, Minas Gerais, Brazil.*

1 INTRODUCTION

In recent decades, one of the most significant advances in blast furnaces has been the technology for injecting pulverized coal into the reactor through the tuyeres. This injection aims to reduce and/or partially replace metallurgical coke. As pulverized coal is around 40% cheaper than metallurgical coke, its use leads to a reduction in overall costs, as well as gains from environmental issues linked to the improved energy efficiency of the process. Another advantage is the coking plants' life extension [1]. The coal combustion in blast furnaces is a complex process involving the interaction of the fuel with the high-temperature pressurized air, which begins when the coal leaves the injection lance and ends in the raceway [2,3].

As a result of greater environmental pressures, an alternative evaluated by the steel mills is the injection of hydrogen-rich gases at additional tuyere levels or next to the pulverized coal. For Usiminas in particular, Natural Gas (NG) and/or Coke Oven Gas (COG) are being evaluated as potential substitutes for coke in the blast furnace reduction process.

In this context, it was developed a mathematical model to determine the potential for using coals, whether or not associated with natural gas and coke oven gas, applying computer simulation. The model uses the physical properties and phenomenology involved in a gas/solid combustion process. The methodology used in this work involved an initial stage of development of the three-phase flow model coupled with heat transport, application of the model to simulate a standard combustion test to assess the combustibility and chemical kinetics of the reactions involved. The model was validated by comparing it with experimental results. As a result, the behavior of coals and gases in the tuyere region of Blast Furnace 3 (BF#3) was obtained through simulation.

The aim of this work was to evaluate the fuels performance in the co-injection scenario by computer simulation, considering the flow of gases and solids and their respective combustion in the raceway region.

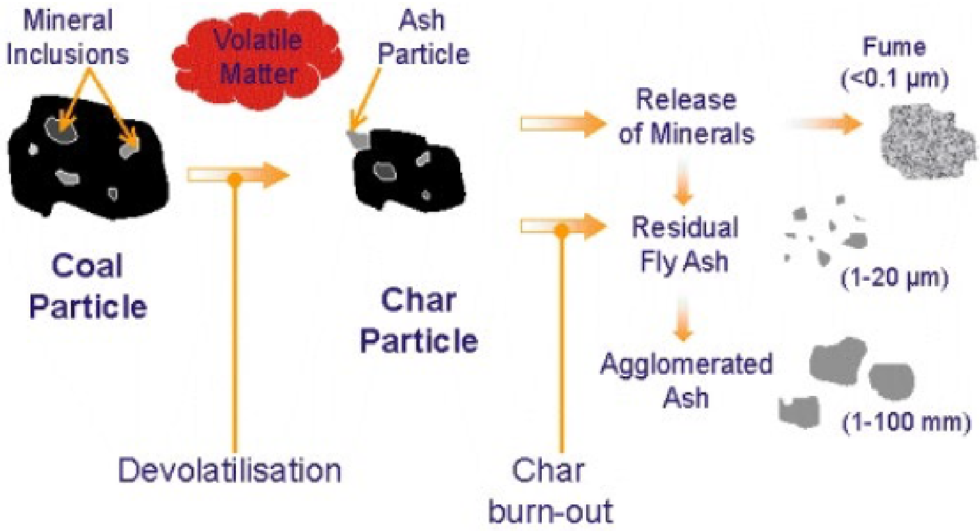
2 DEVELOPMENT

2.1 Coal Combustion

Combustion is a set of physical-chemical reactions that take place during the complete or partial oxidation of a fuel by the oxidizing element. This phenomenon is exothermic and is made sensitive by the presence of a flame, which is the heat source. Fuels, as in the case of the organic portion of coal, are composed of carbon, hydrogen, oxygen, nitrogen, and sulfur. The oxidizer is usually air or pure oxygen, but it can also be water (H_2O) and carbon dioxide (CO_2).

When the coal is injected into the raceway through the blowpipe/tuyere assembly, its combustion in the blast furnace becomes very complex and is, by its nature, a multi-stage process.

According to Hutny et al. [4], when a coal particle leaves the injection lance it enters the tuyere, absorbs heat from the hot air, and begins to devolatilize and burn. This process, which starts in the tuyere, must be completed inside the raceway, or it will increase the fuel rate by operational difficulties, and consequently reduce the furnace productivity. The products of incomplete combustion (unburned char and ash) can block the raceway. Figure 1 shows schematically the combustion mechanism of a coal particle.



10 **Figure .** Schematic description of the coal’s particle combustion.

2.2 Computational Fluid Dynamics Simulation (CFD)

Computational fluid dynamics consists of using computational methods to quantitatively predict the characteristics of flows, including heat and mass transfer, phase changes, chemical reactions, mechanical aspects, stresses, and displacements of immersed or surrounding solids [5,6].

One tool used to simulate fluid dynamics problems is the ANSYS-CFX/FLUENT [7] software, which uses the finite volume method to discretize and prepare the set of equations to be solved. It is a complex and highly efficient tool for simulating single-phase and multiphase flows, providing results similar of the real process ones, as long as the modeling is consistent with reality. CFX is divided into three modules, detailed below.

Pre-processing - provides all the model configuration, such as considerations to be made, initial and boundary conditions for the components and the system, after defining the geometry and mesh to be used; it is the problem setup.

Solver - enables the actual solution of the problem; some adjustments are allowed in this module according to the user's convenience and the problem’s peculiarities.

Post-processing - allows the results’ static and dynamic visualization, during and after the numerical solution of the problem has been completed; some adjustments are allowed according to the user's convenience for the results’ presentation.

To generate the geometry mesh, there is a tool attached to the software which can generate an unstructured mesh, with the possibility of refining it in the desired locations and also generating a multigrid mesh which gradually increases the step increment as the solution converges, speeding up the simulation.

The methodology was based on computer simulation capable of evaluating the gases combustion in the Combustibility Furnace of the Usiminas Research and Development Center and in the BF#3 raceway. The Combustibility Furnace at Usiminas Research Center was designed based on projects from the simulators at the Universities of Aachen and Federal de Minas Gerais, with the introduction of some improvements that changed the equipment's characteristics and made it distinct from the mentioned simulators, except for the operating principle. The equipment uses two furnaces for its operation: one to preheat the oxygen or air to the blast furnace temperature (approximately 800°C) and another to simulate the thermal conditions in the combustion zone (1600°C). Where the determination of coal combustibility index is indirectly carried out through the levels of CO, CO_2, CH_4, H_2, and O_2 in the combustion products, the mass and elemental analysis of the coal used in the test, and the quantity of oxygen involved in the burning process. The combustion test conditions are related to the injection rate, excess air, coal particle size, and oxygen content, aiming to simulate those employed in a real blast furnace.

A computational fluid dynamic and combustion analysis was carried out using commercial computer simulation software.

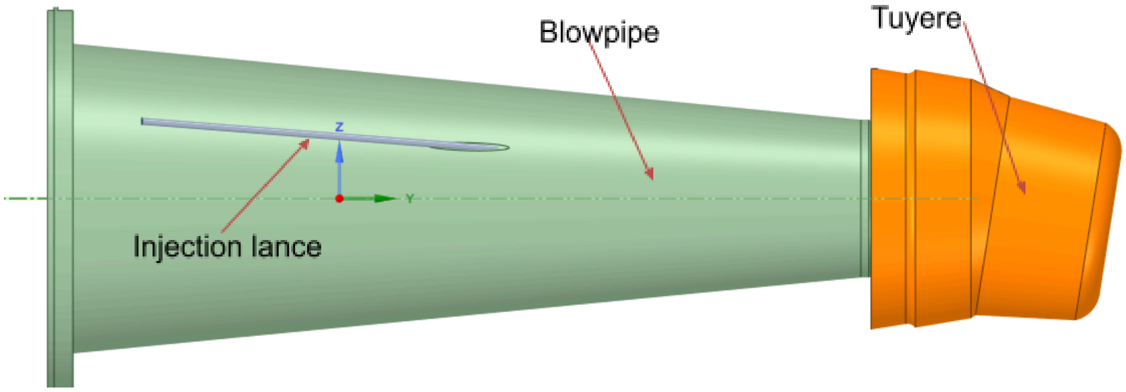
The commercial software used was ANSYS CFX 19.1, which uses the finite volume method to simulate the problem. In this technique, the region of interest was divided into small sub-regions, called control volumes. The conservation equations were discretized and solved iteratively for each control volume, resulting in an approximation of the value of each variable at specific points in the domain.

2.3 Simulation of the Co-injection of Coal and Gases into the BF#3

The computational model was developed using CFX software and the following steps were carried out.

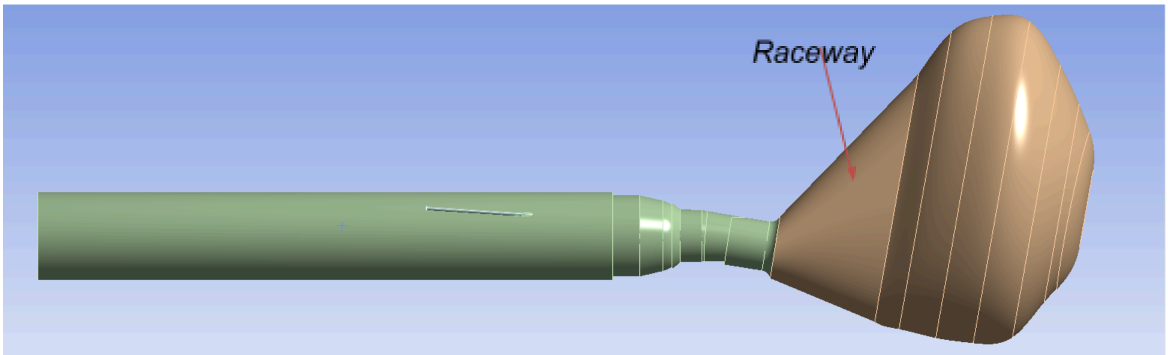
- Generation of the three-dimensional model.
- Generation of the finite element mesh.
- Initial conditions.
- Boundary conditions.

The study region, in addition to the raceway, included the inside of the blowpipe and the tuyere, as well as the fines injection lance, Figure 2. The heated air is sent from the hot stoves to the blast furnace and, after passing through the tuyeres, flows into the furnace. The coal pulverized in the lances meets the hot air current, where it is dragged along and subsequently combusts. Burning begins in the tuyere and ends inside the raceway.



1 **Figure .** Schematic drawing of the BF#3: blowpipe, tuyere, and lance assembly.

Figure 3 shows a side view of the assembly drawn in Ansys/SpaceClaim software. It shows the shape of the inside of the blowpipe, the tuyere and the raceway. The tuyere has a cylindrical shape, followed by a cone trunk inclined at approximately 9° in relation to the blowpipe.



2 **Figure .** Model of the internal space in the blowpipe, injection lance, tuyere, and raceway.

In all simulations, which were carried out under steady state conditions, a Lagrangian approach was adopted to represent the multiphase effect of the flow. The continuous phase is made up of the mixture of gases present (air, gaseous fuels, humidity and contaminants), while the dispersed phase is made up of pulverized solid coal, which has been reduced by the combustion reaction. Table 1 shows the initial particle size distribution for this solid fuel. The solid particles were injected evenly into the lance, carried by the drag gas (N_2, NG or COG), and carried away according to its velocity. The model used for the drag forces was that of Schiller Naumann [8], which considered the total particles' interaction. The analysis of thermal exchange between the dispersed and continuous phases was based on the Ranz Marshall [9] relationship.

Table 1. Particle size distribution of pulverized coal

Mesh (µm)	40	60	100	120
Mass fraction (%)	18	25	36	21

The simulations considered the combustion reactions homogeneously (between oxygen from the air, gaseous fuel and volatile materials from the pulverized coal) and heterogeneously (between the solid coal particles and oxygen from the air). The Eddy Dissipation model [10] was adopted for homogeneous reactions, considering several reaction steps. However, for the heterogeneous reactions, a multiphase reaction model was adopted, which considers the devolatilization of the coal, followed by the combustion of the remaining solid carbon. Regarding process turbulence, the Shear Stress Transport (SST) model was used.

Tables 2 and 3 lists the parameter values for the boundary conditions and the simulations' coal characteristics. The composition of the atmospheric air present at the tuyere inlet was considered the same in all cases, i.e. 21% oxygen, 77.97% nitrogen, 1% argon and 0.03% carbon dioxide.

Table 2. Parameter values for the simulation

Parameter	**Value***
Air velocity at tuyere inlet	125 m/s
Air temperature at the tuyere inlet	1180°C
Gas flow (N_2, NG or COG) in the lance with coal	0.005 kg/s
Coal flow rate in the lance	0.14 kg/s
Natural gas flow rate in the lance with gas	0.081 kg/s
Temperature at lance inlet	200°C

Process pressure	3 atm

*Equivalent to normal BF#3 operation: 80 kg/t pig iron of PCI and 38 kg/t pig iron of NG.

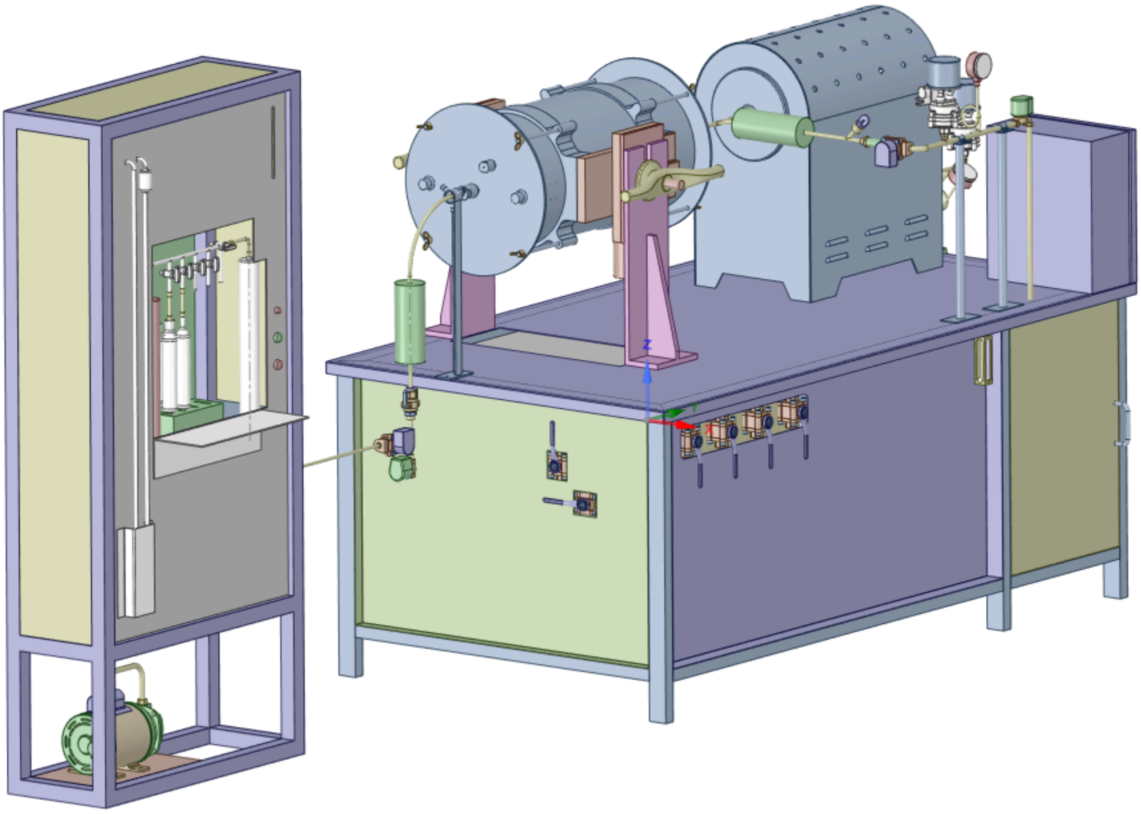
Table 3. Characteristics of pulverized coal (PCI)

Parameter	Value
Humidity	0.5%
Volatile material	22.5%
Fixed carbon	65.0%
Ash	12.0%
Calorific value	32,190 kJ/kg

For all the simulations, it was considered only methane (CH_4) as the natural gas composition injected into the raceway. The model developed does not consider coke burning inside the raceway, only the fuel injected.

2.4 Model Validation

To validate the computer model of gas combustion, it was compared the simulation results with the gas analysis carried out after the combustion test in the Combustibility Furnace at the Usiminas Research Center. Tests were carried out in the furnace burning COG gas and simulated the same condition. Due to the reaction speed of the gases, the time increment considered in the transient analysis was 0.1µs.
From the complete three-dimensional model of the Combustibility Furnace (Figure 4), a simplified model was generated for use in the mathematical modeling of the combustion analysis, shown in Figure 5.



3 **Figure .** Complete three-dimensional model of the Combustibility Furnace.

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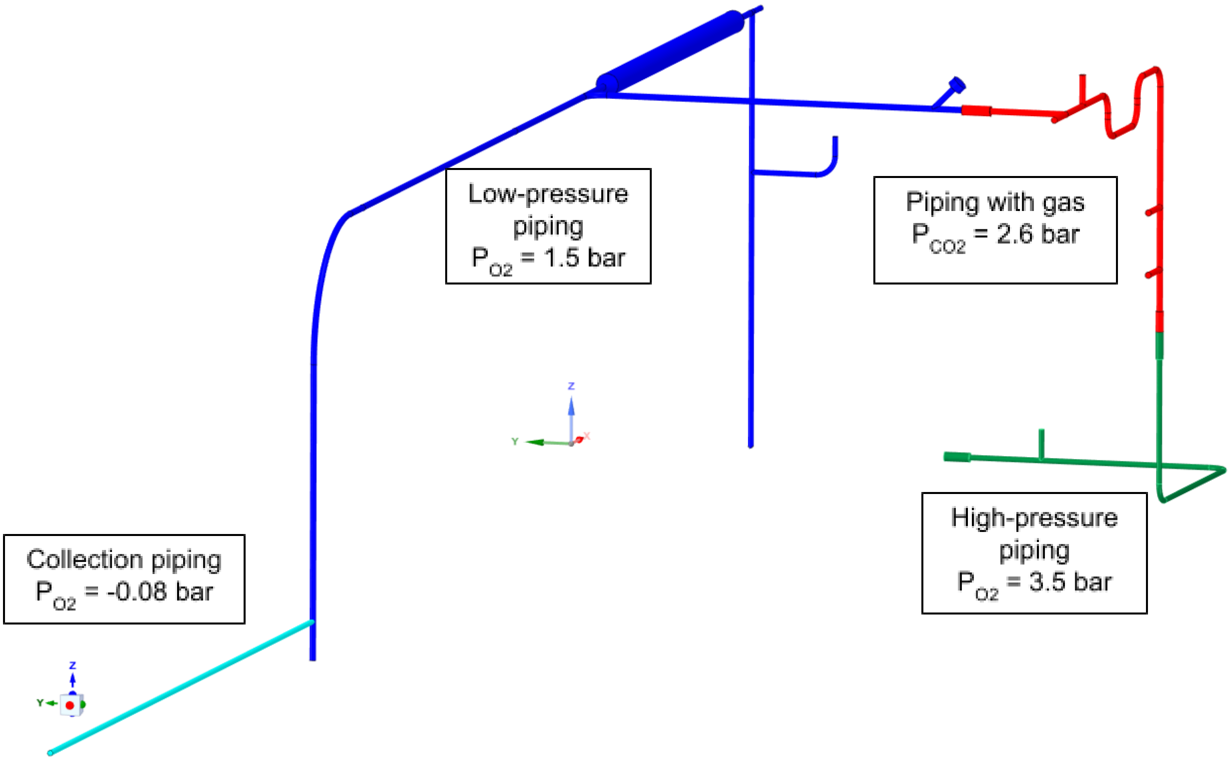
The initial condition of the model was the low-pressure region, the blue pipes in Figure 5, with oxygen at a gauge pressure of 1.5 bar. The COG gas, inside the pipe in red, with a gauge pressure of 2.6 bar. A negative pressure of -80 mbar was considered in the collection area, the pipe in light blue. The oxygen pressure in the high-pressure was 3.5 bar (green lines in Figure 5). The model used an ambient pressure of 1 bar.

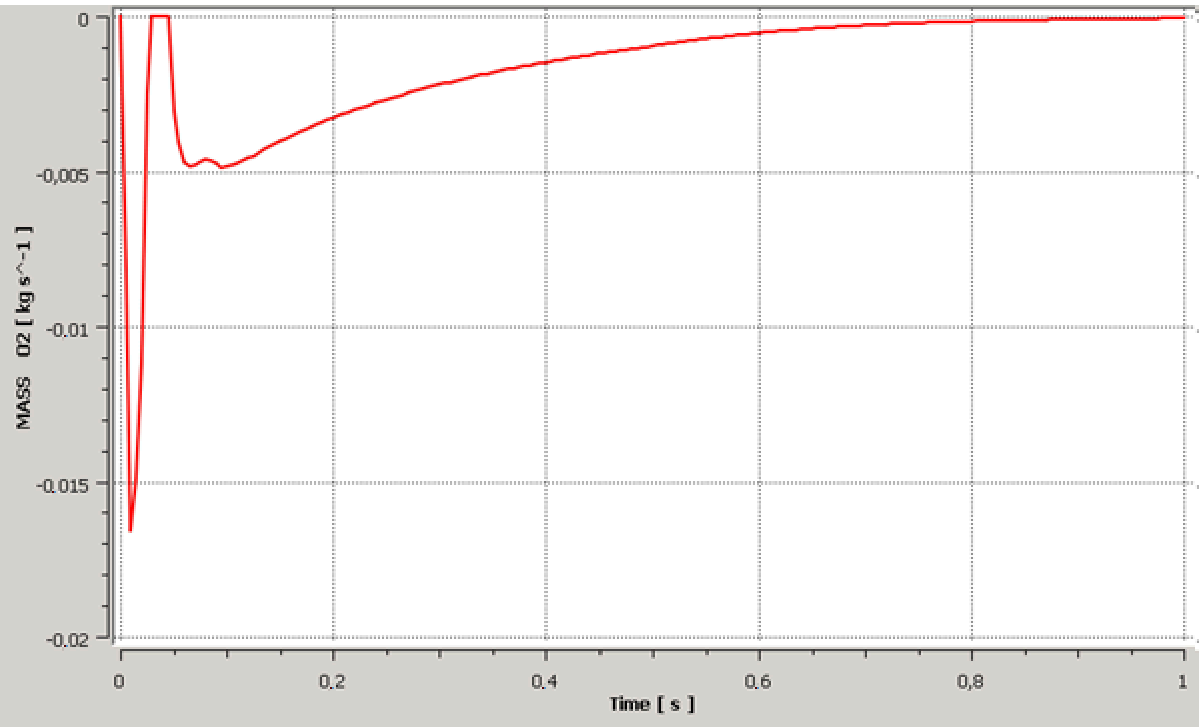


5 **Figure .** Simplified model of the furnace used in the computer simulation.

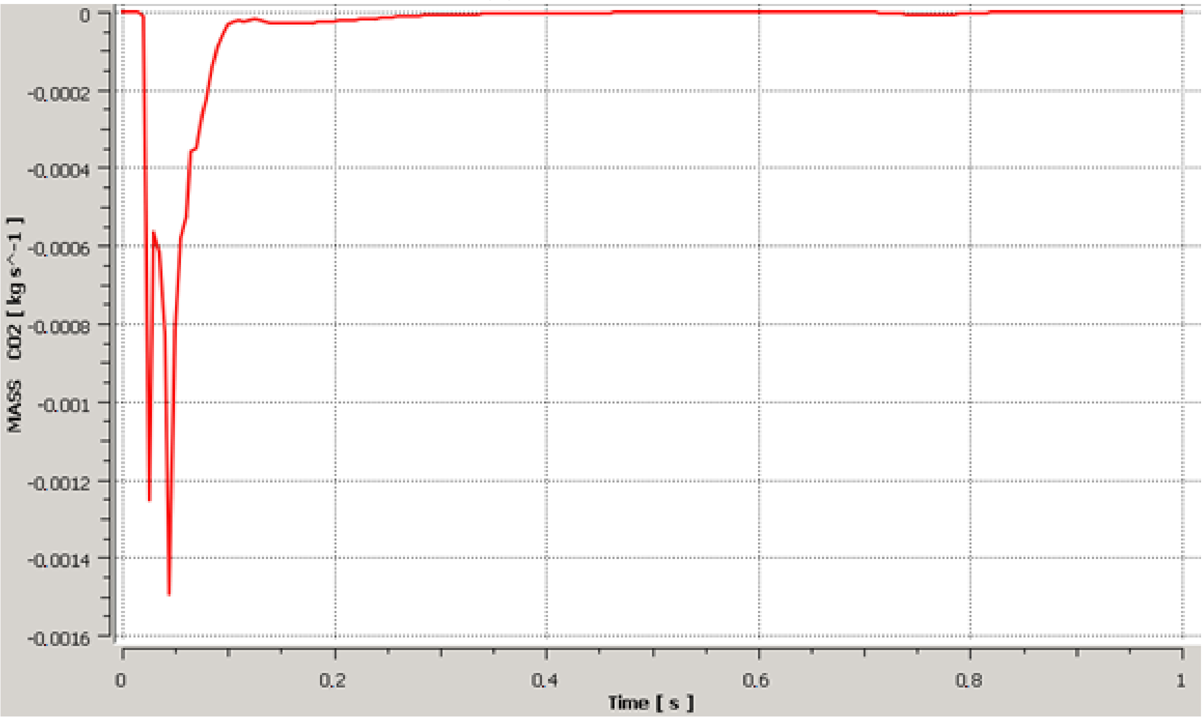
3 RESULTS

3.1 Computer Simulation of the Combustibility Furnace

Figure 6 shows the mass fractions of O_2 and CO_2 leaving the Combustibility Furnace. The graphs show that the entire combustion process inside the equipment takes less than 1 second.



(a) Mass fraction O_2



(b) Mass fraction CO_2

6 **Figure .** Mass fraction of O_2 and CO_2 leaving the collection tube during a time of 1s**.**

Table 4 shows the comparison of the molar fractions of the flue gas components from the CFD model, and the tests carried out in the Combustibility Furnace.

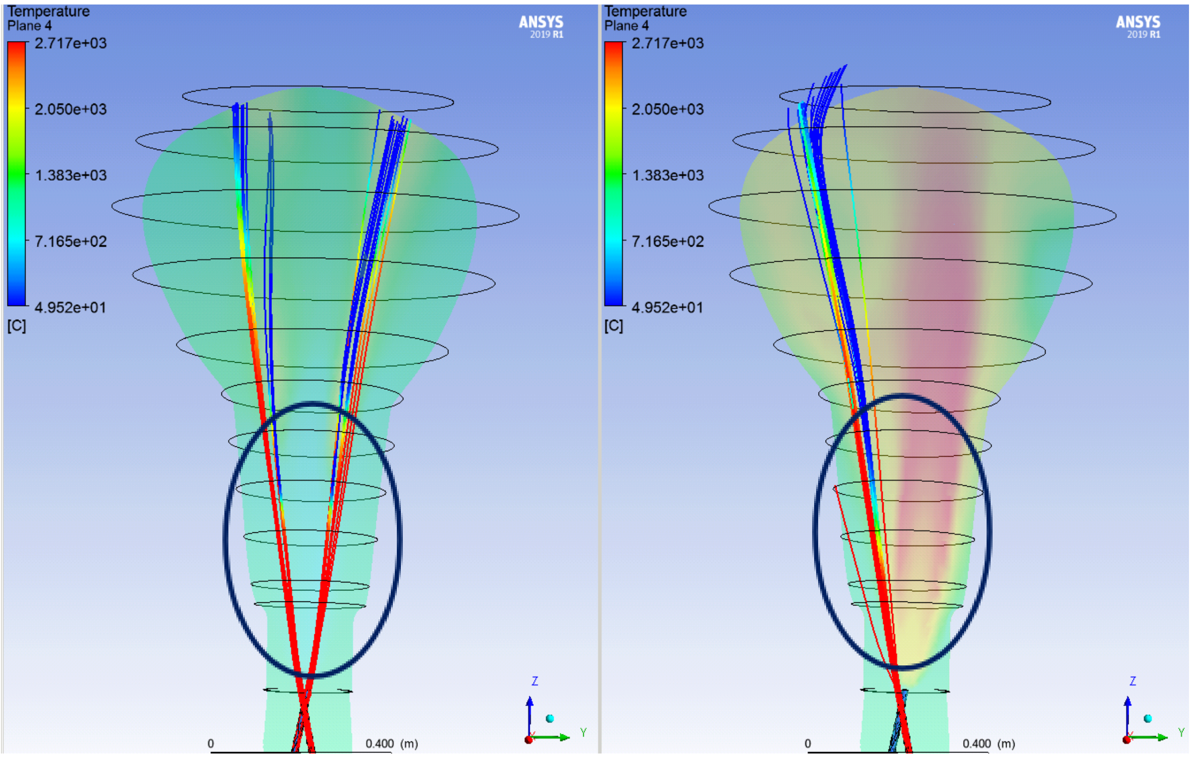
Table 4. Molar fraction values of the chemical components leaving the Combustibility Furnace in the CFD analysis and in the tests carried out.

Elements	Molar Fraction (%)		Difference (%)
	CFD	Tests	
C_2H_6	0.06	0.01	82.2
CH_4	0.87	0.67	23.0
CO	2.16	2.36	9.3
CO_2	10.63	10.55	0.8
H_2	4.24	3.96	6.8
H_2O	4.74	-	-
NO_2	0.41	-	-
O_2	76.43	75.63	1.1
C_2H_4	0.00	0.04	-

Water (H_2O) and nitrogen dioxide (NO_2) are not analyzed in the flue Combustibility gas, as these elements are collected using a bulb filled with water.
The values of the mole fractions of some chemical components are close, such as oxygen, carbon dioxide, and carbon monoxide, validating the computer simulation methodology, since the combustion model used by the CFX software when compared to laboratory tests results.

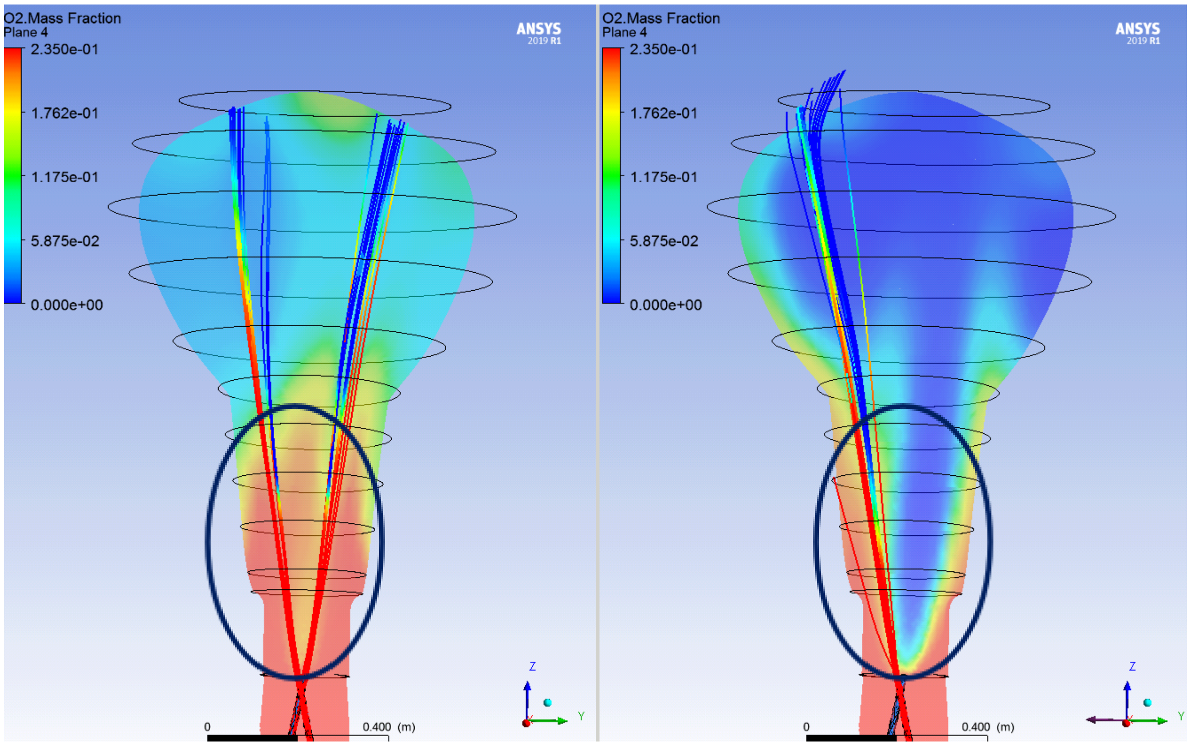
3.2 Raceway Simulation Considering BF#3

In the simulation that considered the injection of pulverized coal and natural gas, a preference for gas combustion over solid combustion was observed, according to Figures 7 and 8, which show the temperature distribution and mass fraction of oxygen in the raceway region.



(a) PCI/N_2 injection (b) Co-injection of PCI and natural gas

7 **Figure .** Temperature distribution in the raceway as a function of co-injection.



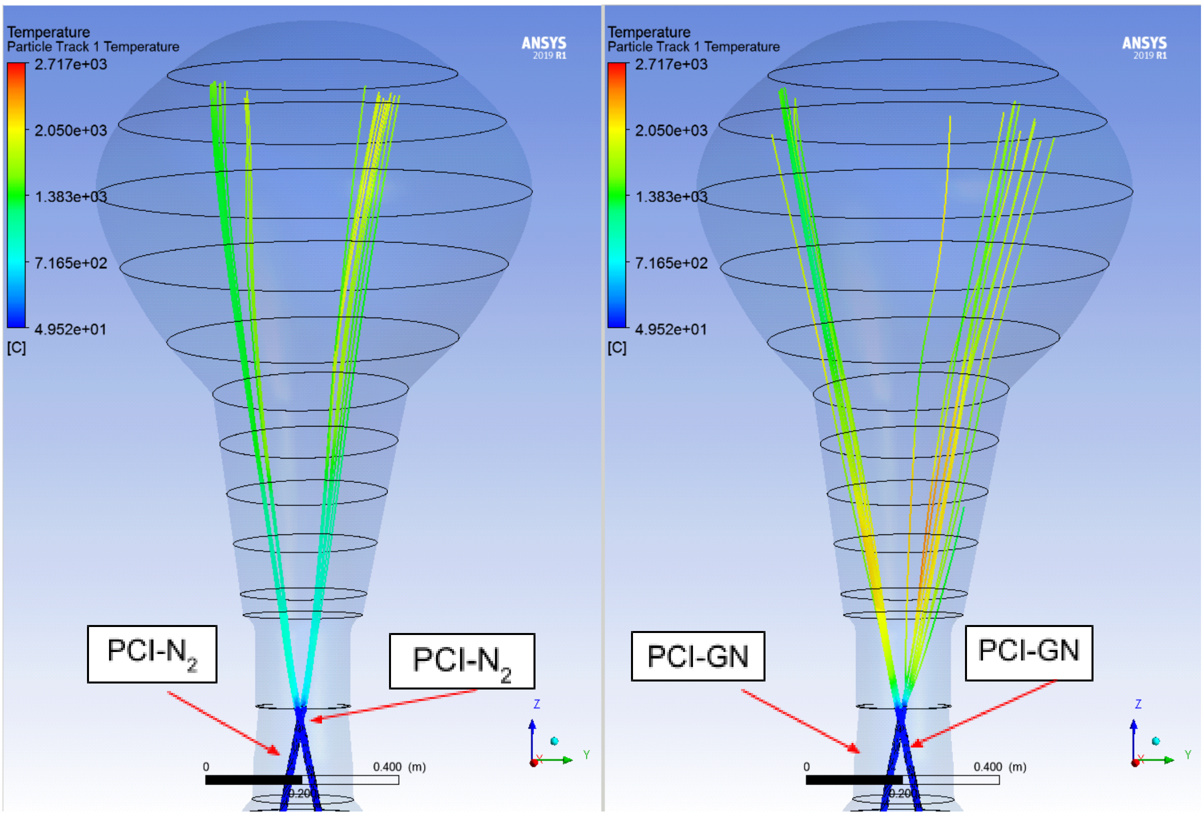
(a) PCI/N_2 injection (b) Co-injection of PCI and natural gas

8 **Figure .** Mass fraction of oxygen in the raceway as a function of co-injection.

The lance injecting natural gas heats up closer to the tuyere in the raceway region, where there was a greater oxygen consumption. This result was expected, since the reaction kinetics of the gas phase are faster than those of the heterogeneous solid phase.

Despite the low oxygen availability for pulverized coal, burning natural gas increases the temperature in the vicinity of the solid particles, which consequently increases the PCI temperature. Raising the temperature of the pulverized coal particles can have a significant effect on the combustion reaction, as it increases the reaction kinetics.

The simultaneous co-injection of pulverized coal and natural gas into a single lance can significantly contribute to a better combustion reaction of the solid particles. If they are injected into the same chamber, the two fuels will be subject to closer interaction, with a greater exchange of energy between the homogeneous and heterogeneous reactions. Figure 9 shows the temperature distribution of the pulverized coal particles during their trajectory in the raceway region.



(a) PCI/N$_2$ on both lances (b) PCI and NG in both lances

9 **Figure .** PCI particle temperature for co-injection conditions.

Figure 9 shows the results of simulations of pulverized coal and natural gas injected together into the same lance. The temperature of the solid fuel particles is higher as soon as they leave the lances comparing with the injection of these fuels into separate lances.

A greater spread of pulverized coal particles was also observed in cases where there is co-injection, regardless of whether it is in the same lance.

The results presented were obtained from simulations, considering the composition of the blown air as that of atmospheric air, without oxygen enrichment. Generally, this enrichment is used in blast furnace operation, which makes it possible to supply more of this fuel for the combustion reactions to take place. In a scenario where pulverized coal is injected with natural gas, enrichment is particularly important since there is no combustion for the pulverized coal combustion reaction.

4 CONCLUSION

The model developed using the Combustibility Furnace computer simulation technique proved to be efficient in calculating gaseous combustion, showing values similar to those of the tests carried out for the mass fractions of the main combustion gases components.

The model is suitable for use in addition to the tests carried out in the laboratory, to help determine the combustibility index of the gases as a function of the process variables, increasing the accuracy for optimization of gases to be injected into the blast furnaces.

The results of the computer model developed to simulate the flow of the blast and the fuels injected into the tuyere revealed that adopting certain operational practices can help optimize the combustion of natural gas and, above all, pulverized coal to obtain a reduction in production cost and/or reactor stability. The injection of pulverized coal with natural gas in separate lances is highly beneficial for the combustion reactions of the first fuel, since the increase in the temperature of the gases in the tuyere is caused by the combustion of natural gas, compared to a scenario in which the injection of pulverized coal is limited. Another factor in favor of pulverized coal combustion is the simultaneous co-injection of natural gas into the same lance. In all the simulated scenarios, the number of remaining coal particles decreased in the geometric domain considered, which demonstrates superior performance in terms of burning pulverized coal compared to cases where the fuels are injected separately. Coal and natural gas injected into the same lance is the best option for the combustion efficiency of the solid particles.

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