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DESIGN AND CONSTRUCTION OF A PCI RIG FOR EVALUATION OF PULVERIZED FUELS COMBUSTION: EQUIPMENT FEATURES

René Lúcio Rech [1]
André da Silveira Machado [2]
Claudia Caroline Teixeira Barbieri [3]
Juliana Gonçalves Pohlmann [3]
Janaina Gonçalves Maria da Silva Machado [4]
Maurício Covcevich Bagatini [2]
Nilson Romeu Marcílio [1]
Antônio Eduardo Clark Peres [2]
Antônio César Faria Vilela [3]
Eduardo Osório [3]

Abstract

Pulverized coal injection (PCI) is a technique worldwide used in blast furnaces (BFs) to reduce coke consumption. Burning of pulverized coal injected into tuyeres of BFs takes place under medium pressure (up to 450 kPa), high flame temperatures (around 2500 K), very fast heating rates (10^5–10^6 K/s) and very short residence times, less than 40 ms. Since there are no standard tests for evaluation of coal combustibility at PCI conditions, lab scale injection rigs are usually employed for this purpose. This work shows relevant characteristics of the injection rig developed by LASID-UFRGS, which operates at automated injection mode. The main rig features are direct measurement of pressure and temperature inside the combustion zone during combustion process, temperature measurement with ultra-fast thermocouples (ms), high speed control and data acquisition (ms) and collection of both solid and gaseous combustion products. First results showed pressure and temperature evolution along throughout the combustion test, with and without sample, combustion gas composition and coal burnout for different coals. Experimental data statistics showed good repeatability for all tested coals.
Keywords: Pulverized coal injection; Coal combustion; Injection rig; Blast furnace raceway.

PROJETO E CONSTRUÇÃO DE UM SIMULADOR DE PCI PARA COMBUSTÍVEIS SÓLIDOS PULVERIZADOS: CARACTERÍSTICAS DO EQUIPAMENTO

Resumo

A injeção de carvão pulverizado (PCI) é uma técnica utilizada em altos-fornos (AFs) para reduzir o consumo de coque. A queima do carvão pulverizado injetado nas ventaneiras do AF ocorre em pressões médias (até 450 kPa), temperaturas de chama elevadas (cerca de 2500 K), taxas de aquecimento muito elevadas (10^5–10^6 K/s) e tempos de residência muito curtos, abaixo de 40 ms. Como não há testes padronizados para avaliação da combustibilidade de carvões nas condições de PCI, simuladores de combustão em PCI são comumente utilizados para esse fim. Este trabalho apresenta as características relevantes do simulador de PCI desenvolvido pelo LASID-UFRGS, que opera com pulso automatizado de injeção. As características principais do simulador são a medida direta de pressão e temperatura dentro da zona de combustão durante o, a medição de temperatura com termopares ultrarrápidos (ms), a aquisição de dados e controle em alta velocidade (ms) e a coleta dos produtos sólidos e gasosos da combustão. Os primeiros resultados mostraram a evolução da pressão e temperatura durante o pulso de injeção, com ou sem amostra, o grau de conversão (*burnout*) do carvão e a composição dos gases de combustão para diferentes carvões. A análise estatística dos dados experimentais demonstrou uma boa repetitividade para todos os carvões testados.
Palavras-chave: Injeção de carvão pulverizado; Combustão de carvão pulverizado; Equipamento laboratorial de combustão; Zona de combustão do alto-forno.

[1] *Programa de Pós-graduação em Engenharia Química – PPGEQ, Universidade Federal do Rio Grande do Sul – UFRGS, Porto Alegre, RS, Brasil.*
[2] *Programa de Pós-graduação em Engenharia Metalúrgica, Materiais e de Minas – PPGEM, Universidade Federal de Minas Gerais – UFMG, Belo Horizonte, MG, Brasil. E-mail: andre.machado@ufrgs.br*
[3] *Programa de Pós-graduação em Engenharia de Minas, Metalúrgica e de Materiais – PPG3M, Universidade Federal do Rio Grande do Sul – UFRGS, Porto Alegre, RS, Brasil.*
[4] *Departamento de Engenharia Metalúrgica e de Materiais – DEMM, Universidade Federal do Ceará – UFC, Fortaleza, CE, Brasil.*

1 INTRODUCTION

Pulverized coal injection (PCI) is a technology widely used in blast furnaces (BFs). PCI is effective both in reducing the consumption of coke, which is directly linked to the cost reduction of produced hot metal, as in increasing productivity in BFs. Apart from these advantages, PCI can reduce the environmental impact of steel plants, through combined injection of fine charcoal and coal or associated with cleaner fuels such as natural gas. In recent decades, PCI rates have increased in most BFs, reaching values between 150 – 220 kg/t hot metal [1,2].

Despite the recognized economic and environmental advantages of PCI, some coal-related technical difficulties may limit the level of coke substitution such as generation of char, which is residual solid with unburned carbon, soot and tar during the fast pyrolysis and combustion of coal injected [3]. Fine char particles carried by the ascending exhaust gases at high PCI rates may accumulate along the BF, leading to a decrease of bed permeability and unstable operation, as well as undesirable gas and temperature distribution and possible hanging of the burden [3,4]. Due to the very short residence time in the raceway, incomplete combustion of coal carbon is likely to happen, so that the carried char carbon will further react outside the raceway somewhere in the BF. The aim of the PCI operation is always to keep the amount of unburned carbon in char in the BF stack at a low level while increasing the PCI rate [3].

The devolatilization and combustion of injected PC into the tuyeres of BF occurs under extreme conditions of temperature (around 2500 K), heating rate (10^5 to 10^6 K/s), pressure (450 kPa) and residence time (10 to 40 ms), under an atmosphere of preheated oxygen enriched air [2]. The amount of unburnt carbon will depend on several factors such as particle size, oxygen enrichment, blast temperature and coal properties. Many of these operational parameters cannot be modified beyond certain technological limits and therefore proper coal selection may improve the burnout [5]. When all injected oxygen is depleted, the main carbon consuming reaction is char gasification by CO_2. This is thought to take place at the end of the raceway and in the furnace shaft [6].

Comparing coals and chars regarding combustibility and reactivity in BF is a very difficult task. There is still no standard test to assess these parameters. Moreover, obtaining experimental measurements from the combustion of solid materials in the tuyere and raceway of BF faces with enormous technical difficulties due to the harsh conditions that prevail in those areas. The assessment of prevailing local operational conditions requires large investments in sophisticated sensors and equipment (2). Another approach to evaluate the coal combustion performance could be the analysis of the dust carried by waste gas at the BF top by techniques such as optical microscopy and X-ray diffraction (XRD) [7]. Additionally, computational theoretical models of coal combustion in the raceway can also be used. Due to the complexity of the phenomena taking place in this region this via needs experimental validations to improve the model and optimize the results [8].

A feasible alternative of study from technical and financial points of view, used by several research centers around the world, is the evaluation of coal combustion process injected into the BF by testing coal behavior with laboratory/pilot scale equipment operated under conditions as near as possible to the ones of the actual raceway. Some equipment typically used in laboratory scale for this purpose are thermobalance (TGA) [9], drop tube furnace (DTF) and PCI injection rig. PCI injection rigs, also known as PCI simulators, are considered the most appropriate device to assess the combustion of coal for PCI due to operation in very similar conditions of those in BF raceway [7,10].

1.1 PCI Injection Rigs

The direct investigation of pulverized coal combustion injected into the BF is very difficult because of the hostile conditions prevailing in the tuyere and raceway zones. Direct measurements in BFs in operation are expensive and require sophisticated equipment (2). Various research institutes around the world developed different PCI injection rigs and procedures to evaluate the combustion of coal [10-17].

The PCI injection rig developed in the 80s at the IEHK/RWTH Aachen University, Germany, deserves special mention [18]. This equipment has relatively compact structure and is easy to operate. This injection rig was initially built in a horizontal position, but in the 90s was modified to an upright position to prevent the formation of deposits and clusters. This equipment simulates the BFs zones from the injection lance and tuyere to part of raceway [8].

The operation of Aachen's injection rig is as follows: the coal sample is blown by a high-speed stream into a preheated gas of 1400 K, simulating the hot blast. Thereafter, the coal-gas mixture passes through a high temperature zone of 2000 K, simulating the raceway. While passing through the high temperature zone, the sample converts into reaction gas and char. The char is collected on a filter and cooled with nitrogen to prevent further combustion. The reaction gas is analyzed on line in regard of contents of CO, CO_2, CH_4, H_2 and O_2. Based on the concentrations of these components, sample weight, composition and experimental conditions, the conversion degree can be calculated. The results are plotted in diagrams showing the conversion degree vs. the O/C atomic ratio of the sample and gas atmosphere [19].

In Brazil, all the injection rigs used to simulate the injection of coal are based on the horizontal Aachen's model. Possibly its compact design and simple operation, as mentioned earlier, were the main reasons for adopting it. Currently there are three Brazilian PCI injection rigs in operation: two at different steel plants (Usiminas and Companhia Siderúrgica Nacional – CSN) [19-22] and one at Ouro Preto Federal University (UFOP) [21]. All of them comprise two furnaces, one for preheating oxygen to the blowing temperature in the furnace and the other to simulate the thermal conditions in the combustion zone.

1.2 Objectives

This paper aims to present the injection rig developed at the Iron and Steelmaking Laboratory of the Federal University of Rio Grande do Sul, Brazil (LASID-UFRGS), as well as its possibilities and some kinetic and thermodynamic aspects of the tests to be developed in this equipment. Preliminary experimental results are also presented and discussed.

2 METHODOLOGY

2.1 Rig Conception and Design

The PCI injection rig developed at LASID was designed to perform lab-scale combustion tests at conditions as close as possible to those prevailing at the BF raceway. Additional design requirements were easy low-cost operation, solid and gas product samples collection, high level automation, high-speed data acquisition system, flexible operational parameters control, one-shot sample injection and potential to be adapted to continuous injection of gaseous and solid fuels. The selected concept basis was the upright injection rig built at the IEHK-RWTH, at Aachen, Germany.

Figure 1 shows schematically the LASID lab-scale injection rig. As others PCI simulators, the rig simulates the solid fuels behavior along the raceway from the fuel injection zone to the combustion zone, with the same sequence of heating, devolatilization and reaction zones.

The PCI injection rig consists basically of three regions: I – fuel injection and combustion; II – exhaust gas collection; III – high-pressure gas pulse trigger. These regions operate on different pressure levels. The fuel combustion region, which is the largest part of the simulator, operates at pressures of 200 to 300 kPa, in all its sections: the combustion gas preheating, the solid fuel sample injection, the combustion zone, the post-combustion cooling and reacted residual solids collection. The exhaust gas collection region operates under vacuum, from 10 to 50 kPa. The injection gas trigger region, which generates the high-speed gas pulse to entrain the solid fuel particulate sample, operates at pressures above 400 kPa.

The injection rig was designed to operate in pulse mode. Although, conception and dimensions were selected to allow future upgrade to operate with fuel injection both in continuous and pulse mode. The pre-heating furnace (F55) is positioned horizontally while the combustion furnace (F73) is

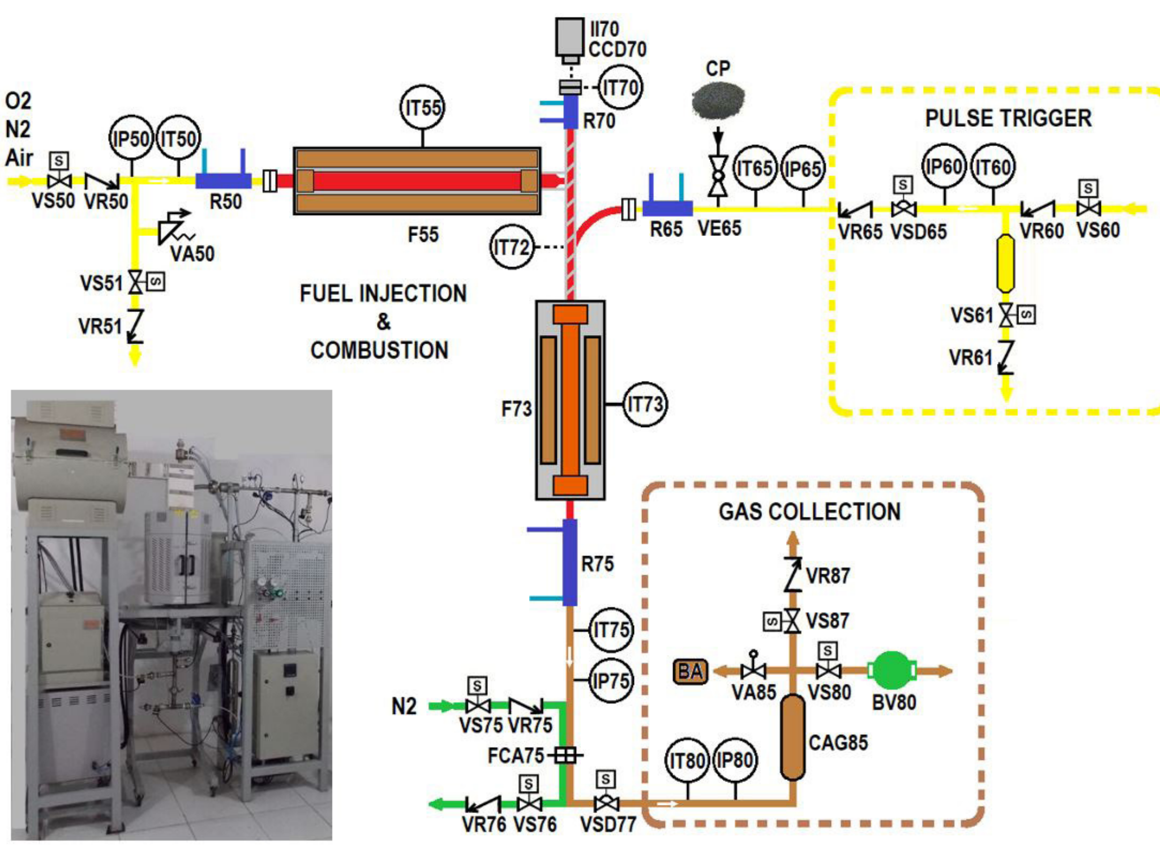

Figure 1. The LASID PCI injection rig scheme and view.

placed vertically. This arrangement allows to evaluate more efficiently the thermal profile of the temperatures inside the combustion furnace and along the combustion axis, where heating, devolatilization and combustion of injected fuel take place. This arrangement also allows continuous temperature reading at the mixing point of the solid fuel particles with the pre-heated oxidant gas.

The equipment consists of a series of pressure and temperature sensors (IP, IT) controlling input variables, coolers efficiency (R) and providing data to be collected during the tests. The pressure sensors have a response time lower than 1 ms, which allows to measure the residence time of fuel sample inside the combustion furnace (combustion zone). Fast thermocouples with time constant less than 1 ms are used for the same purpose. A series of high performance valves (VS, VSD) allows setting and control of the time intervals of the automated operational routines. After combustion, gases and particulates are collected in a sintered brass filter (FCA75) to separate the exhaust gas from residual char. A vacuum pump (BV80) is responsible for evacuation of the whole system during the purge and to produce vacuum at the gas collector. The gases resulting from combustion or pyrolysis are collected in bags and sent to chromatographic analysis. After the gas collection, valves (VS75, VS76) are triggered to send a nitrogen stream flow through the brass filter cooling the sample.

Tests conducted on PCI injection rig are basically composed of the following sequential steps: pre-heating of the furnaces, pressurization test, purging, gas collection system evacuation, fuel feeding, system pressurization, injection pulse and reaction, collection of the gases, cooling and collection of char.

2.2 Equipments and Materials

2.2.1 PCI rig components

The combustion reactor is a 1" internal diameter high-purity alumina tube, 600 mm long, 3 mm wall thickness, selected to allow pre-heating temperatures to 1800K, combustion conditions (temperature, radiation) close to those prevailing at the blast furnace raceway. A stainless steel SS310 reactor can also be used to operate at pre-heating temperatures below 1300 K. All other parts of the rig are made of refractory stainless-steel SS 310, sch40, to withstand pressures to 1000 kPa and temperatures to 1300 K.

The horizontal tubular pre-heating furnace, supplied by Fornos Jung from Blumenau, Brazil, has 2.0 kW thermal power, 1450 K maximum temperature. The vertical tubular combustion furnace, supplied by Carbolite, Hope Valley, England, has 4.5 kW thermal power, 2000 K maximum temperature. Both furnaces have 60 mm internal diameter and 900 mm length.

The rig control system is composed by pressure and temperature sensors connected to field loggers, gas flow valves and mass flow controllers. All data are fed to a programmable logic controller (PLC), which controls flow valves, vacuum pump, furnaces and cooling system. The PLC is programmed with several routines to perform different kind of tests, like combustion with oxygen and oxygen-nitrogen mixtures, pyrolysis, rig zones leakage evaluation, and furnace heating and cooling routines. The test parameters may be set directly at the PLC or sent to PLC by the supervisory system. This is also possible for the tests execution. Data acquisition is made through a supervisory system fed with all PLC and field loggers data. A high-speed camera, Fastec TS3L, resolution 800 × 600 at 1250 fps, can be used to record the combustion process.

2.2.2 Gas analysis

After combustion tests, gas samples from the gas collector are taken and stored in 1 liter bags. Gas composition of N_2, H_2, CO, CO_2 and CH_4 is obtained by gas chromatography analysis, with a chromatograph Shimadzu model GC-2014. In this kind of simulators, relative amounts of CO, CO_2 and CH_4 are used to calculate combustion efficiencies [18-22].

2.2.3 Solid fuel samples

Three coals HV1, HV2 and LV were selected for the pre-operational rig tests under different combustion conditions. HV1 and LV are bituminous high volatile and low volatile coals, respectively, and HV2 is a sub bituminous high volatile coal.

The proximate and ultimate analysis of the tested coals are shown in Table 1. Test samples, grain size 36-75 μm, were prepared by successive milling and sieving steps.

2.2.4 Experimental conditions

The prepared fuel samples were dried at 40 °C and stored in a desiccator. Test samples of 1.0, 1.5 and 2.0 grams were burned under two different combustion pressure conditions 2 and 3 bars. All experimental conditions were tested at least in triplicate.

Both pre-heating and combustion furnaces were heated to 1300 K. All combustion tests were done under pure oxygen atmosphere, following routines previously

Table 1. Proximate, ultimate, and free swelling index analysis results of fuel samples

Fuel	Proximate analysis (wt% db)			Ultimate analysis (wt% dafb)					FSI
	Ash	VM	FC	C	H	N	O	S	
HV1	10.8	38.0	51.2	73.6	5.0	1.6	8.3	0.8	2.0
HV2	18.9	32.3	48.8	63.8	4.1	1.1	11.5	0.6	0.0
LV	10.6	15.4	74.0	81.4	3.9	1.7	1.6	0.7	1.5

VM: volatile matter; FC: fixed carbon; db: dry basis; dafb: dry ash free basis. FSI: free swelling index; HV1: bituminous high volatile coal; HV2: sub bituminous high volatile coal; LV: bituminous low volatile coal.

mentioned at item 2.1. Combustion gases were collected and analyzed as described below and char samples were cooled with N_2 and collected for burnout evaluation.

2.2.5 Burnout evaluation

Coal burnout was measured by ash tracer method examining the ash balance of combustible matter before and after each test. The ash percentage in the residue A_f was measured by the TGA instrument by burning it in air upon heat-up to 1273 K at a heating rate of 30 K/min. By employing the original ash content (A_i, wt% on dried basis) of the sample injected, the burnout (B) can be calculated by using Equation (1) below [23]:

$$B(\%) = \left(1 - \frac{A_i}{A_f}\frac{(100 - A_f)}{(100 - A_i)}\right) \cdot 100 \qquad (1)$$

3 RESULTS AND DISCUSSION

3.1 Experimental Pressure, Temperature and Gas Composition Profiles

Figure 2a depicts a supervisory drawn graph from a pulse shot test without coal sample (empty shot), showing temperature and pressure histories at the injection and combustion regions along the pulse time interval. Figure 2b shows temperature and pressure profiles along the time at the combustion test of a 1.5 g coal sample.

In coal combustion tests, in less than 10 ms after pressure equalization, the pulverized coal sample mixes with the pre-heated oxidation gas and reaches the combustion zone. Along the combustion process, pyrolysis gases combustion and heat generation produces significant increases of system pressure and temperature. Similar patterns of pressures and temperature behaviors were obtained for all tested conditions, showing that the combustion phenomena prevailing are the same, but with different intensities. At the next step of this work, the evaluation of those phenomena will be deepened.

Figure 3 shows peak temperature, peak pressure, CO/CO_2 ratio and burnout from combustion tests of HV2 coal with pure O_2 for 3 test sample masses and 2 combustion pressure conditions. Peak temperatures were measured at the coal and pre-heated oxygen mixing point, at about 50 cm above the combustion zone. The use of special thermocouples to measure temperature profiles along the combustion zone is planned for future work.

For higher test pressures at the same coal weight, higher peak temperatures were obtained for all tested coal weights. This behavior was expected as higher operational pressure means higher O/C ratio, allowing higher combustion rates.

For both tested combustion pressures, peak temperatures increased with coal weight from 1.0 to 1.5 g and decreased with 2.0 g. The 1.5 g samples combustion produced the highest peak temperatures. Fast initial temperature increase is explained by the volatiles fast combustion and initial char combustion, producing CO_2, CO and H_2O [2, 24]. Temperature peaks of this high-volatile coal are associated to the very fast combustion of volatiles generated at the previous fast pyrolysis step, which occurs in few ms [6,25]. The 2.0 g samples combustion produced a lower peak temperature and a smaller peak pressure increase than the 1.5 g samples, which may be explained by the lower O/C ratio, resulting in slower volatiles combustion.

Peak pressure increase was very similar for all coal weights tested, despite the different volatiles amount generated and burned in each case. A possible explanation could be that the volatiles generation and burning rate is limited by the heat transfer rate from gas to coal to supply the needed energy for the high endothermic pyrolysis step. Coal sample weight increase produced also increased CO/CO_2 ratio, probably due to associated O/C ratio decrease. Temperature

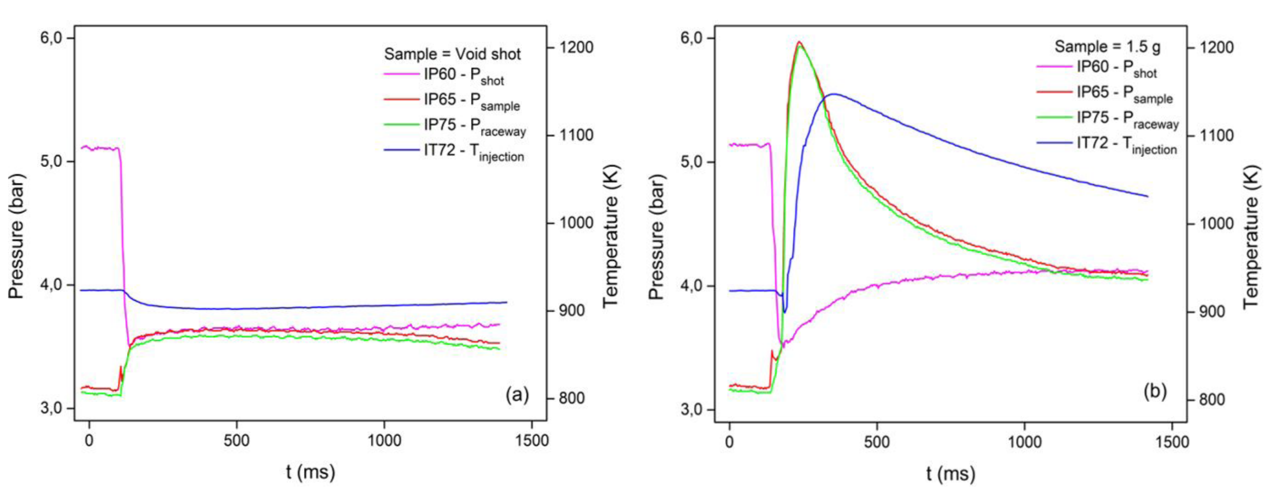

Figure 2. Experimental combustion: (a) Pulse without coal injection; (b) Combustion (1.5 g, O_2, 3 bar).

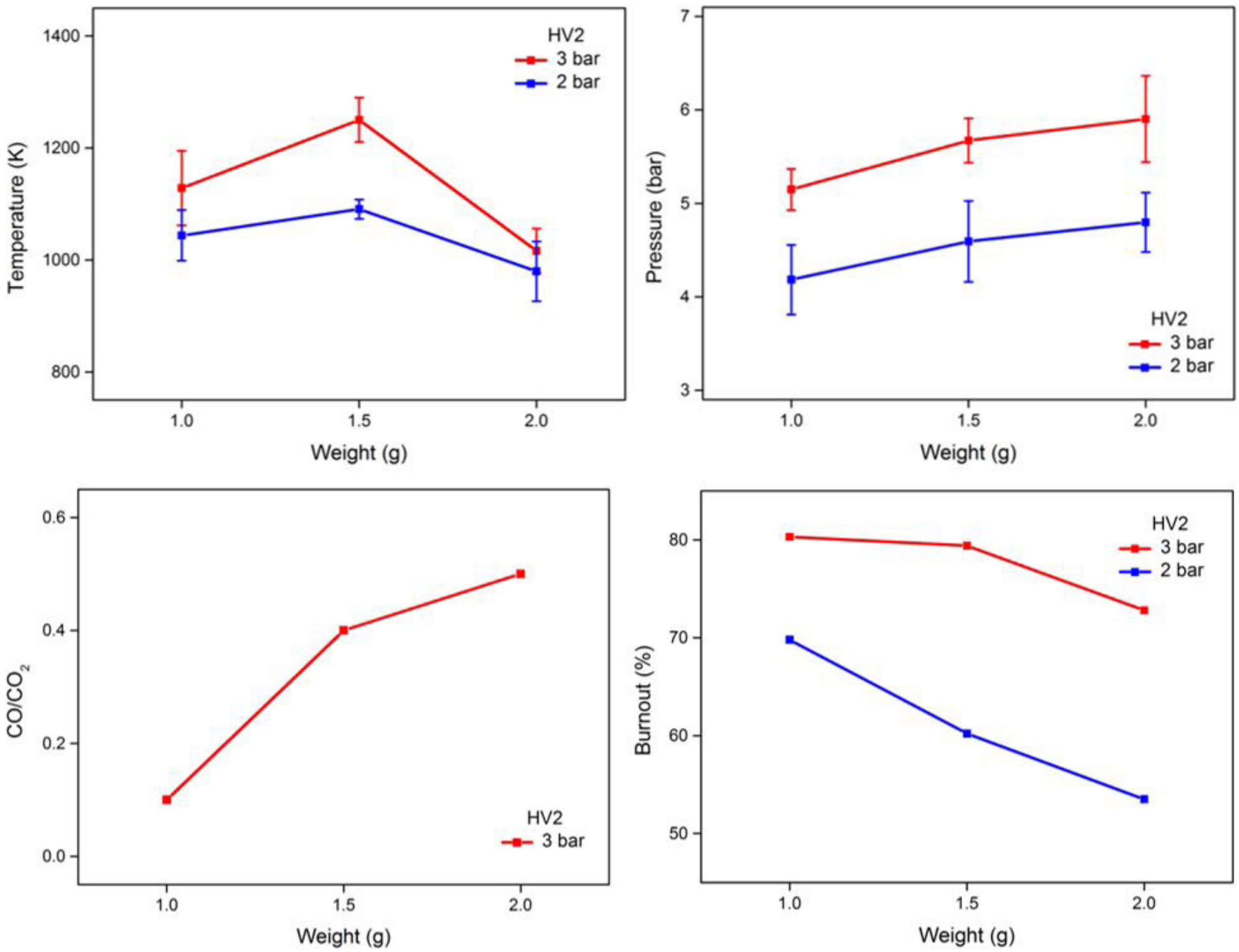

Figure 3. Influence of injected coal weight and O_2 pressure on peak temperature, peak pressure, CO/CO_2 ratio and burnout for coal HV2.

increase also contributes to pressure increase in a closed constant-volume reactor, like this PCI simulator. For the 2.0 g samples, we may infer that the positive contribution of the volatiles generation and burning to the peak temperature increase was counterbalanced by the higher heat consumption at the pyrolysis step and the reduced heat generation due to higher less energetic CO production relatively to lower high energetic CO_2 production. In the BF, the coal volatile content can affect char formation, blast momentum and generate coke fines in the raceway [2]. For PCI coal blends, the total volatile matter composition must be controlled to avoid problems at the BF operation.

Burnout values increased with oxygen pressure and decreased with coal weight as expected, due to O/C ratio increase with oxygen concentration and decrease with fuel amount. Oxygen concentration also impacts thermodynamic equilibrium conditions and reaction rates in both cases of chemical kinetics and gas transport rate control. Additional experiments beyond the scope of this work will contribute with new data to a better understanding of the relevant controlling combustion phenomena.

3.2 Experimental Burnouts

Table 2 presents the statistical analysis (SPPS 24.0) of burnouts obtained at combustion pressure of 2 bar for the three studied coals (1.5 g).

Considering the limited data available, less than 30 tests, it is needed to evaluate if the results follow a normal distribution. The statistical analysis software *Statistical Package for Social Sciences (SPSS), version 24.0* was used for that purpose, performing normality test of Shapiro-Wilk (S-W) with a 95% confidence degree. Values for the significance level (p-value) were greater than 0.05, which characterizes a normal distribution. Therefore, the burnouts distribution obtained at this simulator can be defined by mean and standard deviation.

As expected, both high-volatile coals HV1 and HV2 showed higher burnout values than the low-volatile coal LV. Also, the sub-bituminous coal HV2 showed higher burnout than the bituminous HV1 coal, probably explained by the higher reactivity of sub-bituminous coals compared to bituminous coals, which coal molecules have a more compact chemical

Table 2. Burnouts statistical analysis (SPSS 24.0)

Fuels	Burnout (%)					Mean	Standard deviation	p-value Shapiro-Wilk
HV1	43.9	51.3	58.0	48.3	48.6	50.0	5.2	0.708
HV2	67.6	63.2	60.7	60.8	61.7	61.8	2.9	0.356
	68.3	63.3	51.0	59.8	67.6			
	58.6	54.6	58.5	68.3	63.6			
LV	35.9	42.8	47.6	48.8	37.9	42.6	5.7	0.487

HV1: bituminous high volatile coal; HV2: sub bituminous high volatile coal; LV: bituminous low volatile coal.

structure. Higher FSI compared to HV2 (see Table 1) may explain some particle agglomeration observed at the HV1 char. Bigger particles formed after pyrolysis may contribute to a lower combustion rate and lower burnout. The influence of coal rank and FSI will be subject of further studies planned for the LASID PCI simulator.

The first combustion data obtained at the LASID injection rig fulfilled the expectations based on the characteristics of the tested fuels. Combustion experiments in this kind of injection rigs may be conducted at conditions very similar to those prevailing at the BF tuyeres and raceway zones. The LASID injection rig can be operated at pressures of 1 to 5 bars, residence time below 50 ms, with pre-selected controlled atmosphere and temperature, similar to typical BF conditions, producing chars with almost the same structure and properties as the ones from a BF. Therefore, the combustion evaluation of coals made on this PCI simulator will give high quality information to support the selection of best fitted PCI fuels and/or fuel blends and to forecast their combustion performance at the BF. Like any other lab scale experiment, injection rig data must be validated on commercial size BFs. Such validation is planned as a next step of this study.

4 CONCLUSIONS

The LASID injection rig is a new additional tool developed to be used in academic studies of coal combustion to better understand the pulverized coal injection – PCI process in blast furnaces.

The major findings from this study can be drawn as follows:

1. The statistical evaluation of temperature, pressure, combustion gases composition (CO/CO_2) and burnout data showed that the tests performed at the LASID simulator have good repeatability and can be used to evaluate the phenomena involved at the devolatilization and combustion of coals and related solid fuels
2. The behavior of temperature, pressure and CO/CO_2 ratio contributed to a better understanding of the combustion phenomena for different test conditions.
3. Combustion tests results with a high-volatile coal showed the influence of the volatile matter content on the combustion behavior and burnout.

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