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Original Article

# Combustion behavior of granulated and pulverized coal in a PCI rig: combustibility and pressure variation analysis

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ABSTRACT

The effect of the coal volatile matter content and particle size has been investigated in a new lab-scale pulverized coal injection rig (PCI rig) in terms of combustion efficiency and pressure variation. Two coals typically used for blast furnace injection (a high and a low volatile bituminous coal) and their blends experienced combustion under pressurized conditions and extremely high heating rates and short residence times such as those experienced by coal particles in industrial process. Combustion tests were conducted for a low volatile coal prepared in the particle size ranges of 25–75 μm, 105–250 μm and 250–500 μm. Burnouts were lower for the larger particle size sample, but the intermediate particle size sample (105–250 μm) yielded similar conversion to that of the finer sample. The burnouts of the high and low volatile coal, as well as those of their blends were proportional to the volatile matter content of samples in the test conditions. The measurement of pressure variation in the reactor chamber indicated a displacement in the beginning of reactions to longer times as larger was the particle size of coal. The high volatile coal reached the maximum pressure variation earlier than the low volatile one and the combustion of this coal in the blends may have anticipated the reaction of the low volatile coal portion in the blends.

## 1. Introduction

Pulverized coal injection (PCI) reduces coke consumption, contributes to operational flexibility and improves productivity in blast furnaces [1,2]. It is desirable operating under high injection rates with the highest possible coke replacement ratio. However, increasing the injection of solid particles in the blast furnace can cause operational instability and, therefore, demands appropriate coals selection and optimization of operational parameters, which are directly connected to a better understanding of coal behavior during combustion.

Due to the extremely severe conditions experienced for coal particles when entering through the injection lance and

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the limitations of conventional analytical techniques in reproducing them, numerous research centers invested in the construction of reactors able to submit particles to conditions close to those observed during the injection process [3–6]. A new device has been also built in the Ironmaking Laboratory at UFRGS aiming at investigate coal behavior under conditions close to those experienced by coal particles in PCI and contribute on coal selection for industrial application [7,8].

Combustion process of coal in PCI can be separated in several steps, which overlap one another due to the severe heating condition, but can be separately named as, heating, devolatilization, volatile ignition and combustion and char combustion and gasification. The extension of each step in the injection system depends on coal properties and combustion conditions [2]. Considering the reactions kinetics, combustion can be briefly divided in two stages, a faster one corresponding to the consumption of the volatiles by oxygen and a slower one, which is the heterogeneous gas-solid reactions of char with oxygen and $CO_2$ [9]. Thus, coal characteristics such as the volatile matter content and the particle size influence on the beginning and extension of reactions and, consequently, affect the combustion efficiency, as investigated in specially developed devices for PCI studies [10,11] and industrial tests [12].

The effect of coal particle size on PCI process was investigated by Hutny et al. [13], who found lower burnouts for granular coals compared to pulverized samples. Conversely, Steer et al. [14,15] and Vamvuka et al. [11] observed that in some cases, larger particle size coals can improve combustion due to fragmentation of particles. The injection of granular coals is desirable since it could increase the mill production capacity, reduce problems related to the pneumatic transport of coal to the tuyeres and reduce the energy consumption and maintenance costs in the grinding unit [16]. It is reported that the installation of a granular coal injection system in the blast furnace reduced up to 60% the energy consumption for the coal grinding, besides reducing problems related to handling, without compromising the stability and the replacement ration in the blast furnace [17].

Some authors have mentioned the impact of the coal properties on the pressure variation in the reactor and its effect on the blast furnace stability. Using a single tuyere raceway investigation rig, Atkinson and Willmers [18] were able to control the blast pressure during coal injection tests. By measuring the differential pressure across the tuyeres using a pilot scale apparatus for PCI simulation Mathieson et al. [19] evaluated the flame stability of pulverized charcoal types to assess likely effects on maximum injection rates and blast furnace permeability. The authors found that the increase in the pressure drop related proportionally to the volatile matter content of samples. Suzuki et al. [9] simulated coal injection using a tunnel furnace constructed in similar scale of an industrial injection system. In such facility, the authors were able to measure the pressure increase in the blowpipe due to the coal injection rate increase, but the effect of coal properties on pressure variation was not explored. Despite the importance of the pressure variation caused by coal properties, the availability of laboratory facilities able to easily measure this parameter during combustion is scarce.

This work aims to study the effect of the volatile matter content and particle size on coal combustion in a new laboratory facility operating under pressurized conditions, extremely high heating rates and short residence times such as those experienced by coal particles in blast furnace injection process. A high and a low volatile bituminous coal, as well as their blends were studied according to the burnout behavior and pressure variation in the furnace chamber.

## 2. Materials and methods

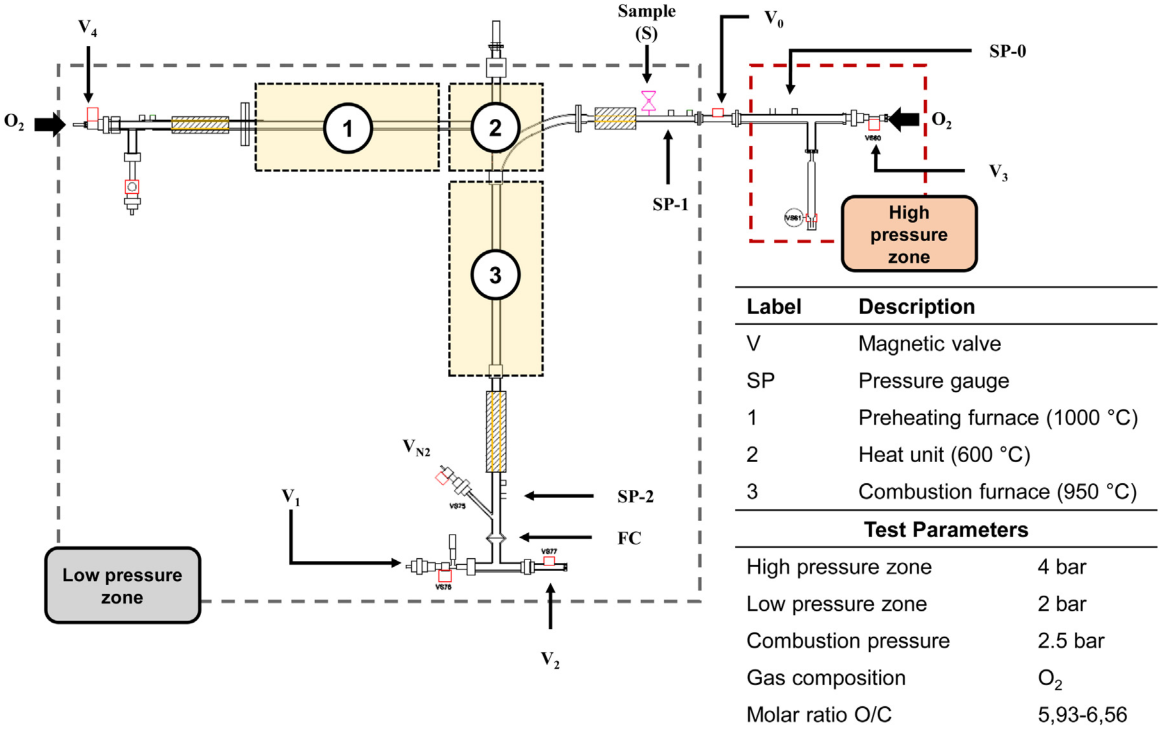
### 2.1. PCI rig

A lab-scale PCI rig was developed in order to investigate coal combustion under blast furnace injection conditions. Fig. 1 shows a scheme of the facility and its complete description is made elsewhere [8]. Basically, the PCI rig consists of three heating units (represented by the numbers 1, 2 and 3 in Fig. 1) which work on a closed system and is composed by pressure and temperature sensors, gas flow valves and mass flow controllers. A programmable logic controller (PLC) controls flow valves, vacuum pump, furnaces and cooling system, allowing the facility to perform varied test and cleaning routines.

Both the preheating and the combustion units (1 and 3 in Fig. 1, respectively) consist of a tubular resistive furnace with a length of 900 mm and an internal diameter of 60 mm. The preheating furnace is maintained at 1000 °C to pre-heat the reactant gas and the combustion furnace works at 950 °C. These furnaces are connected by a heat unit (2 in Fig. 1) composed of a thermal tape capable of maintaining the temperature at 600 °C.

The feeding system follows the same principle as those “one-shoot” of German reactors [20] with programmed intermittent gas and sample feeding. The reactor is divided into two regions separated by a magnetic valve ($V_0$): the high pressure zone (HPZ) and the low pressure zone (LPZ). The sample is placed in the sample holder (S, Fig. 1) with the system at ambient pressure. The LPZ and the HPZ are pressurized to 2.0 and 4.0 bar, by opening $V_4$ and $V_3$, respectively. The LPZ starts to slowly depressurize by opening $V_1$ until the LPZ reaches 2 bar, when a high-speed gas pulse is generated from the opening of $V_0$, blowing down the sample and the pre-heated gas into the combustion furnace. Residual char is cooled with nitrogen from $V_{N2}$ and trapped in a bronze filter (CC). The fast reading of the pressure sensors (lower than 1 ms) allowed measuring the pressure variation during the test, giving an additional and innovative response for this kind of facility.

Particles experience heating rates in the order of $10^4$ K/min and the residence time was estimated to be in the order of 500 ms by using the pressure variation curves as an indicative of when particles probably enter the combustion furnace. The tests in this work were performed with 100% oxygen to achieve maximum combustion efficiency. Each condition tested run twenty times with coal aliquots of 0.50 g, i.e., each burnout or pressure result is an average of twenty pulses (or shots) in the reactor in order to generate suitable amount of char. The data acquisition system recorded the variation of the pressure due to coal combustion and particles burnout was calculated using



| Label | Description |
|---|---|
| V | Magnetic valve |
| SP | Pressure gauge |
| 1 | Preheating furnace (1000 °C) |
| 2 | Heat unit (600 °C) |
| 3 | Combustion furnace (950 °C) |

| Test Parameters | |
|---|---|
| High pressure zone | 4 bar |
| Low pressure zone | 2 bar |
| Combustion pressure | 2.5 bar |
| Gas composition | $O_2$ |
| Molar ratio O/C | 5,93-6,56 |

Fig. 1 – Schematic diagram of the PCI rig.

**Table 1 – Coals characterization.**

| Coals | Chemical analysis (db) | | | | | | | | Petrographic parameters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | VM % | Ash % | $C_{fix}$ % | C % | H % | N % | $S_{tot}$ % | O* % | Rr % | V | L<br>% vol. mmf. | I |
| A | 38.0 | 10.8 | 51.2 | 73.6 | 5.0 | 1.6 | 0.80 | 8.2 | 0.61 | 82.73 | 2.56 | 14.71 |
| B | 15.4 | 10.6 | 74.0 | 81.4 | 3.9 | 1.7 | 0.70 | 1.7 | 1.54 | 68.84 | – | 31.15 |

db: dry basis; VM: volatile matter; Cfix: fixed carbon; Stot: total suphfur content; O*: oxygen calculated by difference; mmf: mineral matter free; Rr: random reflectance; V: vitrinite; L: liptinite; I: inertinite; vol: volume.

**Table 2 – Sets of samples used in PCI rig.**

| Samples | Particles size | Composition | VM (wt%, db) |
|---|---|---|---|
| A1 | 25-75 μm | 100% A | 39.63 |
| B1 | 25-75 μm | 100% B | 16.26 |
| B2 | 105-250 μm | 100% B | 15.92 |
| B3 | 250-500 μm | 100% B | 15.50 |
| A75B25 | 25-75 μm | 75% A + 25% B | 33.61 |
| A50B50 | 25-75 μm | 50% A + 50% B | 27.93 |
| A25B75 | 25-75 μm | 25% A + 75% B | 21.96 |

VM: volatile matter; db: dry basis.

the ash-tracer equation (Eq. 1):

$$Burnout\ (\%) = \left[1 - \left(\frac{Ash_{coal}}{100 - Ash_{coal}}\right) \times \left(\frac{100 - Ash_{char}}{Ash_{char}}\right)\right] \times 100 \quad (1)$$

where $Ash_{coal}$ is the ash content of coal or blend and $Ash_{char}$ is the ash content of the char collected in the furnace.

## 2.2. *Samples*

Two coals typical of blast furnace injection were select for this work. Proximate, ultimate and petrographic analyses of coals are shown in Table 1. The coals present similar ash and Sulphur contents, within the suitable limits for PCI use. Coal A is a vitrinite-rich high volatile bituminous coal (38.0% of VM) with vitrinite reflectance of 0.61% and coal B is a low volatile bituminous coal (15.4% of VM) with a vitrinite reflectance of 1.54% and moderate inertinite content (31.15%).

The influence of particle size was evaluated from the combustion of three ranges of particle sizes of the low volatile coal: 25–75 μm (B1), 105–250 μm (B2) and 250–500 μm (B3). Both coals were sieved to 25–75 μm and mixtures were prepared by weight in the proportions of 75% A + 25% B (A75B25), 50% A + 50% B (A50B50) and 25% A + 75% B (A25B75) in order to investigate the influence of volatile matter content in burnout and in pressure change during combustion. Table 2 summarizes all samples prepared to this study. Since the sample weight was exactly the same for all samples in the PCI rig

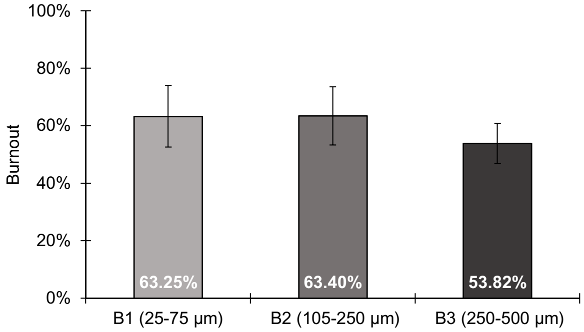


**Fig. 2 – Burnout of low volatile coal classified in different particle size ranges.**

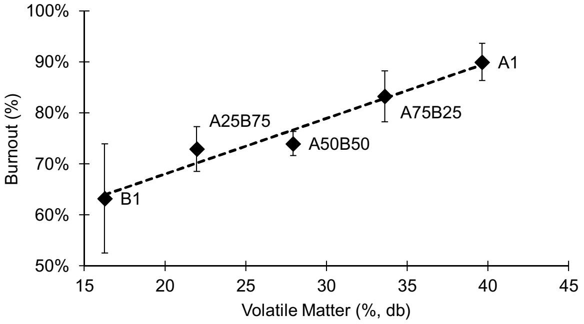


**Fig. 3 – Effect of volatile matter content on combustion efficiency of individual coals and their blends.**

(0.50 g), based on the composition of each coal the O/C ratio in the tests was calculated as 6.56 for coal A and 5.93 for coal B.

## 3. Results and discussion

### 3.1. *Effect of particle size on coal burnout*

Fig. 2 presents the behavior of the low volatile coal combustion for the different particle size ranges. It is known that, in general, kinetic phenomena favor the reaction the smaller the particle size is. In fact, the lower burnout (53.8%) was observed for the coarser particles (sample B3). The combustion process of coal particles when leaving the injection lance and enter the raceway follows at least two well-defined stages: the rapid devolatilization and volatile burning and the slow heterogeneous reaction of char combustion and gasification [9]. The thermal gradient from the surface in relation to the center of a coarse particle tends to be larger than for thicker ones. Consequently, these particles need more time to reach the temperature required for devolatilization, which retards the combustion [21] and reflects in lower burnouts. The intermediate particle size (sample B2), however, yielded burnouts similar to the finest sample (B1) (both samples showed burnouts in the order of 63%). Such improvement on coal combustion could be attributed to the fragmentation of the larger particles, induced by high pressure and temperature gradients inside these particles and could generate smaller and more reactive fragments [11,14]. Since these are preliminary results in this work, such phenomenon must be better investigated with a greater range of coal rank and varied combustion conditions in the injection rig.

### 3.2. *Influence of volatile matter on coal burnout*

Fig. 3 shows the burnouts of individual coals and their blends according to the volatile content. As expected [9,10,12], the high volatile coal (A1) showed higher burnout than the low volatile coal (B1). As the high volatile coal increased in blend proportion, burnout increased linearly, indicating that in the conditions tested, coal particles did not interact or presented synergistic effect on burnout behavior, as also observed elsewhere [22,23]. In fact, the volatile matter content is one of the main parameters affecting the combustion efficiency, since the volatile matter content is directly related to ignition temperature [24] and generates more reactive chars [25], passing through combustion stages more quickly and resulting in higher burnouts.

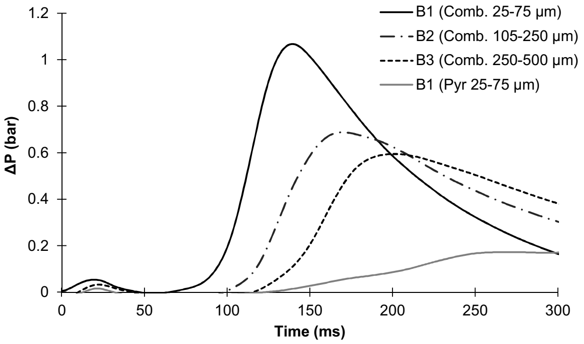


**Fig. 4 – Pressure profiles of low volatile coal under different particle sizes.**

### 3.3. *Pressure variation during combustion*

Fig. 4 presents the pressure variation in the PCI rig chamber in function of time for the combustion of the low volatile coal in different particle size ranges. Fig. 4 also presents a pyrolysis curve for coal B (in the same particle size range of sample B1, 25–75 μm) in order to elucidate what could be the best interpretation for the physical significance of the pressure variation in the reactor chamber. The most likely phenomena associated to the pressure variation in the reactor chamber due to combustion are the devolatilization, volatile ignition and burning and char oxidation reactions, the latter being a much slower reaction than the first ones. Comparing combustion and pyrolysis curves for coal B, it is seen that the combustion curve rises in shorter time and reaches greater pressure variation than pyrolysis curve. Since coal pyrolysis is associated only to volatile release step, it could be inferred that volatile ignition and combustion predominates on pressure variation within the reactor.

As the particle size increased the pressure profile tended to decrease to lower pressure variations and shifted to longer times, so there was a delay in the production and ignition of the volatiles during the combustion due to increase in particle size. Two hypotheses could explain this behavior. The first one

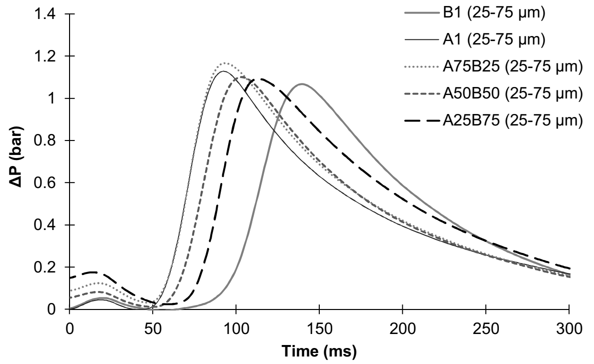


**Fig. 5 – Pressure profiles of individual coals and their blends.**

is that the particle size affects the heat transfer and the heating rate inside the particle, so the higher the particle size is, the slower the heating of the particle as a whole, which delays the devolatilization process [21]. The second one is that the products generated during devolatilization in the center of the particle must migrate outside. In the migration process, these products may crack, condense or polymerize and deposit into the particle walls. The larger the particle size is, the greater the amount of deposited material, as a consequence there is a reduction in the volatile content yield, which could also retard volatile release and reduce pressure variation [26].

Fig. 5 shows the pressure variation in the PCI rig chamber in function of time for the combustion of the high (A1) and low volatile (B1) coals as well as their blends 25–75, 50-50 and 75-25% under the same particle size range (25–75 μm). The high volatile coal reached a maximum pressure variation of 1.14 bar at 92 ms, while the low volatile coal showed the maximum peak at 1.08 bar and 139 ms. Despite the small difference in maximum pressure variation, it is clear on Fig. 5 that when the high volatile coal reaches the maximum pressure variation, the low volatile one is still at the beginning of the process, which could be significant on the gas formation profile in the raceway.

As expected [10,27], as the proportion of the high volatile coal increased in the blends, the pressure variation profiles shifted to the left, thus indicating a shorter time for the beginning of the devolatilization and ignition process as higher the volatile matter content in the blend. However, all blends shifted to shorter times than expected, indicating a possible synergistic effect in which the combustion of the high volatile coal could anticipate the devolatilization and ignition of the low volatile coal portion in the blend.

Since the volatile matter content strongly influences on blast pressure, the type of coal, or blend used in PCI will also act as a determining agent on burden permeability, pressure drop, back pressure in the tuyeres and in the flame stability [9,18]. Hence, measuring the pressure variation during coal combustion in a lab-scale facility, in addition to contribute to the understanding of combustion stages for different coals, could help in the selection of coals for individual use or for blends composition as well as in defining the operating adjustments of PCI process.

## 4. Conclusion

The effect of the coal volatile matter content and particle size were investigated in a new pulverized coal injection rig and the following aspects can be pointed out in terms of combustion efficiency and pressure variation:

Combustion of a low volatile coal prepared at different particle sizes evidenced the higher combustion efficiency for the finest particle size range. However, burnouts for the particle size range of 250–500 μm was similar to that of samples between 25 and 75 μm, which could be attributed to the fragmentation of the coarser particles.

The burnouts of the high and low volatile coal, as well as those of their blends showed a directly proportional relation with volatile matter content of samples in the test conditions.

The volatile ignition and combustion led to an increase in pressure inside the PCI rig combustion chamber. Larger particle size coals showed lower pressure rise inside the PCI rig and particles combustion was delayed to longer times.

Despite the small difference in maximum pressure variation for the two different coals, it was clear that when the high volatile coal reached the maximum pressure variation, the low volatile one was still at the beginning of the process, which could be significant on the gas formation profile in the raceway.

As the proportion of the high volatile coal increased in the blends, the pressure variation profiles showed earlier ignition and burning than expected, indicating a possible synergistic effect in which the combustion of the high volatile coal could anticipate the devolatilization and ignition of the low volatile coal portion in the blend.

The use of a lab-scale facility to measure pressure variation during coal combustion has proved to be an important tool for the understanding of combustion stages for different coals, as well as could contribute in the selection of coals for use in PCI process.

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