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COMPARING THE PERFORMANCE OF A BLACK COAL AND AN UPGRADED BROWN COAL BY BRIQUETTING IN IRONMAKING BLAST FURNACE

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ABSTRACT

Pulverized coal injection (PCI) technology has been practised in ironmaking industry for years due to various benefits in particular cost reduction, where black coal was used widely in the past. Victorian brown coal with a lower cost has a great potential of being used in PCI technology and further reducing the cost by replacing the black coal. Usually Victorian brown coal can be upgraded by briquetting or pyrolysis to remove the massive moisture. There is a lack of understanding the in-furnace phenomena including aerodynamic and physicochemical behaviours related to the use of brown coal in a blast furnace (BF). A previous study indicated similar evolutions of combustion characteristics between black coal and the brown coal upgraded by pyrolysis under a given temperature. But it is unclear yet whether the brown coal upgraded by briquetting has similar combustion performance. In this study, an industry-scale three-dimensional CFD model is used to compare the in-furnace combustion phenomena of an upgraded brown coal by briquetting vs. a black coal under BF conditions. They are compared in terms of flow, temperature, gas composition and coal combusts characteristics. Results from the simulation indicate that the performance evolution of pulverized brown coal upgraded by briquetting is different from that of black coal due to the higher VM content in brown coal product upgraded by briquetting. Numerical modelling offers a cost-effective way to further optimize and control the pulverized brown coal injection process.

Keywords: brown coal, black coal, numerical modelling**,** pulverized coal injection, ironmaking blast furnace

NOMENCLATURE

m	mass
U	mean velocity of gas, m s^{-1}
f_D	drag force from a particle, N
d	particle mean diameter, µm
ρ	density, kg m^{-3}
C_D	drag coefficient
Re	Reynolds number

INTRODUCTION

Ironmaking blast furnace (BF) contributes significantly to the greenhouse gases emissions and global warming due to the massive use of coke and thus coke ovens, which is responsible for considerable CO_2 emissions. It is necessary to optimize the operation of BF and take the most advantage of other fuels. Pulverized coal injection (PCI) has been practised and brought great benefits such as reducing production cost and CO_2 emission in ironmaking by reducing coke consumption, and increasing furnace controllability. Generally, pulverized coal is injected through an injection lance and carried by a stream of gas mixture introduced from blowpipe, forming a high speed jet. Then coal combustion takes places in a cavity named raceway and the combustion of coke and coal generate massive heat in a short time. The schematic of PCI technology and internal structure around raceway in a BF is illustrated in Figure 1.

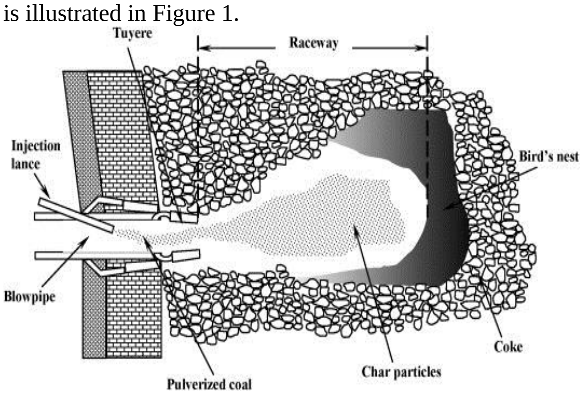

Figure 1: Schematic of PCI technology and internal structure around raceway in a BF (Chen and Wu 2009)

Victorian brown coal has been used in electricity generation only in the past. On the other hand, it is reported that the emission of greenhouse gases can be greatly decreased when combusts dried brown coal(Karthikeyan *et al.* 2009). Compared with black coal, high moisture content (~65 wt%) is one of the key problems of the application of Victorian brown coal. Usually Victorian brown coal can be upgraded by briquetting or pyrolysis to remove the massive moisture. Desirable characteristics, such as high reactivity, relatively low sulphur content, abundant in reserves and cheap, make upgraded Victorian brown coal a good solid fuel. Many advanced combustion technologies have been developed to make use of brown coal as fuel, meanwhile reduce emissions of CO_2, NO_x, and SO_x (Doukelis *et al.* 2009; Wall *et al.* 2009; Kanniche *et al.* 2010). However, these studies are based on the combustion of brown coal in the power plant.

In order to utilize brown coal in BFs, as a reliable and low-cost energy source, the understanding of aerodynamic and physicochemical combustion phenomena of brown coal products is required. The lower part of BF including lance-blowpipe-tuyere-raceway-coke bed (LBTRC) region, is not easily accessible as its working environment is severe (high temperature, melting phase of iron etc.). Mathematical modelling offers an effective way to

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replicate the comprehensive in-furnace phenomena, providing insights to understanding and optimize the use of brown coal and control the BF operation. Modelling of the operation of PCI in BF has been investigated for years from 1D e.g. (He *et al.* 1986), to 2D e.g. (Aoki *et al.* 1993; Takeda and Lockwood 1997), where simple combustion characteristics in the blowpipe-tuyere-raceway region have been predicted but their models are still relatively simple and some in-furnace phenomena cannot be predicted. Due to the experimental test on the real BF is time-consuming and labour-intensive, only a few three-dimensional modelling works can be found in the literature (Nogami *et al.* 2004; Guo *et al.* 2005; Du and Chen 2006).

In this paper, a comprehensive industry-scale model is used to predict the in-furnace combustion phenomena in the LBTRC region of a BF, and compare the in-furnace combustion phenomena of an upgraded brown coal by briquetting vs. a black coal under BF conditions. They are compared in terms of flow, temperature, gas composition and coal combusts characteristics.

MODELLING METHODOLOGY

The model uses a single computational domain to cover the LBTRC region at the lower part of BF. Blowpipe-tuyere-raceway region is treated as a cavity, and coke bed is treated as porous medium. The following physicochemical processes are included in this model: (1) turbulent flow of gas-coal particle in the raceway and coke bed, (2) coal combustion process, (3) gasification and combustion of coke, (4) heat transfer among gas-solid phase. The model is developed on the platform of ANSYS 15.0.

Governing equations for gas-particle flow

A set of 3D, steady-state Reynolds averaged Navier-Stokes equations closed by the standard κ - ε turbulence model equations is used to describe the gas phase flow. The variables in the governing equations of gas phase are mass (m), particle number per unit volume (n_p), momentum (u, v, w), drag force from particle (f_D), heat gain/loss by reaction (H_{reac}), and a number of species (i), including O_2, CO_2, CO, H_2, H_2O and volatile matter. Lagrangian method is used to track coal particles along the discrete particle trajectories without considering interactions between coal particles. Coal particle is treated as a dilute phase, so the contact force between particles is not strong. Changes in particle movements are calculated by Newton's second law, where drag force and turbulent dispersion are considered. Three heat transfer modes are applied to the determination of temperature changes: convective heat transfer, latent heat transfer associated with mass transfer, and radiative heat transfer. They are described in details elsewhere (Shen *et al.* 2010) and will not be repeated in this paper due to page limit.

Chemical reactions and compositions

Combustion phenomena of pulverized coal are regarded as the following in sequence steps: preheating, volatile matter combustion, gaseous combustion and char oxidation. Coke is treated as pure carbon in this study, and coke consumption is refilled as a continuous phase in the modelling region. The gas compositions are obtained from the combustion of coal and coke in the domain, and composition of each gas is obtained by calculating the governing equations of each gas species i. More detail descriptions of these reactions and expressions can be found in ref.(Shen *et al.* 2009).

Simulation conditions

Validation of this model is done in the previous research (Shen *et al.* 2008; Shen *et al.* 2010; Shen *et al.* 2011). Geometry of lance-blowpipe-tuyere of this model is based on a practical BF. The co-axial lance is inclined into the blowpipe with its tip on the centreline at an angle of 10 degree. A mixture of gas stream, which includes conveying gas, cooling gas and hot blast is blown into the domain. The whole domain is divided into four zones based on the porosity differences 1.0, 0.25, 0.5 and 0.4, respectively(Nakajima 1990).

Two coals are compared in this study: one typical black coal widely used in PCI operation; and one brown coal upgraded by briquetting as a potential coal for PCI operation if applicable after evaluation. Although they are different in many aspects, they are compared as two representative coals. The proximate and ultimate analyses of two typical coals (black coal and brown coal) used in this study are listed in Table 1. Coal is injected into BF under the same operating conditions. Particle size distribution of pulverized brown coal in the upper part of boiler is validated against Rosin-Rammler distribution function, where the mean particle size of both black coal and brown coal is 65 μm. Other conditions are listed elsewhere (Liao *et al.* 2015).

Properties	Black coal	Brown coal by briquette(Zhang *et al.* 2015)
Proximate analysis (ad)		
Moisture, %	3.2	9.3 (ar)
Ash, %	9.8	8.9 (db)
Volatile matter, %	32.5	45.2 (db)
Fixed carbon, %	54.5	45.9 (db)
Ultimate analysis (daf.)		
Carbon, %	83.5	65.9
Hydrogen, %	5.3	4.4
Oxygen, %	8.6	22.31
Nitrogen, %	1.95	0.48
Sulphur, %	0.6	0.41

ar is air dried, db is dried basis.

Table 1: The proximate and ultimate analyses of black coal and brown coal

RESULTS AND DISCUSSION

Gas flows

Velocity distribution of gas phase, including blast steam, cooling gas and conveying gas, inside the raceway is showed in Fig. 2. It can be seen that a high speed jet of gas phase mixture is blown through the tuyere, ranging up to 225 m/s. Gas velocity increases dramatically from the tuyere at ~100 m/s to ~200 m/s along the axis, and decreases in the upward direction and then flow reversely above the jet. Gas velocity of both cases decreases fast upon the surface of raceway. It can also be seen that gas phase in the brown coal briquette case is accelerated to a higher rate than the black coal along the axis due to lower density. Comparison of particle trajectories coloured by travelling time is illustrated in Fig. 3. Along the main coal plume, both cases show a similar residence time within the raceway at a short time range (~10 ms). After reaching to the end of raceway, a relatively large part of coal particles in the brown coal briquette case is travelling backward to

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the −Y direction and then travelling upward along the cohesive zone, while more particles are travelling until the deadman zone in the black coal case. Meanwhile, recirculating coal particles travelling within the raceway can reach to ~1s.

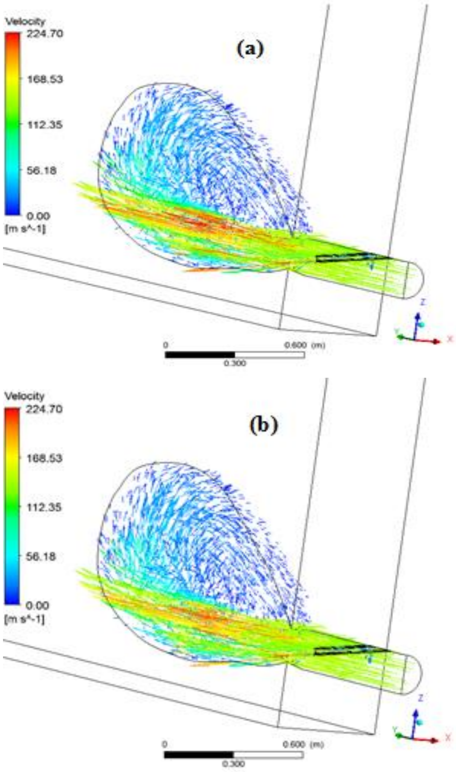

Figure 2: Gas velocity distribution in the raceway region: (a) brown coal briquette, (b) black coal.

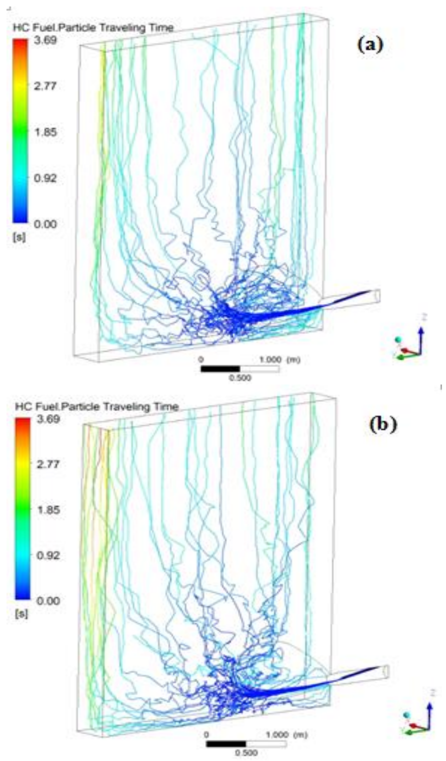

Figure 3: Particle trajectories coloured by particle travelling time: (a) brown coal briquette, (b) black coal.

Thermo-chemical characteristics

Fig. 4 compares the gas distribution in the whole computational domain, in terms of O_2, CO_2 and CO (see Appendix). Oxygen content decreases dramatically after exits the lance tip and is reacted with the surrounding coal and converted to CO_2, after this, O_2 content decreases to a very low level around the coke bed where black coal has a higher O_2 profile due to its lower VM content. Most CO_2 is formed along the main coal plume and retains at the lower part of the raceway. When coal plume reached to the surface of raceway, CO_2 is quickly converted to CO by reacting with the surrounding coke bed after leaving the raceway. It can be seen from Fig. 4(c) that almost no CO exists in the raceway, where the main chemical reactions are coal devolatilization and volatile matter combustion. Gas distribution along the tuyere axis is quantified in Fig. 5. It is indicated that brown coal briquette has a faster conversion from O2 to CO_2 due to higher VM content and thus faster VM reactions and slower conversion from CO_2 to CO due to lower carbon content.

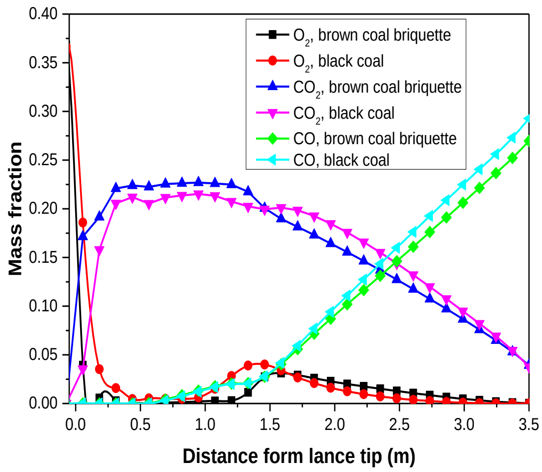

Figure 5: Gas compositions along the tuyere axis.

Contours of temperature field for both cases are illustrated in Fig. 6. Along the main coal plume, both cases show a similar high temperature of up to 3200 K in the downstream of raceway region, but temperature field in this part of brown coal case is higher than the black coal case due to higher VM content which releasing more fuel gas. A recirculation region in the upstream within raceway is observed in both cases, and temperature field (~2300 K) is quite different from the temperature in the main coal plume. The annular-like high temperature zone named flame front is observed and located at the surface of coal plume and in front of tuyere. No significant temperature difference is found between brown coal case and black coal case at the region beyond the raceway and the surrounding coke bed due to the strong heat sink.

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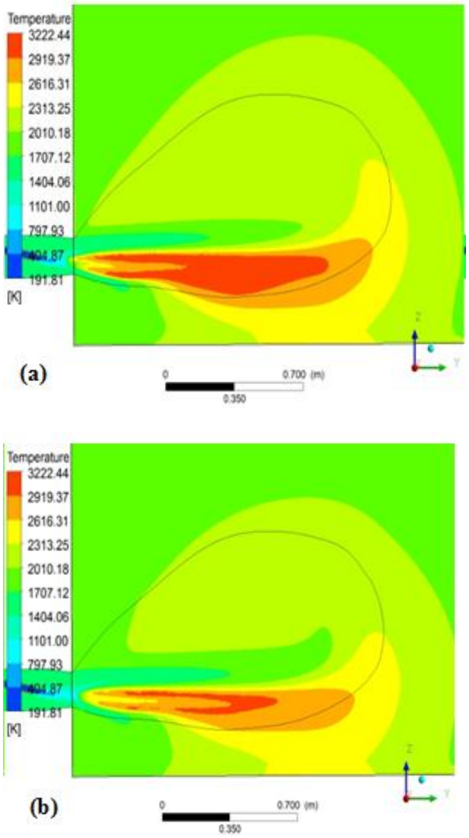

Figure 6: Contours of temperature along the symmetry plane of the whole domain: (a) brown coal briquette, (b) black coal.

Fig. 7 compares the burnout of both cases in the form of coloured particle trajectories in the raceway region, and burnout varies significantly. In the upstream of raceway, burnout rate is up to ~1 and is higher than the counterpart in the downstream which is around 0.5. In addition, burnout in the recirculation zone is higher due to the distribution of O_2. As a result, char oxidation can be processed more completely to achieve a higher burnout, subsequently higher temperature. Both cases show a similar burnout trend. Main difference in burnout rate can be found along the main coal plume, and is quantitatively illustrated in Fig. 8. Burnout in the brown coal briquette case shows a higher overall burnout rate than the black coal case, where levelling-off burnout within the raceway for brown coal and black coal are ~85% and ~64%, respectively. Meanwhile, burnout increases quickly along the tuyere axis at ~0.55m in the brown coal briquette case, reaches to the level-offer at around 0.7m. Faster and higher burnout in the raceway also attributes to the higher temperature filed in this region for the brown coal briquette case.

To summarize, this 3D model can qualitatively simulate the comprehensive in-furnace coal combustion phenomena with PCI technology in the whole LBTRC region, in an industry scale. Injection of brown coal show a good prediction, in terms of gas composition and burnout, which means the injection of brown coal briquette in BF is feasible. Predictions of temperature and burnout in brown coal case display a better result than the black coal case in this simulation.

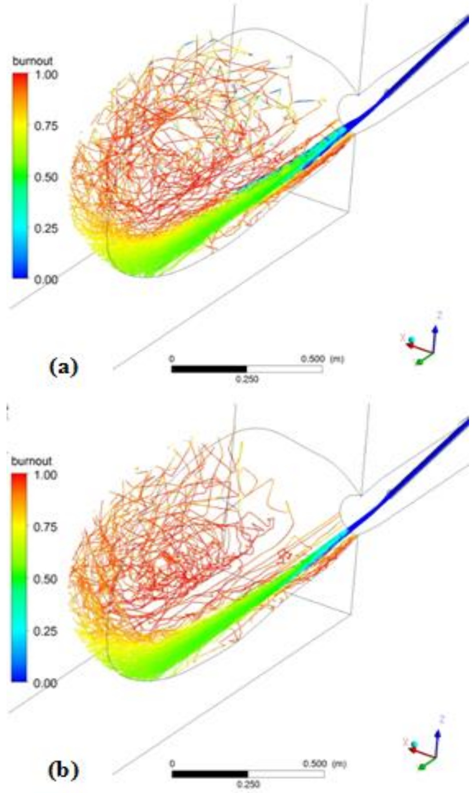

Figure 7: Coal burnout coloured by particle trajectories in the raceway: (a) brown coal briquette, (b) black coal.

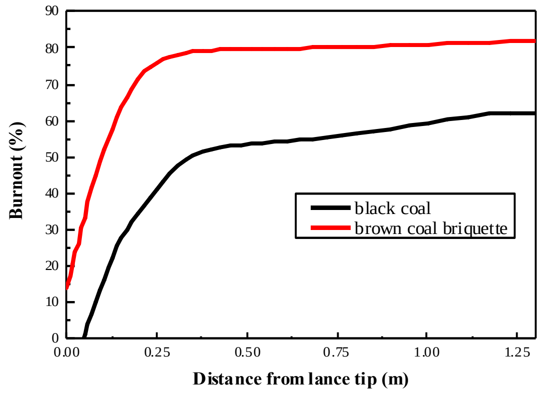

Figure 8: Coal burnout along the tuyere axis within the raceway cavity.

CONCLUSIONS

A 3D CFD numerical model is used to predict the comprehensive in-furnace coal combustion characteristics under PCI operation. The computational domain includes the lance-blowpipe-tuyere-raceway-coke bed region in the lower part of ironmaking BF. Complicated chemical reactions (gas-gas, gas-particle etc.) are considered in this model, and various combustion characteristics can be simulated, in terms of temperature, gas compositions, particle travelling time etc.

The conclusions are as below:

(1) Temperature along the main coal plume is much higher than other places in the coke bed due to stronger reactions. Under the same operating conditions, higher temperature is observed in the main coal plume in the brown coal briquette case due to higher volatile matter in brown coal

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than black coal. (2) The injection of brown coal briquette is able to achieve a higher overall burnout than the black coal case within the raceway, which is also due to the supply of O_2 in this region. (3) The simulation results show that the use of Victorian brown coal is able to meet the demand of heating requirement of BF, but may present different combustion behaviours in comparison with the conventional black coal.

A previous study indicate that it is feasible to replace one black coal with one upgraded brown coal due to similar combustion performance(Liao *et al.* 2015). This study however indicate different upgraded brown coals may have different combustion performance and thus need further detailed study, such as identification of new adaptive operating conditions for different brown coal products by different upgrading methods. Numerical modelling offers a cost-effective way to optimize and control such pulverized brown coal injection process.

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Appendix

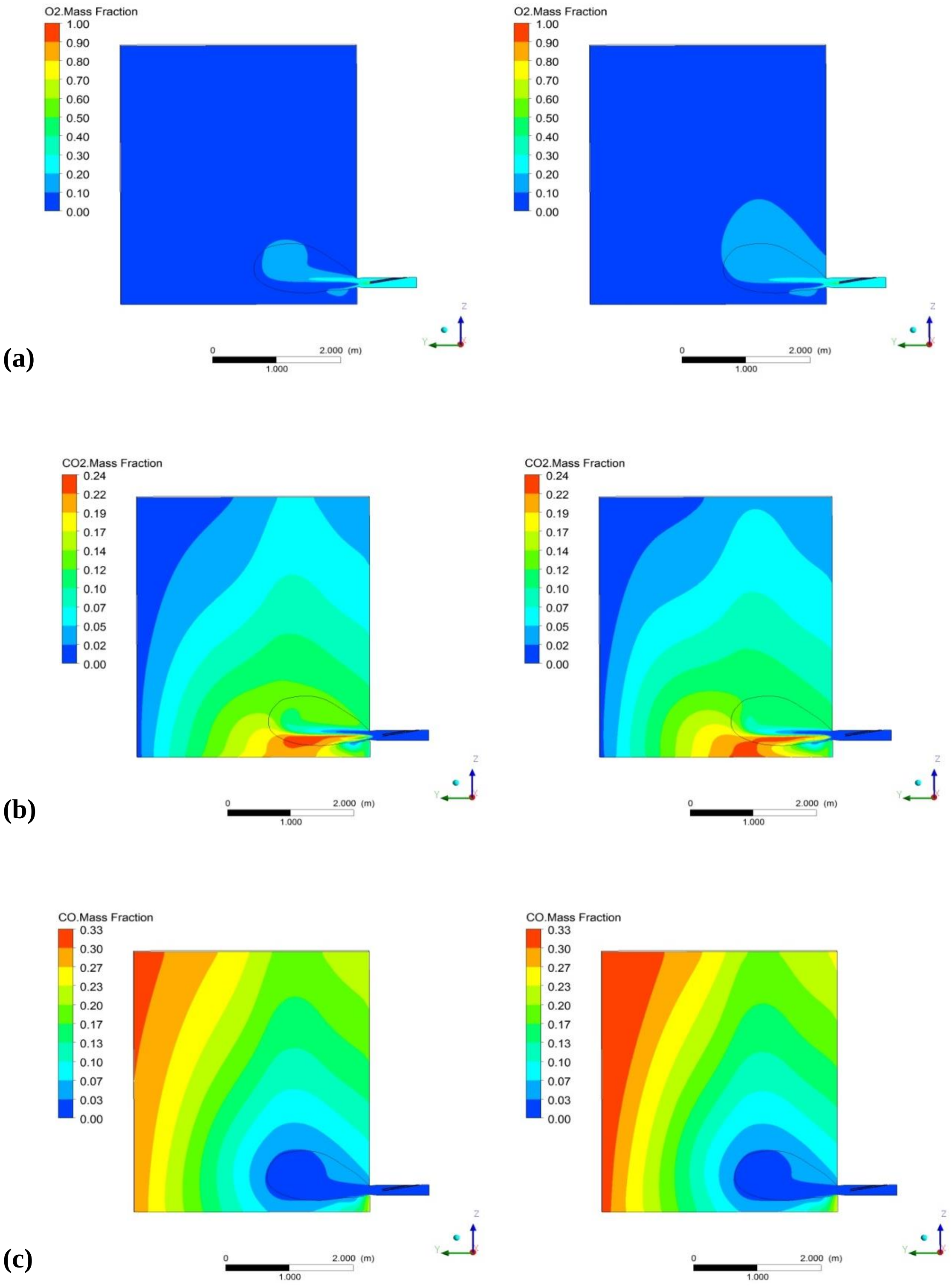

Figure 4: Comparisons of gas distribution in the whole domain between brown coal briquette (left) and black coal (right): (a) O_2 mass fraction, (b) CO_2 mass fraction, (c) CO mass fraction.

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