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PREDICTION OF RACEWAYS IN A BLAST FURNACE

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ABSTRACT

In a blast furnace, preheated air and fuel (gas, oil or pulverized coal) are often injected into the lower part of the furnace through tuyeres, forming a raceway in which the injected fuel and some of the coke descending from the top of the furnace are combusted and gasified. The shape and size of the raceway greatly affect the combustion of the coke and the injected fuel in the blast furnace. In this paper, a three-dimensional (3-D) computational fluid dynamics (CFD) model is developed to investigate the raceway evolution. The furnace geometry and operating conditions are based on the Mittal Steel IH7 blast furnace. The effects of Tuyere-velocity, coke particle size and burden properties are computed. It is found that the raceway depth increases with an increase in the tuyere velocity and a decrease in the coke particle size in the active coke zone. The CFD results are validated using experimental correlations and actual observations. The computational results provide useful insight into the raceway formation and the factors that influence its size and shape.

Key Words: Iron making, Blast Furnace, PCI, Raceway. CFD, Model

1. INTRODUCTION

As early as the middle of 19th Century, injection of carbonaceous materials into the blast furnace was tried. Between 1840 and 1845, injection of charcoal powder was tested at a blast furnace in France. After more than one hundred years, in 1950's, fuel injection trials of industrial scale were started. In 1960's, fuel injections technologies were developed successfully and employed world wide. At present time, more than 90% of hot metal in the world is produced in the blast furnace with fuel injections. The selection of fuel for blast furnace injection is depended on the natural resource and the market, which are different from country to country and from time to time. Before 1990's, the injection fuel are mainly natural gas in USA and Russia, mainly heavy oil in Western Europe and Japan, and mainly coal in China. Since 1990's, the coal has become the injectant choice because of its relative abundance and low cost [1].

In addition to its low cost, coal injection at blast furnaces reduces the net energy consumption and the overall CO_2 emission in the ironmaking process, including the cokemaking. The high coal injection rate and low coke rate is a common goal for most of the blast furnaces operation world wide for reducing the cost of the hot metal production. Further more, the high coal injection rate will also reduce the requirement on metallurgical coke for prolong the life of Blast Furnace Ironmaking because of the coking coal resource is not unlimited.

A good combustion of the injected coal inside the raceway is the key to achieve a high coal injection rate and low coke rate for a blast furnace. The combustion performance of injected coal in a raceway usually is determined by the burn-out rate. The coal burn-out rate is depended on the coal type, injection technology, injection rate, and the combustion conditions.

For the high burn-out rate, the understanding of the essential behavior and the combustion process of pulverized coal inside the raceway is very important. The combustion kinetics of the pulverized coal had been studied widely [2]. Certain of them were conducted under the condition similar to the blast temperature and pressure of iron making blast furnaces. However, the real combustion process of injected coal inside the raceway had been touched very rarely because of the difficulties in laboratory simulation and the measurement. The most difficult point is measurements of both gas phase and solid phase contains information of the combustion from both coal and coke because the injection coal is combusted together with the active coke inside the raceway. Fortunately, the combustion of the injected coal and coke in the raceway is in the same circumstance and under the same oxygen potential. Under the shared oxygen potential, the complex oxidation/reduction process of different reactants can be determined by using the kinetics of the simple reaction process of the individual reactants [3]. The computational fluid dynamics (CFD) is capable to simulate the raceway formation and the complex combustion process in the raceway based on the fundamental kinetics of coke and injected coal combustions. This paper will present one part of the injected coal investigations based on the CFD technology, which focuses on the raceway formation and its shape, including the size.

In a blast furnace, iron-bearing materials and coke with flux are charged in alternate layers into the top of the furnace. Preheated air and fuel (gas, oil or pulverized coal) are blown into the lower part of the furnace through tuyeres; forming a cavity called a raceway in which the injected fuel and part of the coke descending from the top of the furnace are combusted and gasified. The techniques for the prediction of raceway can be broadly grouped into three categories, experimental, numerical and empirical methods. Experimental methods consist of using a simplified two dimensional setup to study the factors that influence the raceway and then using these factors to obtain correlations based on dimensional analysis for the radius of the raceway that is assumed spherical.[5] The numerical studies consider a mass and momentum balance to predict the raceway size, assuming the shape as a sphere.[6,7] A two-phase Eulerian – Eulerian model was used to develop a numerical model to predict the shape and size of the raceway for different coke bed porosities, coke bed heights and tuyere velocities by Mondal *et al* [8], the profiles thus predicted were closer to reality.

All the above techniques are based on simplified model assumptions and based on greatly simplifying the furnace conditions. No effort was done yet to predict the three dimensional shape of the raceway. Also the effect of the cohesive zone, burden quality, and burden distributions have not been considered in all the other authors' articles which are found so far. In this paper, the 3-D CFD model is developed based on FLUENT. This model is capable to predict effects of following variables on the shape and size of the raceway in a blast furnace.

- Tuyere velocity
- Size of the coke particle at tuyere level
- The thickness and permeability of ore layer
- The thickness and permeability of coke layer
- The central coke chimney size and permeability.
- Cohesive location and shape

The effect of injection rate and combustions of coal and coke on the raceway shape and size will be discussed in the further model development.

NOMENCLATURE

V	Volume of a phase, m^3
α	Volume fraction of a phase
i	Phase index, p, i or j
v_i	Volume fraction of each phase
$\overline{\overline{\tau}}_i$	Stress tensor
g	Acceleration due to gravity, m/s^2
K_{ij}	Momentum transfer coefficient
ρ_i	Density of each phase, kg/m^3
τ_i	Particulate relaxation time, s
R_{ei}	Phasic Reynolds's number
d_p	Diameter of particle phase, m
$v_{r,s}$	Terminal velocity, m/s
D_r	Raceway depth, m
D_T	Tuyere diameter at exit, m
ρ_{eff}	Effective density, kg/m^3
v_b	Tuyere velocity, m/s
μ_w	Wall frictional coefficient
H	Average bed height, m
W	Average bed width, m

2. MATHEMATICAL MODEL

Multiphase flow is involved in the raceway and PCI process. In this work, a commercial CFD code, FLUENT^{TM}, is used to predict the shape and size of the raceway generated. In this paper the effect of fuel injection on the raceway size and shape had not been considered yet; it will be considered in later simulations. The most comprehensive Eulerian approach is selected to describe the gas-coke particle flow. In the Eulerian approach, the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of phasic volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. These equations are closed by providing constitutive relations based on kinetic theory.

The phasic volume fraction is denoted here by α. The volume fractions represent the space occupied by the different phases and the conservation equations are satisfied by the individual phases.

The volume of a phase is given as

$$V = \int_V \alpha dV \qquad (1)$$

and the effective density of the phase is given as

$$\overline{\rho} = \alpha\rho \qquad (2)$$

The continuity equation for each phase, here coke and air, is given as

$$\frac{\partial(\alpha_i \rho_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \overline{v_i}) = 0 \qquad (3)$$

where $\overline{v_i}$ is the velocity vector for the gas or solid phase. The above equation assumes that there is no mass transfer between the two phases for now because the coke combustion has not been considered in this model yet. It is also assumed that there is no mass source term in the computational domain. The momentum equation for each phase is given as,

$$\frac{\partial(\alpha_i\rho_i\bar{v}_i)}{\partial t}+\nabla\cdot(\alpha_i\rho_i\bar{v}_i\cdot\bar{v}_i)=$$

$$-\alpha_i\nabla p+\nabla\cdot\bar{\bar{\tau}}_i+\alpha_i\rho_i\bar{g}+K_{ij}(\bar{v}_i-\bar{v}_i),i\neq j \tag{4}$$

where $\bar{\bar{\tau}}_i$ is the stress tensor. $\bar{g}$ is the acceleration due to gravity and p is the pressure, common to the two phases. The last term in the above equation is the momentum exchange between the phases, where K_{ij} is the momentum transfer coefficient.

Syamlal-O'Brien model is employed to predict the momentum transfer coefficient. The same is given in general form as,

$$K_{ij}=\frac{\alpha_i\rho_i f}{\tau_i} \tag{5}$$

where τ_i, the particulate relaxation time is given as

$$\tau_i=\frac{\rho_i d_i^2}{18\mu_j} \tag{6}$$

where i denotes the solid phase and j donates the gas phase properties .The term f is defined as below,

$$f=\frac{R_{ei}\alpha_j}{24v_{r,s}^2}\left(0.63+\frac{4.8}{\sqrt{R_{ei}/v_{r,s}}}\right)^2 \tag{7}$$

where $v_{r,s}$ is the terminal velocity correlation for the solid phase. The Reynolds's number is given as,

$$R_{ei}=\frac{\rho_j d_i\left|v_i-v_j\right|}{\mu_j} \tag{8}$$

The subscripts i and j denote the solid and gaseous phase respectively.

Syamlal-O'Brien model is based on measurements of the terminal velocities of particles in fluidized or settling beds, with correlations that are a function of the volume fraction and relative Reynolds number. Thus the fluid – solid momentum exchange coefficient has the form,

$$K_{ij}=\frac{3\alpha_i\alpha_j\rho_j f}{4v_{r,s}^2 d_i}\left(\frac{\mathrm{Re}_j}{v_{r,s}}\right)\left|\bar{v}_i-\bar{v}_j\right| \tag{9}$$

The terminal velocity is given as,

$$v_{r,s}=0.5\times[A-0.06\,\mathrm{Re}_i+$$

$$\sqrt{\left(0.06\,\mathrm{Re}_i\right)^2+0.12\,\mathrm{Re}_i(2B-A)+A^2}\,] \tag{10}$$

where, $A=\alpha_j^{4.14}$ and $B=0.8\alpha_j^{1.28}$.

The subscripts j and i denote the gas and the particle phases respectively.

The first step is to solve for the volume fraction of the secondary phase using the continuity equation shown in equation (1). This value along with the fact that the sum of volume fractions of the primary and secondary phases is unity is used to calculate the volume fraction of the primary phase. A multi-fluid granular model is used to describe the flow behavior of the fluid-solid mixture. The solid-phase stresses are derived by making an analogy between the random particle motion arising from particle-particle collisions and the thermal motion of molecules in a gas, taking into account the inelasticity of the granular phase. As is the case for a gas, the intensity of the particle velocity fluctuations determines the stresses, viscosity, and pressure of the solid phase.

3. SIMULATION CONDITIONS

The computational domain consists of three tuyeres located 9 degrees apart, with an inlet Tuyere diameter of 0.15m. The Tuyere length is 0.437m and is at an angle of 6 degrees downward. The coke bed in hearth at the tuyere level is assumed basically as cone shape with a deadman at its center. The detailed size, diameter and height of coke cone are depended on the furnace inner profile and the cohesive zone shape and location. Figure 1 shows the geometry used for the simulation, which is based on the geometry of IH7 Blast Furnace of Mittal Steel USA. The coke layer thickness in the burden and the cohesive zone is 0.18m and the ore layer thickness is 0.3m for the base case. The average width of the cohesive zone is 1.2m. The chimney radius for the base case is 1m. The effects of assumed burden distributions are modeled separately for giving the upper boundary conditions of gas velocity and pressure. The tuyere velocity for the baseline case is 185 m/s. The parameters for the base case are given in Table 1. These parameters are consistent with the observations and measurements made in-situ at Mittal Steel's IH7 blast furnace. The various conditions for the parametric studies are shown in Table 2.

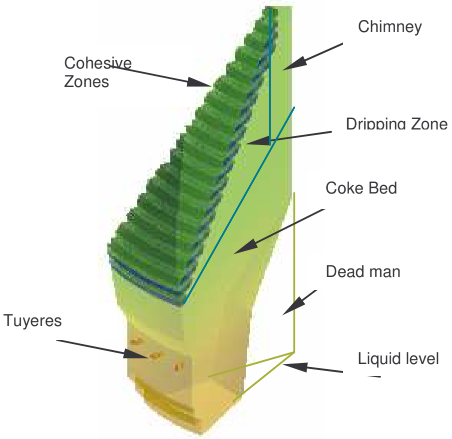


Fig. 1 Geometry of the blast furnace for raceway simulation

Table 1./ Simulation Conditions for the base line case

Burden	
Coke layer Porosity	0.5
Coke Diameter	0.038m
Ore layer Porosity	0.35
Ore Diameter	0.012m
Ore to Coke Ratio	0.6/0.4
Coke Bed	
Porosity	0.5
Coke diameter	0.03m
Chimney	
Porosity	0.5
Coke Diameter	0.038m
Cohesive Zone	
Number of Ore layers	19
Number of Coke Layers	19
Coke Porosity	0.5
Ore to Coke Ratio	0.6
Coke Diameter	0.03m
Ore Layer	Impermissible

Table 2 Simulation Conditions for the parametric studies

Coke Bed	
Coke bed Porosity	0.45, 0.5, and 0.55
Coke Diameter	0.02m, 0.03m, and 0.038m,
Burden	
Coke layer thickness	0.1636m, 0.1818m, and 0.2m
Ore layer thickness	0.2728m, 0.3031m, and 0.3333m
Chimney	
Diameter	0.5m, 1, and 2.0m
Tuyere velocity	150 m/s, 185 m/s, and 220 m/s

From the computational point of view, the computational domain consists of 564,032 gird cells, which was achieved after a grid sensitivity study.

4. RESULTS AND DISCUSSION

The boundary of the raceway that separates from the coke bed is defined as the isoline of constant initial coke volume fraction. The term of porosity is defined as the volume fraction of the gas phase with respect to the total volume of gas and solid phases, which is 1 minus the solid particle volume fraction $(\varepsilon = 1 - \alpha_p)$. Figures 2 and 3 show the porosity distributions of the side and top views.

The velocity distribution inside the raceway is an important factor that decides the combustion behavior of the coke and other replacement fuels like pulverized coal or natural gas. It is observed as in Figure 4 that the flow is predominantly moving upward as expected. Also observed are stagnation zones at the top and bottom of the raceway near the wall of the furnace. This is also observed from the stream lines of flow in Figure 5

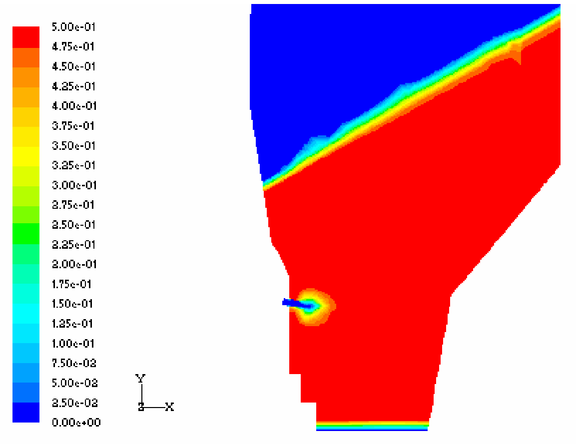


Fig. 2 Side view of the Raceway, contours of coke volume fraction

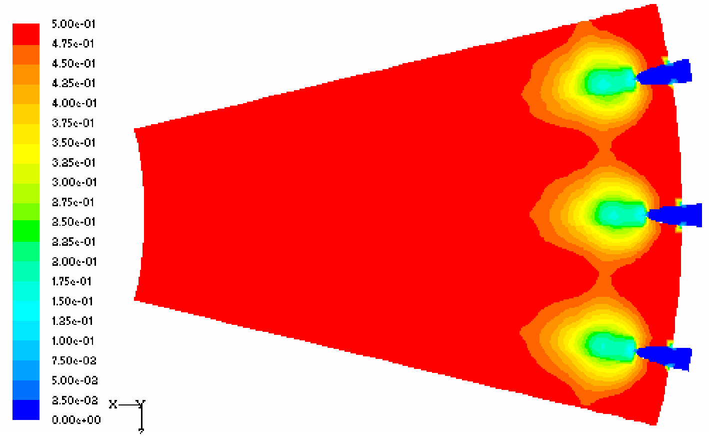


Fig. 3 Top view the raceway, contours of coke volume fraction

The velocity vectors near the chimney and the cohesive zone are shown in Figure 6. The gas velocity in the chimney is higher as the chimney offers the least path of resistance for flow, which corresponds to actual observations in the blast furnace.

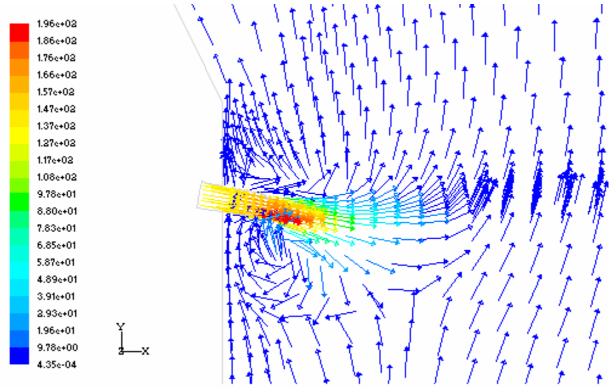


Fig. 4 Velocity (m/s) vectors of gas flow near the raceway

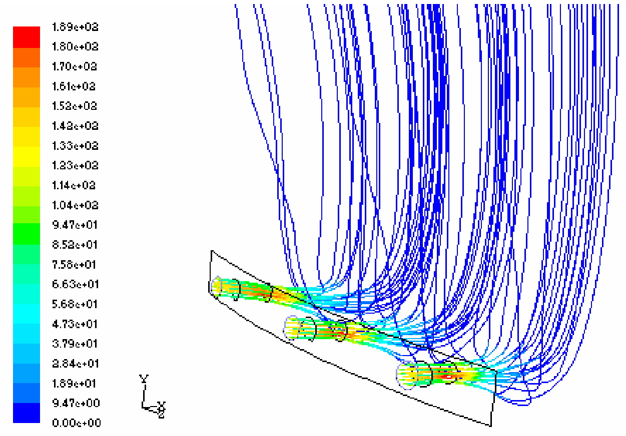


Fig. 5 Streamlines of gas flow (m/s) near the raceway

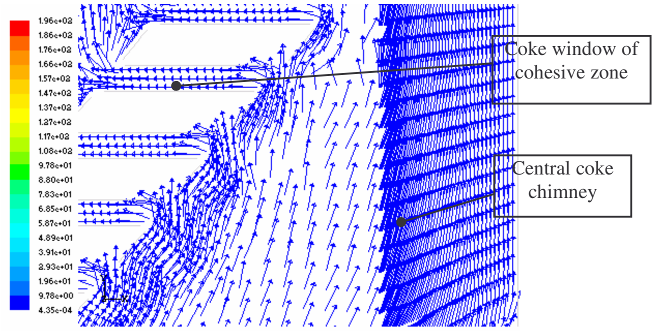


Fig. 6 Gas flow velocity (m/s) vectors near the chimney and the cohesive zone.

The effect of the tuyere velocity is shown in Figure 7. The raceway size increases as the tuyere velocity rises. An increase in the Tuyere velocity increases the momentum of the gas phase, which in turn causes a larger momentum exchange with the solid particles, moving them further away from the Tuyere towards the center of the furnace. The same effect is seen in Figure 8**,** in the top view comparison between the different velocities at the center of the tuyere for different velocities. The raceway is larger for a higher Tuyere velocity. It is also observed that the interaction between the different raceways increases, with the increase of the Tuyere velocity. Better interaction between the raceways is preferred, as this increases the iron production. These results match with the observation of the blast furnace operators. And this model will quantify the detailed shape and size of the raceway according to the tuyere parameters.

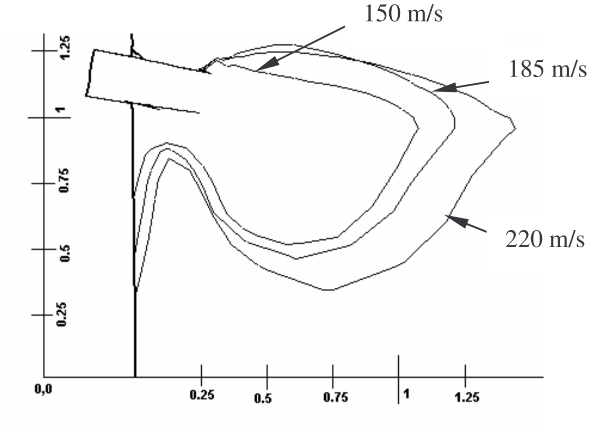
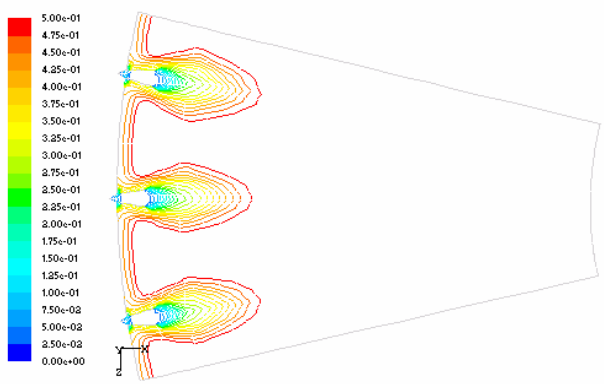
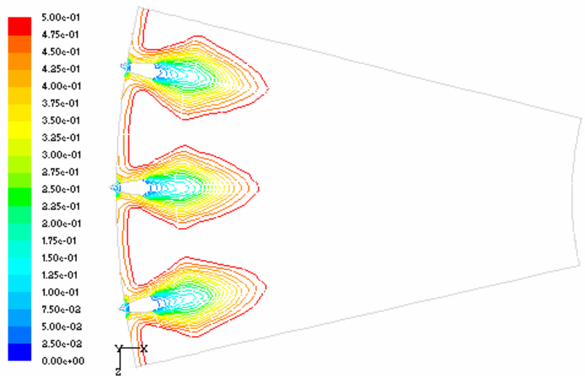


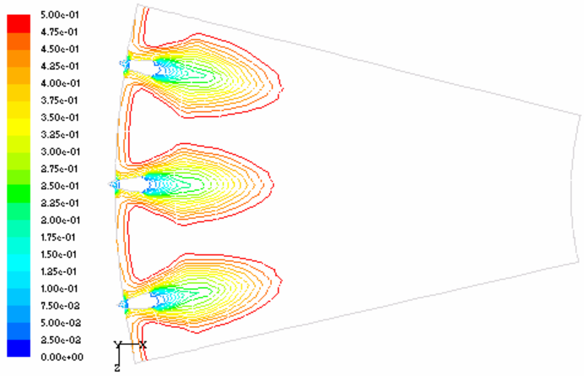
Fig. 7 Size and shape of the raceway for different tuyere velocities. Length is specified in meter



(a) Tuyere velocity: 150 m/s



(b) Tuyere velocity: 185 m/s



(c) Tuyere velocity: 200 m/s

Fig. 8 Size and shape of the raceway at tuyere height for different Tuyere velocity - top view

The effect of coke particle size is shown in Figure 9. The coke particle size is changed from 0.03m for the base case to 0.02m and 0.038m. The results in Figure 8 shows that the raceway size increases as the coke size decreases, because smaller particles have larger specific surface area and gains stronger drag force from the gas flow with respect to their mass/weight. This is in agreement with various experimental observations and correlations obtained using dimensional analysis by Rajneesh *et al* [5], where it is observed that the raceway shape is inversely proportional to the coke particle diameter.

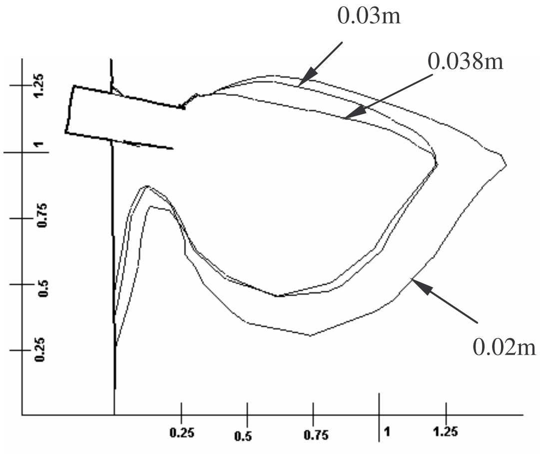


Fig. 9 Size and shape for different coke particle sizes in the coke bed. Length is specified in m

The raceway shapes for different Tuyere angles are presented in Figure 10.It is shown that as the angle is increased, the raceway moves up. Another important observation is that even if the Tuyere is pointing upward, the raceway is predominantly larger in the lower half, due to the force balance and the interaction of the gas and coke particle phases. Of course the raceway shape will also be influenced by the liquid level, the size and shape of the deadman in the heath. These effects will be simulated and discussed later.

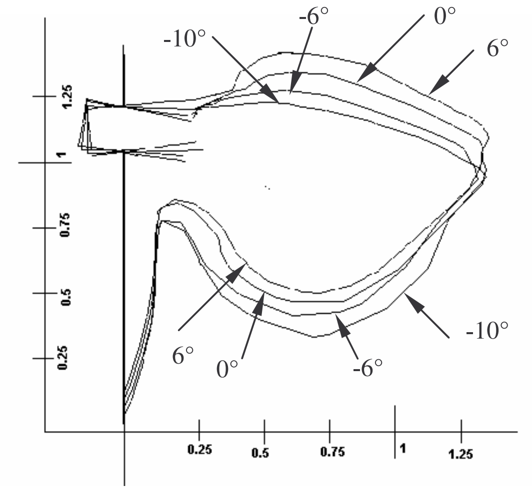


Fig. 10 The sizes and shapes of raceway for different Tuyere angles. Length is specified in m

Validation of CFD results

The CFD results that are presented above are validated using the experimental correlations and dimensional analysis by Rajneesh *et al* [5]. The diameter or the depth of the raceway is given by equation (11), which is obtained from dimensional analysis [5]

$$D_r = 164\left(\frac{\rho_g v_b D_T^2}{\rho_{eff}\, g d_p H W}\right)^{0.8} \mu_w^{-0.25} D_T \tag{11}$$

The term D_r is the depth of the raceway and D_T is the diameter of the Tuyere exit. The effective density ρ_{eff} is given as

$$\rho_{eff} = \varepsilon\rho_g + (1-\varepsilon)\rho_s \tag{12}$$

The term μ_w is the wall-particle frictional coefficient and has a value of 0.1 for coke. Please refer to the nomenclature for the definition of the other terms used in equation (11).

Table 3 Validation Conditions

Coke bed Porosity	0.5, 0.45, 0.55
Coke Diameter	0.038m, 0.03m, 0.02m
Wall frictional coefficient	0.1
Tuyere exit diameter	0.075 m
Gas density	0.6 kg/m^3
Tuyere velocity	185 m/s, 150 m/s, 220 m/s
Effective density	350.3 kg/m^3, 385.135 kg/m^3, 315.33 kg/m^3
Acceleration due to Gravity	9.81 m/s^2
Average Bed height	8.4 m
Average Bed width	5 m

The conditions used for validation are shown in **Table 3.**

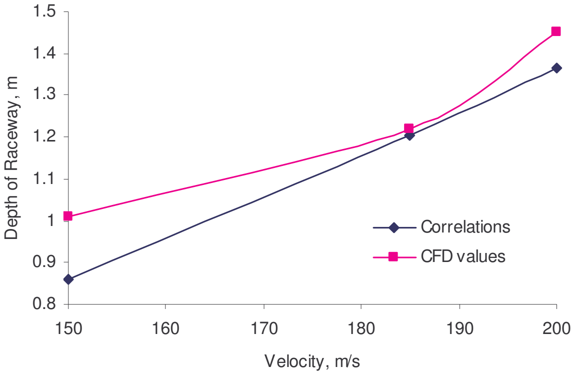


Fig. 11 Effect of velocity - CFD vs. Correlations

The comparisons of the values that are obtained from experimental correlations by Rajneesh *et al* [5] and the CFD results are shown above for velocity, particle diameter. It is observed that there is a good agreement between CFD and experimental observations. An average variation of 3.81% is obtained.

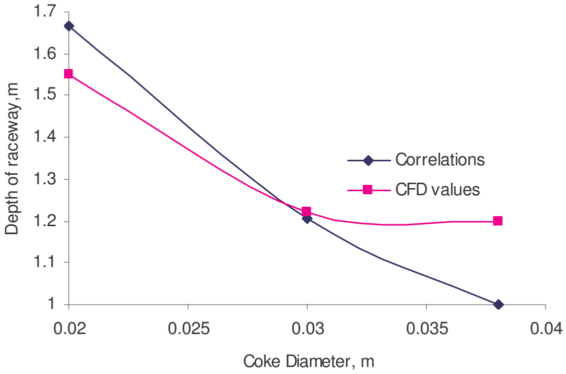


Fig. 12 Coke particle diameter - CFD vs. Correlations

5. SUMMARY

A 3-D CFD model based on the Fluent has been established for simulating the raceway formation. This model is capable to predict the raceway shape and size based on the detailed and tuyere parameters, tuyere coke size, burden distributions, cohesive zone shape, size and location, and the conditions of deadman. The effect of the coal rate and coal combustion on the raceway shape and size will be studied in next step.

ACKNOWLEDGEMENT

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