Prediction of Raceway Size in Blast Furnace from Two Dimensional Experimental Correlations

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It has been reported in the literature that raceway measurement made during the decreasing gas velocity is relevant to operating blast furnaces. However, no raceway correlation is available for decreasing gas velocity and none of the available correlations either in increasing or decreasing gas velocity take care of frictional properties of the material. Therefore, a systematic experimental study has been carried out on raceway hysteresis. Based on experimental data and using dimensional analysis, two raceway correlations, one each for increasing and decreasing gas velocity, have been developed. Results of these correlations have been compared with the data obtained from literature on the cold models and plant data along with some experimental data. A good agreement exists between the correlations and other data.

KEY WORDS: raceway; blast furnace; correlations; decreasing velocity; increasing velocity; hysteresis; penetration factor and frictional forces.

1. Introduction

In the blast furnace, gas is introduced laterally at a high velocity through a port, called tuyere, into the packed bed of coke. This creates a cavity in front of the tuyere called a raceway. Coke is burnt in this zone to supply heat to the process. Therefore, coke particles get consumed in this region and they are replenished by fresh coke particles from the surrounding of the raceway. So the whole burden descends in the downward direction. The size and shape of the raceway affects the aerodynamics of the furnace and thus affects the overall heat and mass transfer. Due to this reason, the raceway has been studied extensively both theoretically and experimentally. A good review on the previous raceway work is presented in Ref. 1). In case of the blast furnace, many authors have presented raceway correlations to predict the raceway size which are listed in **Table 1**. Most of these correlations are based on cold model study and some of them are based on hot model and plant data study. Unfortunately, none of these correlations predicts the raceway size in industrial conditions reasonably and they also differ to each other.[2–3] It is observed that all the experimental correlations have been based on various forms of Froude number. The raceway size has been intuitively correlated with this number along with some other parameters such as height of the bed, width of the model and tuyere opening. However, these correlations[4–8] are not evolved based on a systematic study *i.e.* by applying dimensional analysis and finding the relevant groups. In fact, some of the earlier correlations are not dimensionally consistent as mentioned in Ref. 9). On the other hand, theoretical correlations have been obtained by simplifying the actual theoretical equations logically.[1,10] These correlations are more systematic. Most of the empirical correlations[1,6,10] for the two and three-dimensional models, have been obtained for the velocity increasing case. In few correlations it was not mentioned. However, we believe these correlations are also belong to increasing velocity as decreasing velocity observation were not made until 1985 except Taylor *et al.*[5] who mentioned about the hysteresis. It must be mentioned here that one can get two raceways size at the same gas velocity depending on whether the measurement is made in the increasing or decreasing gas velocity. This phenomena is called raceway hysteresis which has been described in detail by various authors[2,3,11] and it has been reported[3] that the decreasing velocity correlation is more relevant to blast furnace. Since the raceway size in the increasing and decreasing velocity case vary by approximately a factor of 4, the raceway size can affect considerably the predictions of heat, mass and momentum transfer in the blast furnace. At this juncture something about the raceway hysteresis should be mentioned because the background of the correlations developed in this study is based upon this phenomena.

Recently Sarkar *et al.*[3] have explained raceway hysteresis phenomenon in details and have proposed that raceway hysteresis can be represented by the following simplified equation (in absence of chemical reaction), based on their experimental results.

$$\text{Pressure force} - \text{Bed weight} \pm \text{Frictional forces (Stresses)} = 0 \quad \text{..........(1)}$$

The physical interpretation of this equation is that when the raceway is expanding, the particles near and above the raceway are being moved by the force due to fluid drag in the upward direction. So the frictional stresses will tend to oppose this motion of the particles and hence act in the down-

Table 1. List of various raceway correlations with remarks.

Investigator	Correlation	Type	Comments
Elliot et al.[4]	$D_r \propto \left\{ \frac{1/2 M V_b^2}{t} \right\}$	Pseudo 2D Cold model & furnace data	Raceway was related to kinetic energy of jet. No particle properties were considered.
	$D_r \propto \left\{ \frac{A_t \rho_g V_b^2}{P} \right\}^{0.5}$	3D Cold model	Raceway was related to momentum of the jet.
Taylor et al.[5]	$D_r \propto \left\{ \frac{\rho_g V_b^{1.55}}{d_p} \right\}$	Pseudo 2D Cold model & furnace data	Raceway size was related to blast momentum and particle size. Observed hysteresis in cold model but not included in analysis.
	$D_r \propto \left\{ \sqrt{\frac{\rho_g}{d_p}} V_b^{0.7} \right\} d_t$	Hot model & furnace data	
Wagstaff and Holman[6]	$D_r \propto \left\{ \frac{\rho_g V_b^2 d_t}{(\rho_s - \rho_g) g \sqrt{S}} \right\} \left(\frac{A_t}{A_m} \right)^{0.75}$	3D pie-slice model & furnace data.	Raceway factor was defined arbitrarily and was related to raceway penetration factor.
Szekely & Poveromo[10]	$D_r \propto \left\{ \frac{4 \rho_g^2 V_b^2 d_t}{\rho_r \varepsilon_r^2 (1-\varepsilon) \rho_s g H} \right\}^{0.5}$	Pseudo 2D cold model.	Raceway relations were obtained, after simplifying the equations, derived from first principles of force and momentum balances. Neglected the frictional forces. Material properties were considered.
	$D_r \propto \left\{ \frac{\pi^2 \rho_g^2 V_b^2 d_t^2}{\rho_r \varepsilon_r (1-\varepsilon) \rho_s g H} \right\}^{0.5}$	3D cold model.	
Hatono et al.[7]	$D_r \propto \left\{ \frac{\rho_g V_b^2 d_t P_0 T}{\rho_s g d_p P T_0} \right\}$	Experimental furnace	Raceway size relation was obtained assuming that it is directly related to gas momentum and inversely to acceleration of gravity. Particle properties were considered.
Nakamura et al.[8]	$D_r \propto \left\{ \frac{\rho_g V_b^2 d_t^2}{\rho_s g d_p \varepsilon^3} \right\}^{0.5}$	Pseudo 2D hot model.	Raceway size was related to gas momentum including void fraction and particle properties.
Flint and Burgess[1]	$D_r \propto \left\{ \frac{\rho_g V_b^2 d_t^2}{\rho_s g d_p H_{eff} \varepsilon^3} \right\}$	First 2D model.	Raceway correlation was obtained after simplifying the theoretical equations, which were derived, based on pressure and bed weight forces. Introduced the concept of effective bed height. Observed hysteresis in cold model, but not included in correlation.

ward direction and is fully mobilized. When we start to decrease the blast velocity from a maximum value, the particles above the raceway are trying to fall down. So the frictional forces act against this movement and start increasing in magnitude in the upward direction progressively. Once the frictional stresses acting in the upward direction become fully mobilized, further reduction in blast velocity results in decrease in the raceway penetration. There is a transition period in which frictional stresses change their directions when the velocity is started decreasing from a maximum value. This corresponds to the constant region of raceway size which is described in Fig. 3 later.

From the above description of the hysteresis, it is obvious that frictional forces and thus the frictional properties of the material play an important role in determining the raceway size. However, none of the previous correlations (Table 1) consider the importance of frictional forces which have been recognized as important forces in the force balance. Although, some of the earlier investigators[9,11,12] did recognise the importance of it and attributed the discrepancy

Table 2. List of geometrical and experimental variables.

Apparatus number	Bed dimensions (H X W X T), mm	Tuyere opening (mm)	Tuyere Protrusion, mm	Gas velocity (m/s)	Bed height, m	Material	Experimental condition
1	2300×1000×100	6,10,25, 50 & 79	78	0 - 120	0.2 - 1	Polyethylene	Both (increasing & decreasing velocity condition)
2	1800×600×60	5	50	0 - 110	0.2 – 1	Glass, Plastic	Both
3	830×380×40	5.5	50	0 - 40	0.1–0.5	Plastic, Mustard seed	Both
4	700×285×17	5	50	0 - 25	0.1–0.5	Quartz	Increasing

between the experimental and predicted results to frictional forces. MacDonald and Bridgewater[9] have studied the phenomenon of void formation in stationary and moving beds of solids and unified the behaviour using dimensional analysis and the description of fluidisation. Experimentally, they have found that the decreasing velocity condition is applicable to a moving bed. They recognised the importance of frictional forces in cross flow; however, in the dimensional analysis they neglected it due to the complexity of the problem. In this study, the authors had derived an expression for the cavity size based on dimensional analysis. However, the final form of the expression has been adopted on a similar line as it was done for the fluidized bed study by others.[13] Apte *et al.*[11] have studied the stress distribution analysis around a cavity formed by an upward gas blast from the bottom of a two-dimensional packed bed. This set-up cleverly simplified the force balance along the streamline coincident with the nozzle axis. They wrote the one dimensional elemental force balance between the pressure, bed weight and frictional force. They did not predict the size of cavity based on their analysis. Mostly their study was concentrated on the stress distribution in a packed bed under increasing gas velocity. Raceway phenomena have been studied theoretically by expressing all the terms appearing in the Eq. (1) in proper mathematical terms by other authors in detail.[14] They have clearly shown the importance of frictional forces in packed bed region. Their study was concentrated for increasing gas velocity. Recently, a few authors[15,16] have tried to understand stresses in the granular bed using Discrete Element Method (DEM). In fact, some authors[17] have tried to explain the hysteresis phenomena using discrete element analysis combined with continuum model for fluid flow. In this model all the forces have been considered as described by the Eq. (1). This approach is still in its infancy but quite promising. However, this approach also clearly shows the importance of frictional forces in describing the raceway phenomena.

It has also been reported that raceway sizes obtained in pseudo two-dimensional and two-dimensional apparatus could be different.[18] Two-dimensional models are those in which a tuyere, in the form of a rectangular slot, is introduced across the entire width of the model. Thus, the phenomenon is confined strictly to two dimensions and there is no expansion of jet occurs in the third dimension. In pseudo two-dimensional model, a jet of air is introduced through a tuyere placed in the longitudinal central plane of the model. The jet can expand in front of the tuyere in all directions but it is assumed that there is a negligible effect due to the jet expansion in the direction perpendicular to the tuyere axis.

In this article, only two-dimensional models have been used and two correlations one each for increasing and decreasing gas velocity have been developed based on dimensional analysis taking the frictional properties of the material into account. Predictions by correlations have been compared with the published, experimental, and plant data to verify their validity.

2. Experimental Plan

As such the experimental raceway size is a function of physical and frictional properties of the material and geometrical parameters of the experimental setup. Therefore, many experiments were performed to obtain the raceway size as a function of these parameters in both increasing and decreasing gas velocity. **Table 2** shows the range of various variables (geometrical) along with experimental variables used during the experiments. All the particles, which were used during the experiments, were having the ratio of apparatus thickness (opening) to particle diameter always greater than 12 or more. All experiments were carried out in two-dimensional cold models which were reinforced using iron bars to prevent the bulging. PVC slot tuyeres were used. A schematic diagram of the equipment is shown in **Fig. 1**.

The bed was packed with a desired material to a desired bed height above the tuyere level. Room temperature air was used as the blast gas to form the raceway. The air flow rate to the tuyere was increased gradually until the point at which the raceway just began to form, then it was shut off immediately. This procedure was necessary to clear the tuyere of the beads which entered the tuyere when the bed was filled. The air flow rate was then increased gradually from zero to the fluidisation limit of the bed in steps. At each step, two minutes were allowed for the raceway size to reach equilibrium, then the raceway penetration (size in the gas entry direction) and height were measured directly using a ruler and tracing the raceway boundary on a transparent graph paper. When the maximum gas flow rate for the experiment was reached, the flow rate was reduced through the same steps. Raceway penetration and height were measured in the same way. Each experiment was repeated more than three times. However, average value has been used in developing the correlations.

Various physical properties of the materials used in the experiment, are listed in **Table 3**. Hundreds of experiments were performed to obtain the raceway size by changing the dimensions of the apparatus, bed height, tuyere opening,

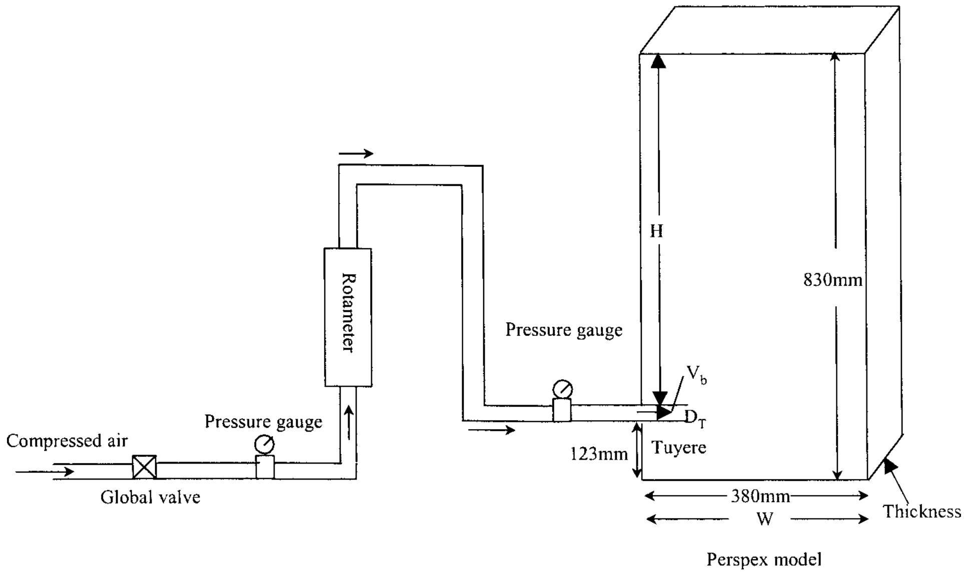

Fig. 1. Schematic of experimental setup.

Table 3. Physical properties of the materials.

Material	Shape	Density (kg/m^3)	Particle diameter (mm)	Particle wall friction (μ_w)	Shape factor	Min. fluidization velocity (m/s)	Void fraction
Plastic	Spherical	1080 ± 20	Variable (5.8 ± 0.04, 2.1 ± 0.1)	0.22	1.0	1.37 (for 5.8mm) 0.67 (for 2.1mm)	0.42
Polyethylene	Cylindrical	920 ± 30	4.1 (Equiv. Dia.)	0.29	0.87	0.84	0.42
Glass	Spherical	2770± 90	2.7± 0.01	0.16	1.0	1.39	0.43
Quartz	Irregular	2550 ± 70	Variable (Equiv. Dia 1.09,1.55)	0.2	0.65	0.87 (for 1.55mm)	0.4
Mustard seed	Spherical	1070 ± 10	2.2 ± 0.2	0.22	1.0	0.69	0.39

gas flow rate and material properties.

3. Dimensional Analysis

3.1. Velocity Increasing Case

The raceway is formed due to a balance between the pressure force exerted by the gas, bed weight and the frictional forces as described by the force balance Eq. (1). The pressure force exerted by the gas comprises the inertial and viscous force. The inertial force exerted by the gas depends on the blast velocity (v_b, m/s), density of the gas (ρ_g, kg/m^3) and the tuyere opening (D_T, m). The viscous force exerted by the gas depends on the viscosity (μ, Pa·s) of the gas and the particle diameter (d_p, m). The bed weight exerted by the packing depends on the density of the solid (ρ_s, kg/m^3), acceleration due to gravity (g, m/s^2), height of the bed (H, m) and void fraction of the bed. The frictional forces (or stresses) depend on the internal and wall angle of friction and this causes the introduction of the wall-particle frictional coefficient μ_w and ν, the inter-particle frictional coefficient. Finally, the width of the bed W has also been considered since it has been varied during the experiments as it affects the raceway penetration. In other words, the raceway diameter (D_r, m) in a packed bed is a function of the property of material used for packing, property of the gas injected through the tuyere, the geometrical parameters and the frictional parameters *i.e.*

$$D_r=f(\rho_{eff}, \rho_g, v_b, g, d_{eff}, \mu, D_T, H, W, \mu_w, \nu) \quad ......(2)$$

The effective diameter of the particle is given by $d_{eff}=d_p sh$,[19] where d_p=diameter of the particle and sh=shape factor of the particle. Effective density of the bed is given by $\rho_{eff}=\varepsilon\rho_g+(1-\varepsilon)\rho_s$. Wall-particle frictional coefficient is given by $\mu_w=\tan\phi_w$ and inter-particle frictional coefficient is given by $\nu=\tan\phi$. Where, ϕ and ϕ_w are the internal angle of friction between the particles and angle of friction between the wall and particle respectively.

Since the total number of variables is 12 and the number of independent variables in terms of which the variables can be expressed is 3, the number of dimensionless groups that will be obtained from the dimensional analysis is 9. Using π-theorem, the correlation for the raceway diameter was obtained as

$$\frac{D_r}{D_T}=k\left(\frac{\rho_g}{\rho_{eff}}\right)^a\left(\frac{v_b^2}{gd_p}\right)^b\left(\frac{\rho_g v_b d_p}{\mu}\right)^c\left(\frac{D_T}{W}\right)^d \times\left(\frac{D_T}{H}\right)^e(\mu_w)^f(\nu)^g\left(\frac{d_p}{D_T}\right)^h \quad ....(3)$$

Last group in the above equation can be neglected[9] as raceway formation is dominated by continuum. It has been observed theoretically[14] that in 2D cold model wall particle friction would be more dominating than inter-particle friction. Moreover, the value of ϕ changes with the gas flowrate[20] which makes difficult to assign it single value. Therefore, Eq. (3) in simplified form can be written as

$$\frac{D_r}{D_T}=k\left(\frac{\rho_g}{\rho_{eff}}\right)^a\left(\frac{v_b^2}{gd_p}\right)^b\left(\frac{\rho_g v_b d_p}{\mu}\right)^c\left(\frac{D_T}{W}\right)^d\left(\frac{D_T}{H}\right)^e(\mu_w)^f \quad \text{.....(4)}$$

The first dimensionless group on the right side is the ratio of fluid to solid density. Second group is Froude number which gives the ratio of inertial to gravitational forces. It is used to describe the gas/solid systems. Many previous authors have correlated raceway size with this number. The third group is well known Reynolds number. The left hand side group of Eq. (4) is known as raceway penetration factor.

- Results and Discussion

From the experimental values, obtained in the velocity increasing case, the values of dimensionless groups given in Eq. (4) are evaluated. The resulting data is then subjected to regression analysis to determine the constants *a*, *b*, *c*, *d*, *e*, *f*, and *k*. The values of the constant obtained are $a=0.79$, $b=0.81$, $c=0.0035$, $d=0.88$, $e=0.89$, $f=-0.24$ and $k=243.5$.

From these values it is clear that Reynolds number is of least significance. All other parameters are important. Therefore, after neglecting the Reynolds number term and performing regression analysis again one gets the values of the coefficients as $a=0.79$, $b=0.81$, $d=0.85$, $e=0.88$, $f=-0.23$ and $k=247$. It can be observed that there is not much change in the value of the coefficients after neglecting the Reynolds number. The effect of the Reynolds number is negligible because of the inertial conditions prevailing during the raceway experiments performed. Since the value of coefficients *a*, *b*, *d* and *e* are quite close, we can group them into a single dimensionless group and the simplify form of the correlation can be written as

$$\frac{D_r}{D_T}=k\left(\frac{\rho_g v_b^2 D_T^2}{\rho_{eff} g d_{eff} HW}\right)^a(\mu_w)^b \quad \text{.................(5)}$$

Doing regression analysis again, we get the values of the coefficients as $a=0.80$, $b=-0.25$ and $k=164$. The R^2 value of the correlation was found to be 0.96. Therefore, the final form of the correlation for increasing velocity is

$$\frac{D_r}{D_T}=164\left(\frac{\rho_g v_b^2 D_T^2}{\rho_{eff} g d_{eff} HW}\right)^{0.80}(\mu_w)^{-0.25} \quad \text{...........(6)}$$

3.2. Velocity Decreasing Case

The correlation for the raceway diameter as before is given by

$$\frac{D_r}{D_T}=k\left(\frac{\rho_g}{\rho_{eff}}\right)^a\left(\frac{v_b^2}{gd_{eff}}\right)^b\left(\frac{\rho_g v_b d_{eff}}{\mu}\right)^c\left(\frac{D_T}{W}\right)^d\left(\frac{D_T}{H}\right)^e(\mu_w)^f \quad \text{.....(4)}$$

A regression analysis was performed on the experimental data, obtained in the gas velocity decreasing case, to determine the constants *a*, *b*, *c*, *d*, *e*, *f*, and *k*. The values of constant obtained are: $a=0.60$, $b=0.62$, $c=-0.024$, $d=0.51$, $e=-0.095$, $f=-0.235$ and $k=3.3612$. The R^2 value of the correlation was found to be 0.96.

As before, one can neglect the Reynolds number since its coefficient *c* is very small. Since the values of other coefficients *a*, *b*, and *d* are quite close, one can combined these dimensionless groups into single group. Thus the simplify form of the correlation can be expressed as

$$\frac{D_r}{D_T}=k\left(\frac{\rho_g v_b^2 D_T}{\rho_{eff} g d_{eff} W}\right)^a\left(\frac{D_T}{H}\right)^b(\mu_w)^c \quad \text{............(7)}$$

where *k*, *a*, *b* and *c* have to be determined by regression analysis again. Using the above equation and performing regression analysis, one obtains the following final form of the correlation for decreasing velocity.

$$\frac{D_r}{D_T}=4.2\left(\frac{\rho_g v_b^2 D_T}{\rho_{eff} g d_{eff} W}\right)^{0.6}\left(\frac{D_T}{H}\right)^{-0.12}(\mu_w)^{-0.24} \quad \text{.....(8)}$$

The R^2 value of the correlation was found to be 0.96.

Equations (6) and (8) are the desired raceway size correlations for the increasing and decreasing velocity respectively. It is interesting to note that the bed height and tuyere opening play an important role in increasing than decreasing velocity. Equation (6) shows that raceway diameter is proportional to almost square of the velocity in increasing velocity while the Eq. (8) shows it is almost linear to the velocity in decreasing case.

In **Fig. 2** the experimental data points are compared with the decreasing correlation (8). Each point in the figure is an average of at least three experimental values. A good agreement between the two is apparent. A similar plot was ob-

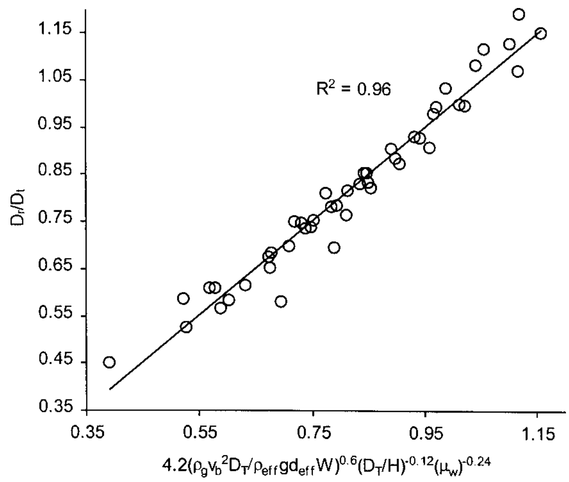

Fig. 2. Decreasing correlation *vs.* experimental data.

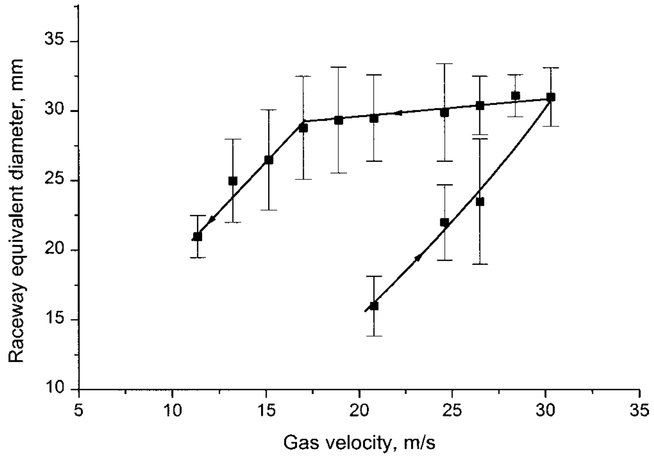

Fig. 3. Experimental raceway hysteresis for plastic beads of 2.1 mm size.

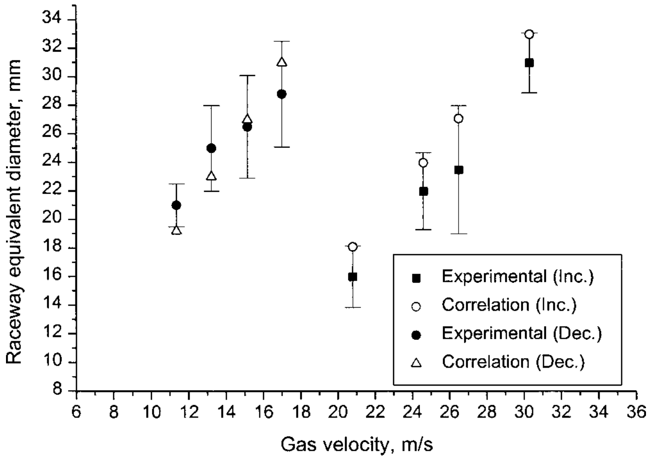

Fig. 4. Comparison of raceway diameter between experimental and correlations in both increasing and decreasing velocity.

tained for increasing correlation.

The results obtained from these correlations are compared with the experiments and plant data below.

- Experimental Data

Figure 3 shows a typical experimental hysteresis plot of raceway size. This plot is for plastic beads of diameter 2.1 mm. Bed height was 600 mm from tuyere level and tuyere opening was 5.5 mm. Apparatus number 3 (see Table 2) was used during the experiments. One can clearly see that raceway size in decreasing gas velocity are always higher than the increasing case and can vary by a factor of 3. The detailed mechanism involved behind it is explained elsewhere.[3,14] However, in brief it can be said that initially, there is no raceway formation with increase in velocity since the pressure force exerted by the gas is unable to overcome the frictional forces and bed weight. Later when the velocity (or pressure force) is sufficiently high to overcome these forces, void or raceway starts forming. As we start increasing the blast velocity further, the raceway size increases in a parabolic manner. After a maximum gas velocity, as one starts decreasing the gas velocity, initially there is almost no change in the raceway size. This is due to the fact that the frictional forces start acting in the reverse direction and increase in magnitude as we start decreasing the gas velocity. Once the frictional stresses acting in the reverse direction become fully mobilized, there is a linear decrease in the raceway penetration with further decrease in the velocity.

Other experimental results are not reported here as they have been discussed elsewhere.[3,14,21–24)]

It should be noted that in all figures (Figs. 4 to 7) comparison of correlation data has been done only with those experimental data which have not been used in developing the correlation. If we use those data that have been used for developing the correlations then there has to be a good agreement between the two as shown in Fig. 2. Therefore, there is no point in comparing those data with the developed correlations.

A comparison between the experimental and predicted (using correlation equation, Eq. (8)) raceway size for decreasing gas velocity is shown in **Fig. 4**. All the experimental conditions are same as given in Fig. 3. An excellent

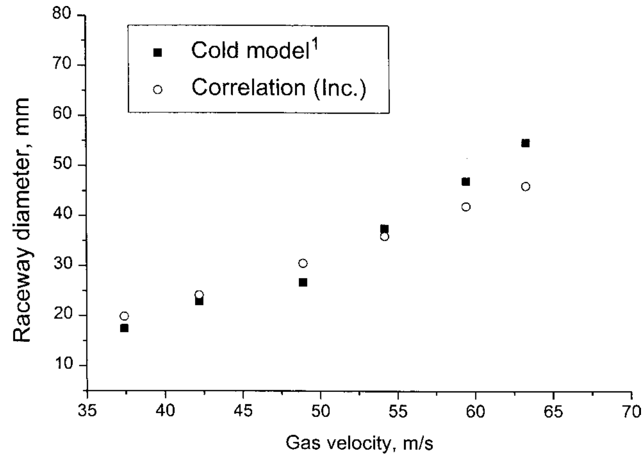

Fig. 5. Comparison of correlation raceway diameter with published[1] data of 3 mm polystyrene.

agreement between the two is apparent. Data in the velocity range of 18 to 28 m/s (where raceway size is constant) can not be compared as the friction is getting mobilized during this period. It is changing its sign/direction and therefore, there is no change in the raceway size. More description of this behaviour is given elsewhere.[3,14] The correlations, which have been developed in this study, are valid only when friction is fully mobilized. Therefore, they are valid for Fig. 3 in increasing case between 0 to 28 m/s velocity and in decreasing case between 0 to 18 m/s. The linear decrease in the raceway penetration with blast velocity is predicted well by the correlation. Similarly, one can see good agreement between the two values in increasing gas velocity as shown in the same figure.

- Cold Model Data

Figure 5 shows a comparison of raceway size obtained using the correlation and published experimental values for a 2D cold model.[1] The experimental values of the raceway diameter have been obtained for polystyrene beads of diameter 3 mm, bed height from the tuyere level 800 mm, and tuyere opening 5 mm. Angle between the wall and particle was taken 18.[23] Other values are given in Ref. 1). Average raceway diameter was used in plotting the value as data were available for raceway penetration and raceway

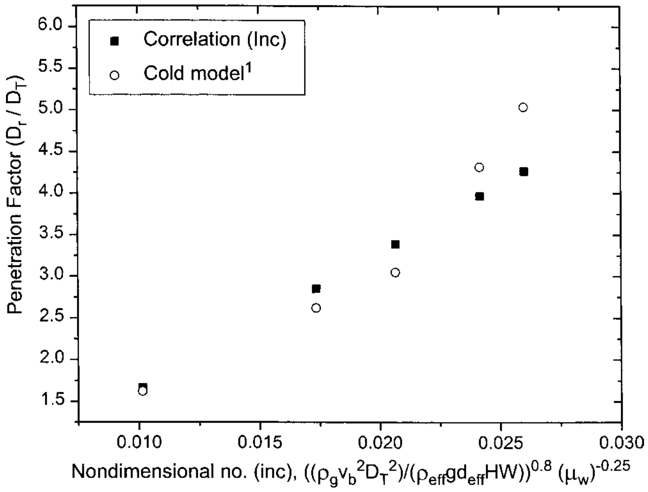

Fig. 6. Comparison of penetration factors obtained from correlation and published[1] data of 0.725 mm ballotini glass.

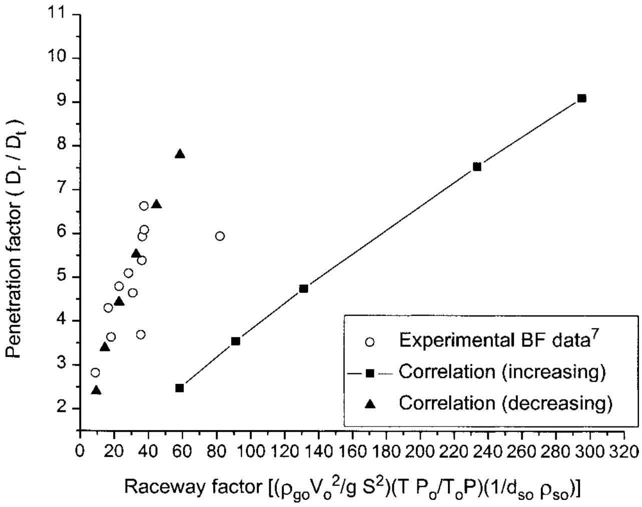

Fig. 7. Comparison of experimental blast furnace[7] and cold model data for both increasing and decreasing velocity conditions.

height.[1] There is good agreement between the experimental values of average raceway diameter and that obtained using the correlation with the maximum error equal to the two particles diameter except at the maximum blast velocity which is close to the fluidisation limit and one can not expect a good agreement for those values. It should be noted that the correlation gives the diameter of the raceway which could be little different, by definition, from the raceway penetration or average raceway diameter as reported by many investigators.

Another published experimental result[1] along with correlation data for the glass bead of diameter 0.725 mm, bed height from the tuyere level 800 mm and tuyere opening 5 mm is given in **Fig. 6**. The results are for 2D cold model in increasing gas velocity condition. Data have been plotted in terms of penetration factor (D_R/D_T) and non-dimensional number $((((\rho_g v_b^2 D_T^2)/(\rho_{eff} g d_{eff} HW))^{0.8}(\mu_w)^{-0.25})$ as given by the Eq. (6). Wall-particle angle was taken 12.4.[11] Again, there is a good agreement between the experimental values of penetration factor with that obtained using the correlation except the last experimental point which is near the fluidisation limit as explained in previous figure.

From Figs. 5 and 6 it is evident that trend of the predicted values is same though they have been plotted in a different way in each figure. This is an expected trend if only one parameter is varied. All other figures have been plotted in dimensionless numbers.

- Plant Data

It was reported by a few authors[2,3,21] that raceway size obtained in decreasing gas velocity is more relevant to operating blast furnaces than increasing gas velocity. It is because large amount of coke is consumed near the raceway during combustion and in reducing the ore. This coke is replenished from the surrounding of the raceway. Also intermittently iron and slag is tapped from the bottom due to which coke descends.

It has also been found[9] that the decreasing gas velocity condition is applicable to the case of a moving bed as in the case of blast furnace. It was observed that the horizontal injection into a moving bed gives effects similar to those encountered with vertical injection into a moving bed. So the decreasing correlation results can be applied to the moving bed irrespective of whether there is horizontal or vertical injection of the gas.

All the previous correlations, which have been given for the raceway penetration till now, are mainly for the increasing velocity. There is a doubt of their applicability to the blast furnaces. Now, it is the time to verify two points:

1. Whether the decreasing gas velocity is relevant to blast furnace or increasing, and
2. Whether the developed correlation, based on cold model results, can represent the commercial blast furnace.

Figure 7 shows the raceway factor values plotted as a function of penetration factor obtained using the correlation in both increasing and decreasing velocity case along with the experimental blast furnace data.[7] In the experimental blast furnace, water cooled probe was used to measure the raceway size through the blow-pipe. In this figure data obtained from the correlation are based upon the cold model experimental data for the case of apparatus 1, tuyere diameter 6 mm, bed height 1m and polyethylene beads of equivalent diameter 4.1 mm. There is an excellent agreement between the raceway factor values obtained in the velocity decreasing case with the experimental blast furnace data when plotted as a function of penetration factor. It confirms both the points mentioned above that raceway size obtained in decreasing velocity is more relevant to commercial blast furnace and the correlations developed here reasonably predict the raceway size.

In Fig. 7, it was difficult to compare the penetration factor with the non-dimensional number, developed in this study, as many of the data were not available. In fact, in most of the published work on commercial blast furnace, many data are missing. However, we have managed to extract most of the data from these papers. Some of the values have been assumed in a reasonable way which are described during the discussion of a particular figure. From Figs. 8 to 11, raceway data are compared using the correlations and actual blast furnace data.

Before we start to compare the data obtained using two-dimensional (2D) cold model correlations with three-dimensional (3D) blast furnace one should reconcile some parameters. W in 2D model is referred to the width of apparatus. In blast furnace this has been taken as radius of the hearth that would be the approximately maximum width one may get in the bosh region in blast furnace. Also, the value of this parameter is easily available in the literature. Tuyere opening in 2D is D_T, however, in the case of blast furnace (3D) tuyere (circular pipe) area has been converted into the equivalent 2D rectangular area keeping one dimension is equivalent to the tuyere diameter (which is in 2D case would be the thickness of the bed, see Fig. 1). The other dimension of the rectangular area will give the tuyere opening, D_T, for the blast furnace. For example, if tuyere diameter is 20 cm then tuyere opening, D_T, in 2D would be=15.7 cm ((area of the tuyere pipe, πr^2)=(area of the rectangular slot, $D_T 2r$)).

Wagstaff[4,6,25] reported the data of commercial blast furnaces almost half a century ago. That time blast furnace technology was not so advanced. We were able to extract most of the data which are required by the correlation to predict the raceway diameter except the height of the burden, coke size, apparent density of solid and hearth radius (as W in the correlation). After going through a few text books,[19,26,27] coke size was assumed 40 mm and bulk density 900 kg/m^3. These values were kept constant in other papers also (if applicable). Hearth diameter, especially for the old furnaces of 1950, was assumed[19] 7 m. Burden height was calculated, for all authors, as effective burden height using the formula suggested by Sastry *et al.*[22] They have shown, based on stresses at the bottom of a 2D apparatus and using modified Janssen equation for a two-dimensional bed, that pressure becomes almost constant at the bottom of the apparatus after a certain burden height. Using their formula and assuming 15 m burden height, it was found that pressure at the bottom becomes constant after 5 m of burden height. Therefore, this height (5 m) was taken as the effective burden height for all the commercial furnaces. It was also found that if burden height is taken to 20 m then there is hardly any change in the effective bed height.

Figure 8 shows a comparison of predicted penetration factor with the actual blast furnace data.[6] Raceway depth was measured using a water cooled probe.[4] All the data belong to one blast furnace. An excellent agreement between the two is apparent. It shows the validity of the correlation to predict the raceway diameter in operating blast furnaces after reconciling a few 3D parameters into 2D.

Another comparison between the plant[6] and correlation data is shown in **Fig. 9** for decreasing gas velocity. Error bars are also shown in the plant data as there is a wide scattering in the experimental data. Each plant data point in this figure belongs to an average of one blast furnace only. Therefore, five blast furnaces data have been plotted along with predicted values. It is pleasing to see a good agreement between the two again. However, the reason for wide fluctuations in the experimental data should be addressed.

In Fig. 9, each furnace data point is an average of 20 or more points except in one case. There were a few points of raceway penetration in each furnace that were either very high or low and hence affecting the overall average value significantly. We have included all the points in calculation.

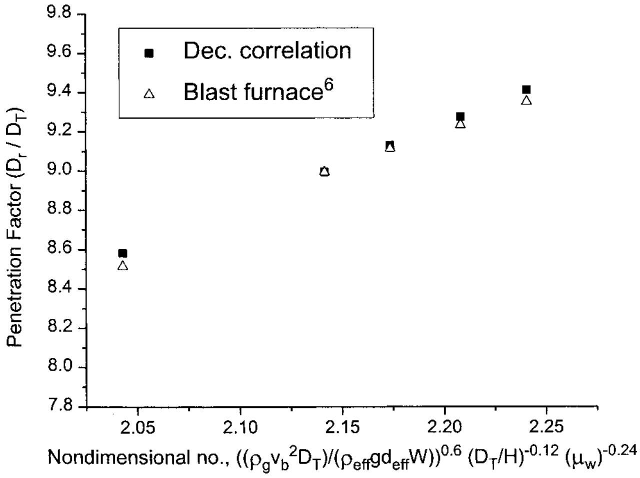

Fig. 8. Comparison of penetration factors obtained from decreasing correlation with published blast furnace data[6] for one furnace.

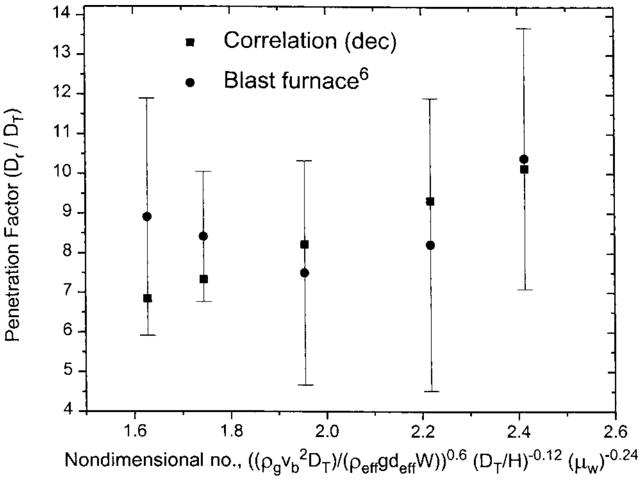

Fig. 9. Comparison of penetration factors obtained from correlation with published blast furnace data[6] of various furnaces.

It was noted that at different time varying raceway penetration, at the same blast velocity, have been reported. This is may be due to that during the raceway measurement[4] probing rod tends to sag of its own weight when it is freely resting in the combustion zone, but when it is pushed back further and strikes the stationary solid material, the end deflects upwards. It has also been found that in some cases, one gets more raceway penetration at less velocity than at high velocity. These all factors can give a different trend to blast furnace curve. However, this is not the case in cold model data where one has more precise and reproducible results.

Figure 10 shows another comparison between the correlation and Japanese blast furnaces.[28] In this paper all the data were available except bulk density of the coke which was taken 900 kg/m^3 as described before. In this figure raceway diameter has been plotted against gas velocity. In this figure seven blast furnace data have been plotted. Each data belongs to one blast furnace. Each furnace has different conditions such as coke size, hearth diameter, blast velocity. For each furnace only one data was available therefore, there is no error bar in the experimental values is

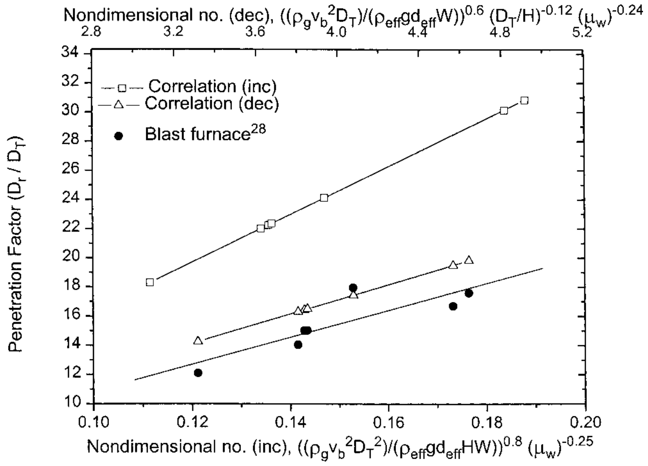

Fig. 10. Comparison of correlations with published blast furnace data of Nishi *et al.*[28]

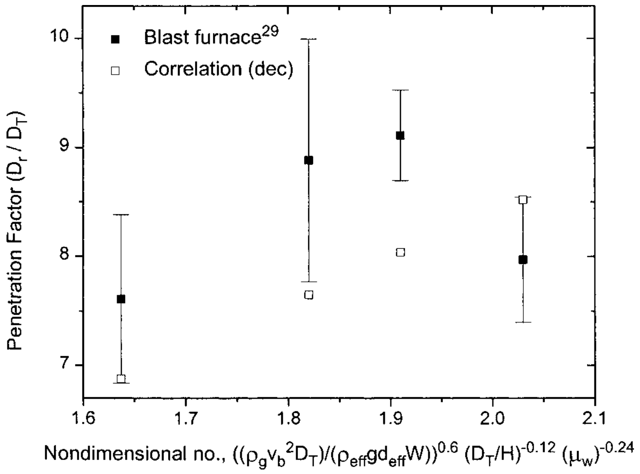

Fig. 11. Comparison of penetration factors obtained from correlation with published blast furnace data[29] of various furnaces.

shown. In this study raceway size was estimated from temperature and gas composition. Here "the wall of raceway" has been defined where there is an abrupt change in temperature has occurred in the raceway. The distance from the raceway wall to the tip of the tuyere was expressed as raceway depth. The temperature within the furnace has been estimated from the graphitization of the coke. Again a good agreement exists between the two. The difference between the two values is mostly within the limit of ±two to four particles diameter. For comparison purpose, increasing velocity data has also been plotted in the same figure. It is obvious that decreasing velocity data are relevant to blast furnaces and are well represented by decreasing cold model correlation.

Another comparison of correlation with operating blast furnace data[29] is shown in **Fig. 11**. In this figure also, almost all data were given in the literature except the coke size and its bulk density which were taken as 40 mm and 900 kg/m^3 respectively. Figure also shows the error bars in the plant data. Each average data belongs to one furnace. The technique to measure the raceway size is not described in the paper. A reasonable agreement exists between the two. Again the same explanation can be given for the wide fluctuations in operating data as it was given in Fig. 9. Besides these, operating data in this figure are affected by fluctuations in blast pressure, auxiliary fuel supply rate and blast moisture which will further deteriorate the comparison which is obvious from this figure.

We must mentioned that no manipulation in the data have been made in order to get the penetration factor from the correlations. However, one should make the judicious choice of the operating parameters, which are not available based on available literature in this area in order to get the raceway diameter. One should be aware of that operating raceway data could fluctuate to any extent depending on the operating conditions of the blast furnace and the fluctuations in the operating parameters such as wind rate, blast temperature and pressure, etc. Also, raceway penetration depends with the casting conditions that whether it has been measured before, after or during the cast. Further study on three-dimensional cold and hot models would be desirable in this area and to extend the correlations to real blast furnace taking into consideration the above mentioned blast furnace conditions.

In the blast furnace coke is consumed in the raceway and therefore the whole burden descends downward towards the raceway. Therefore, friction is expected to oppose this movement and will act in the upward direction and be fully mobilized. This blast furnace condition is satisfied experimentally only when one does the experiments in the decreasing gas velocity. Only under these experimental conditions friction will act in the upward direction as discussed in the begining. In increasing gas velocity, particles are pushed upwards and therefore, friction will act in the downward direction to oppose this motion of the particles which is not the case in a blast furnace. Detailed analysis on this is available in Refs. 2), 3), 9), 14), 21) and 24). The above examples also confirm that raceway data obtained on the operating blast furnaces are related to decreasing gas velocity in the two-dimensional cold model.

4. Conclusions

Two raceway size correlations have been developed one each for increasing and decreasing gas velocity under the cold model conditions. Frictional properties of the material have also been included in these correlations. Two-dimensional correlations have been applied to three-dimensional geometry after reconciling a few parameters such as tuyere and hearth diameters. Raceway size obtained from the correlations and other data such as published cold model, plant and experimental data match reasonably well. It has been shown that decreasing conditions prevails in the operating blast furnace and therefore, decreasing correlation can be used to predict the raceway size. Both the correlations are able to predict the raceway hysteresis in cold model.

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