Effect of Interface Resistance on Gas Flow in Blast Furnace

Mriganshu GUHA,1) Samik NAG,1) Pailola Kumar SWAMY1) and Ramachandran Venkat RAMNA2)

1) Research & Development, Tata Steel, Jamshedpur-831001, Jharkhand, India. E-mail: mriganshu.guha@tatasteel.com
2) H-Blast Furnace, Tata Steel, Jamshedpur-831001, Jharkhand, India.

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Any improvement in Blast Furnace productivity under a given set of operating conditions is fundamentally related to better flow distribution of gas through layered burden structure in Blast Furnace. Flow distribution and hence pressure drop of gas in granular region of blast furnace is dependent on number and thickness of alternating layers of coke and metallic burden. A significant part of this total pressure drop in granular region can be attributed to interfacial resistance between two successive layers. Whereas, pressure drop in porous layers of materials can be described by well known Ergun's equation in terms of all physical parameters, interface resistance needs specific treatment. Systematic study to investigate the effect of interfacial resistance on gas flow between two successive layers of different material has been attempted in this work.

Laboratory scale experiments in scale down model of blast furnace were conducted to establish and quantify interface resistance for different layer configurations.

KEY WORDS: blast furnace; gas flow; layered burden; interface resistance.

1. Introduction

The gas flow inside the blast furnace has attained greatest importance today because of emphasis on larger and larger sized furnaces with higher productivity. Any improvement in blast furnace productivity under a given set of operating conditions is fundamentally related to better flow distribution of gas through layered burden structure in blast furnace. Flow distribution and hence pressure drop of gas in granular region of blast furnace is dependent on permeability distribution, number and thickness of alternating layers of coke and metallic burden.

Pressure drop in porous layers of materials can be described by well known Ergun equation in terms of all physical parameters. The Ergun equation has formed the basis for applied research efforts aimed at improving blast furnace gas flow dynamics in last several decades. Several investigators have suggested the use of the vectorial form of Ergun equation whereby both the magnitude and direction of fluid flow in a packed bed may be calculated.

Layered burden structure inside blast furnace above fusion zone comprises of alternate layers or metallic burden and coke separated by a so-called mixed or ‘interface’ layer. The void fraction at the interface separating regions composed of different particles is of major importance in the definition of non-uniform flow through the stack region of blast furnace. In the past the effect of this layer on the total pressure drop in the furnace has been usually neglected till Furnas developed a useful approach for tackling this problem by assuming the interface layer as consisting of an intimate mixture of coke and ore. Furnas studied the decrease in void fraction when two different sizes of particles were completely mixed together and the overall voidage exhibited minima, for particular compositions, depending on the particle size ratio. As expected, the larger the disparity in sizes, the lower will be the numerical values of these minima. These results were used by different research groups as a first approximation with qualitatively similar results. In blast furnace burdens this factor will be significant since there are many layers and hence many interfaces. The increase in pressure drop due to these interfaces has been studied in the laboratory by Schultz and Abel using actual burden materials. If one has to perform calculations for a simulated burden, with all of the layers that would be present, the results of these workers would show that the interfacial loss would be 20–35% of the total stack pressure drop.

Standish and Williams had studied the structure and flow resistance of coke-ore interface under laboratory conditions. The results have shown that when ore is charged on top of a coke layer, the resulting interface essentially have a directional arrangement of coke and ore. The thickness of which is directly proportional to the coke and ore size ratio and whose flow resistance exceeds that of the coke layer many times its thickness. It has also been found that the ore on coke interface differs fundamentally from a mixed layer which was hitherto been assumed to exist in the stack of a blast furnace and which has been used in all previous calculations of the pressure drop there in.

Propster conducted laboratory scale experiments in order to characterize the local porosity variations in systems, containing layers of different particles, adopting experimental techniques developed by Benenati and Brosilow. Experimental measurements, conducted with spherical particles, indicate that marked local minima in porosity occur when a layer of smaller particles is placed upon a layer of
larger particles. Local minima in porosity are much less marked for other geometric arrangements i.e. the layering of larger particles on smaller, or having shell-core arrangement with vertical interface. These local minima in porosity, which are directional in nature, are due to penetration of smaller particles into the interstices of the larger particles. From a technological viewpoint, the most important finding of the work is the fact that, for spherical particles, appreciable penetration will occur when the particle size ratio exceeds about two. Under such conditions, the interfacial regions could offer a very significant resistance to flow of gas through the system.

Singh et al.\(^\text{12}\) conducted cold model experiments in a cylindrical vessel to study the characteristics of ore/sinter and coke interfaces formed in layer charged burden. It has been found that interfaces do not necessarily represent regions of high resistance to gas flow. The exact behaviour of interfaces depends on the nature and sizes consist of the particles in the two adjacent layers forming the interfaces.

While all of those previously cited work tried to characterize the interface characteristics in terms of bulk properties of particles and established the existence of a local porosity minima across interface but none of those were focused for blast furnace type of geometry. Systematic laboratory scale study to investigate the characteristics of interface resistance on gas flow between two successive layers of different material in a scaled down blast furnace model has been attempted in this work.

2. Experimental

The experimental setup consists of a 1:30 (reduced) scale two dimensional slot type model of the actual blast furnace. The model is 50 mm in depth and has a width of 288 mm at its throat portion. The picture of the physical model is as shown in Fig. 1.

Compressed air was used as the gas flowing through the packed bed of materials inside the model. As the main inlet valve is opened, compressed air flows into the main inlet through pressure regulator valve and gets divided into two parts and enters through the tuyeres inside the model. One rotameter on each side has been provided to control the gas flow rate. Pressure tapping points at different heights have been provided at the back side of the model and pressure is measured using the manometers as shown in the image. At each horizontal level of pressure measurements there are 4–5 nos. of pressure taps, which have been grouped as per their radial locations from wall towards centre and referred as ‘near wall’, ‘mid1’, ‘mid2’ and ‘centre’ in subsequent sections. The heights of the pressure points are shown in Table 1.

It was ensured during experiments that the gas flow remains constant and equal through tuyeres on both the sides. Food grade grains of different sizes which are nearly spherical in shape were used in this study. Physical characteristics of the particles are shown in Table 2.

Model used to be manually filled each time by dumping small portions of the packing material from the hopper top as per desired layer configuration and experiments were conducted with static bed. Initial experiment with the whole model filled with mustard seeds was carried out to have a standard reference case. Study of interface resistance started with single-interface in which the blast furnace model was filled with mustard layer till middle stack level and layer of small mustard was put on top of it. Air was passed at a rate

| Level Id | Level height from tuyere, cm |
|----------|-----------------------------|
| T1       | 75.5                        |
| S1       | 63.4                        |
| S2       | 52.6                        |
| S3       | 41.8                        |
| S4       | 31                          |
| S5       | 25                          |
| B1       | 19                          |
| BS1      | 13                          |
| BS2      | 7                           |
| Tuyere   | 0                           |

Table 2. Size and bulk density of different particles.

| Material   | Particle diameter (mm) | Bulk density (kg/m\(^3\)) |
|------------|------------------------|----------------------------|
| Mustard    | 2.30                   | 760                        |
| Semolina   | 0.50                   | 853.3                      |
| Small mustard | 1.03               | 778.3                      |
| Tapioca    | 3.40                   | 739.9                      |

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Fig. 1. Experimental set up.

Fig. 2. Interface shape.
of 150 l/min and pressure measurements were taken. Air flow rate used was derived from similarity criteria based on modified Froude number calculated at top exit of the model and actual blast furnace. Air flow rates used were also checked to be well below minimum fluidization velocities for the particles used in this study. Further with the same volume of mustard and small mustard, two and four interface configurations were made by re-laying the layers as shown in Fig. 2, starting with mustard at the bottom.

The effect of particle size ratio on interface porosity was done by considering 6 combinations of the particles viz. semolina-mustard, small mustard-mustard, semolina-small mustard, tapioca-mustard, tapioca-small mustard, tapioca-

semolina. Also, experiments for each combination were done at different flow rates to investigate its effect on interface porosity as well. Experimental results are described in the following sections.

3. Results

The pressure at different location and differential pressure obtained were plotted at different height from tuyere zone and shown in Fig. 3 for the reference case. The differential pressure represents the pressure drop between adjacent layers (along height) of pressure points. The graph shows that pressure gradually reduces as we move up from tuyere.

Fig. 3. (a): Absolute pressure vs. height, (b): Pressure difference vs. height.

Fig. 4. Differential pressure drop for different no. of layers (Expt.).
However the pressure drop keeps changing at different height. As we move up from the tuyere till the belly region, the diameter gradually increases and then reduces till the throat portion. Hence due to this geometrical shape, the velocity reduces till the belly region and then increases. Hence the pressure drop also drops in the bosh/belly region and again increases gradually in the stack region. The sudden increase in pressure drop at lower bosh region might be result of local packing density variation.

Pressure drop due to gas flow inside the model is affected by the resistance offered by the packed bed as per Ergun equation as shown below.

\[
\frac{\Delta P}{L} = \frac{150 \mu (1-\varepsilon)}{d_p^2 \varepsilon^3} v + \frac{175 \rho (1-\varepsilon)}{d_p \varepsilon^2} v^2 \quad (1)
\]

Where, \(\Delta P/L\) is the pressure drop per unit height of the packed bed; \(\mu\), \(\rho\), \(v\) are the viscosity, density and velocity of the gas and \(\varepsilon\), \(d_p\) are the porosity and mean particle diameter of the granular medium. For a given gas flow rate, resistance to gas flow depends primarily on void distribution or permeability distribution and particle size which occur due to presence of layers of different sized particles like mustard and small mustard seeds inside the model. Mustard and small mustard seeds are both nearly spherical in shape, with similar bulk density and with narrow size distribution. Though mustard seeds contain slightly smaller porosity (~0.37) than small mustard seeds (~0.42) but the smaller size of small mustard seeds (almost half the diameter of mustard seeds) cause larger resistance to flow of gas in small mustard layers.

**Figure 4** shows the differential pressure measured experimentally for base case (without interface, entire model filled up with mustard seeds) and different no. of layers of alternate-ly filled up mustard and small mustard seeds (1-, 2- and 4-interface). Location of interfaces has been shown by short horizontal lines along the differential pressure plot. This can be observed that differential pressure across small mustard layers is higher than that in mustard layers. Though same amount of mustard and small mustard seeds were used for making no. of layers, the overall pressure drop kept on increasing with increasing no. of layers or interfaces, as shown in **Fig. 5**. This observation proved contribution of some additional resistance component as ‘interface resistance’ due to layer structure of different materials and its significance.

To estimate interface resistance, experimental pressure drop was compared with total theoretical pressure drop across different layers. Difference of experimental and theoretical overall pressure drop was attributed as pressure drop due to interfaces. Interface porosity was further calculated from interface pressure drop. Interface was assumed to be a closely packed layer comprising of single particle of mustard and small mustard seeds. As a result, the thickness of interface was approximated as height of contacting spheres considering layer of smaller sized particles filling the interstices of larger sized particle layer as shown in **Fig. 6**.

Average particle diameter at interface was taken to be arithmetic mean of consisting particles. Interface resistance for mustard-small mustard layers comes out to be independent of its location in blast furnace model. Porosity of interface comprising mustard-small mustard seeds was estimated as 0.26. Pressure drop across this interface of ~3 mm height is equivalent to mustard layer of ~19 mm or small mustard layer of ~6 mm.

**Figure 7** depicts the variation of interfacial porosity with particle size ratio at different flow rates. It can be seen from the plot that increase in particle size ratio for a particular flow rate generally results in decrease in the interfacial porosity. This is expected due to improved particle-particle contact and better packing at the interface as the size ratio between them increases. Although no particular trend to this effect could be established as in many cases it deviated from the expected behavior. These deviations might be the result of uneven packing at the interface during experimentations.

Fig. 6. Approximated interface structure.

![Experimental vs. Theoretical](image)

**Fig. 5.** Overall pressure drop vs. no. of interfaces.

![Interfacial porosity Vs. Particle Size ratio](image)

**Fig. 7.** Interfacial porosity vs. particle size ratio, at different flow rates.
which are inherent characteristics of any granular system.

It was also found that increase in flow rate normally results in the decrease in interfacial porosity as depicted in Fig. 8 due to better mixing at the interface and filling of interstitial voids. Some outliers were also observed due to packing irregularities at interface.

4. Conclusion

Pressure drop in blast furnace across layered burden structure greatly depends on number of alternate layers of different materials. From the above set of experiments, it can be concluded that ‘interface resistance’ in layered burden structure has significant contribution to overall pressure drop. For interface comprising mustard and small mustard layers as used in these experiments, each interface was found equivalent to almost 6 times of its thickness of mustard layer. Interface resistance can be estimated and used for optimization of layer thickness or no. of layers. Interface resistance does depend on size ratio of materials in adjacent layers. Increase in particle size ratio for a particular flow rate generally results in decrease in the interfacial porosity due to improved particle-particle contact and better packing at the interface. Although no general correlation for this observation could be established from these limited set of experiments since in many cases it deviated from the expected behavior due to uneven packing at the interface during experimentations, which are inherent characteristics of any granular system. Also at higher superficial velocity of gas, interface porosity was observed to drop except some deviations due to packing irregularities at Interface. It was concluded from this exercise that effect of interface resistance must be incorporated in estimating pressure drop in granular region of blast furnace.

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