Pressure Drop in the Blast Furnace Hearth with a Sitting Deadman

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(Received on November 26, 2010; accepted on March 14, 2011)

1. Introduction

The extraction of a liquid through a lateral orifice is commonly encountered in a wide range of industrial applications. In the ironmaking blast furnace (BF), the tapping process is far more complex because of issues related to the multiphase flow characteristics and the role of the packed bed of coke (deadman) in the hearth. An efficient and strictly controlled tapping is necessary for guaranteeing a stable viscosity depending on a large number of variables, including the fluid and particle properties, pressure drop, flow length, and pressure profiles.

The major parameters for the CFD modeling experiments (where typically water or oil are used) and from small-scale physical modeling experiments (with slag as flowing media) and from small-scale physical modeling experiments (where typically water or oil are used) are shown in Table 1 and Table 2.

The characteristic flow length should mainly depend on the hearth dimensions and the liquid level in the hearth. Since the hearth dimensions are relatively constant as a result of a balance between refractory erosion and skull formation, attention is here paid to the relation between characteristic flow length and liquid level in hearth.

Even though CFD modeling requires some efforts in generating a proper geometric mesh and much computational effort to solve the flow rate and pressure fields, it is today an established technique for one-phase flow problems. The technique is also well-suited for comparison with experimental results from the true industrial system (with iron or slag as flowing media) and from small-scale physical modeling experiments (where typically water or oil are used).

A set of CFD runs with these fluids and five different dimensionless liquid levels (DL) were considered. The dimensionless height of the taphole, which is the ratio between sump depth from the hearth centerline and the hearth radius, was fixed at 0.88 in this work. Since the diameter of the taphole is small in comparison to the hearth dimensions, the liquid gradually accelerates while flowing toward the taphole. In addition, the liquid levels inside the hearth move up and down periodically because molten materials are produced continuously but removed only intermittently; thus, the liquid flow length varies during tapping. It is therefore difficult to specify the key variables u and l in the KC equation. To tackle this problem, the mean velocity corresponding to the BF production was used as the velocity in Eq. (1).

Furthermore, a characteristic flow length, lc, which can represent the varying flow paths in the BF hearth and facilitate engineering calculations, was introduced in this work: A similar treatment has been adopted by other investigators.8,9)

According to the similarity between the flow through a packed bed and a pipe, the KC equation is rearranged in a general form for pipe flow as shown in Eq. (2), where Re_p is the packed bed Reynolds number, and lc and de are the characteristic flow length and equivalent diameter, respectively. Here, the dimensionless flow length is defined as the ratio of lc and de.

\[
\frac{\Delta p_p}{\rho u^2} = \frac{180 \text{Re}_p^{-1}}{d_e} ; \quad \text{Re}_p = \frac{\rho u d_e}{\eta} ; \quad d_e = \frac{\phi d_c e}{(1-e)}
\]

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As an example, the streamlines and pressure (in Pa) distribution on the symmetric plane of DL4 are presented in Fig. 1. The pressure drop is half of the total because a semicircular geometry was applied in the simulations. It is seen that the streamlines are of very different shape and length from different starting points on the liquid surface. The pressure, in turn, drastically decreases and forms a hemispheric isobar profile in the vicinity of taphole caused by the rapid increase in fluid velocity. For the other cases (DL1, DL2, DL3 and DL5) similar observations were made for the flow and pressure profiles.
To evaluate the characteristic flow length, extensive data of $\Delta p/\rho u^2$ versus $180Re_p/d_e$ (denoted by $Eu_p$ and $DI$, respectively) was generated by CFD simulations. These and fitting curves are plotted in Fig. 2. A linear relation is obtained regardless of the fluid properties and dimensionless liquid level. Moreover, the slope of each line reflects the characteristic flow length for a specific liquid level. The characteristic flow length is then derived and plotted in dimensionless form ($l_c/d_e$) in Fig. 3. It is seen that the flow length increases with the liquid level. Thus, for tapping operations where the initial outflow rate of iron is smaller than the production rate, the flow length first increases, followed by a decrease when the drainage rate exceeds the production rate. This implies that the pressure drop in the BF hearth continuously varies during the tapping operation, which may partially explain the complex tapping behavior observed in practice.

### 3. Verification

To validate the expression, a 3D physical hearth model was built and the pressure drop of water flowing through a sitting deadman was measured. The dimensions are approximately the same as in those in the CFD model. For physical modeling, it is essential to obtain a dynamic similarity between the flows in the model and in the actual process. In this report it is ensured by considering two dimensionless numbers, $Re_p$ and the modified Froude number,

$$Fr_p = \frac{u^2}{(1-\varepsilon)^2\phi d_g g}$$  \hspace{1cm} (3)

Table 3 shows that the magnitudes of $Re_p$ are close to unity and $Fr_p$ are all quite small, even though the values do not have the same magnitudes. Based on the meaning of these

![Fig. 1. Streamlines and pressure distribution (in Pa) on the symmetric plane of DL4 for water.](image)

![Fig. 2. Extensive data provided by CFD and the fitting curves. Solid circles (●), open diamonds (◇), open rectangles (□) and open circles (○) represent the data with water, oil, liquid iron and slag respectively.](image)

![Fig. 3. Relation between dimensionless flow length and dimensionless liquid level (cf. Fig. 2).](image)
two dimensionless numbers, it is evident that the gravitational force is dominant both in the actual hearth and in the physical model.

The experimental set-up is schematically illustrated in Fig. 4. A bed packed with polypropylene (PP) particles was placed inside the tank and the average porosity of the bed was estimated by measuring the voidage volume using water. This packing process was repeated until the anticipated average porosity was reached. To measure the overall pressure drop, two thin glass tubes filled with water were placed in the positions indicated (Points 1 and 2) in Fig. 4. A flow distributor was located at the entrance of the “hearth” to get a uniform inlet flow profile and to prevent the deadman from floating.

Experiments with three different dimensionless liquid levels (DL2, DL3 and DL4) were carried out taking into account the precision of the pressure measurement device and experimental feasibility. The predicted pressure drop was calculated by Eq. (2), in which the dimensionless flow length was extracted from the curve plotted in Fig. 3. Figure 5 shows satisfactory agreement between experimental and predicted results, which demonstrates the validity of the mathematical expression.

4. Discussion

The results of the study clearly demonstrate that Eq. (2) presents a reasonable macroscopic model for predicting pressure drop through a sitting deadman in the BF hearth. However, for engineering applications, the numerical variable \( l_c \) in the model must be evaluated. Figure 3 illustrates the relation between dimensionless flow length \( (l_c/d_e) \) and the liquid level for the conditions of the present study. However, there are some other parameters that influence the dimensionless flow length. According to our preliminary work, the flow length also depends on the geometry of the system, such as taphole diameter, hearth diameter and sump height, as mentioned by other authors. Nevertheless, the present work has revealed some fundamental issues that can be useful in a more detailed modeling of the system.

5. Conclusions and Future Prospects

A new expression is proposed for predicting the pressure drop in the blast furnace hearth with a sitting deadman at relatively low Reynolds number. The expression can be applied in parametric studies of factors that affect the hearth drainage. However, a large number of issues still remain unexplored, e.g. the relation between the dimensionless flow length and geometrical factors of the hearth. Experimental work in the laboratory combined with numerical analysis by CFD will be undertaken to gain a more complete understanding of the effects of these factors on the dimensionless flow length. Future work will also be focused on clarifying the effects of a floating deadman.

REFERENCES

1) T. Fukutake and K. Okabe: Trans. Iron Steel Inst. Jpn., 16 (1976), 309.
2) T. Fukutake and K. Okabe: Trans. Iron Steel Inst. Jpn., 16 (1976), 317.
3) P. Zulli: Ph. D. Thesis, University of New South Wales, Sydney, (1991).
4) T. Nouchi, M. Yasui and K. Takeda: ISIJ Int., 43 (2003), 175.
5) T. Nouchi, M. Yasui, K. Takeda and T. Ariyama: ISIJ Int., 45 (2005), 1515.
6) K. Nishioka, T. Maeda and M. Shimizu: ISIJ Int., 45 (2005), 1496.
7) M. Iida, K. Ogura and T. Hakone: ISIJ Int., 48 (2008), 412.
8) M. Iida, K. Ogura and T. Hakone: ISIJ Int., 49 (2009), 1123.
9) P. C. Carman: Trans. Inst. Chem. Eng., 15 (1937), 150.
10) M. J. Luomala, O. J. Mattila and J. I. Häkkä: Scand. J. Metall., 30 (2001), 225.
11) F. W. B. U. Tanzil, R. J. Nightingale, P. Zulli, B. D. Wright and I. Bean: SCANMET II, Luleå, Sweden, (2004), 321.
12) L. Shao and H. Saxén: ISIJ Int., 51 (2011), 228.