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Cold Model Study of Blast Gas Discharge from the Taphole during the Blast Furnace Hearth Drainage

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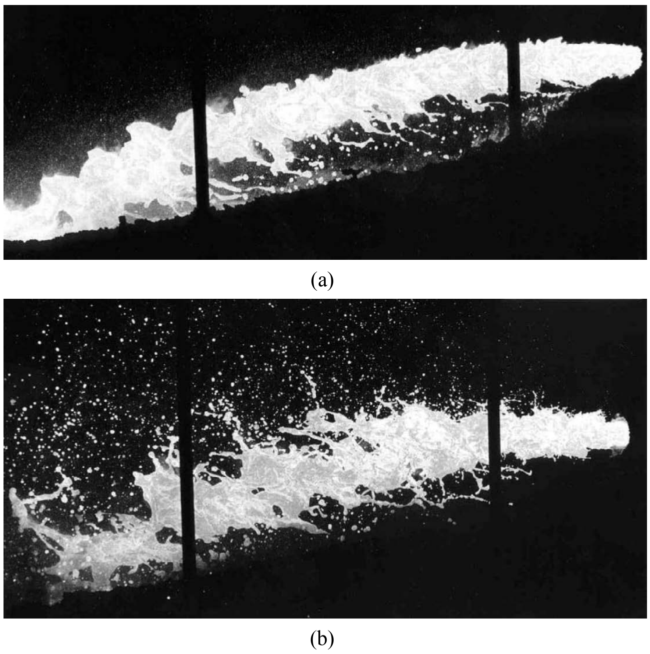
Blast gas discharge from the taphole in the course of the blast furnace hearth drainage was experimentally studied using a packed bed cold model. It was found that gas break-through time was strongly influenced by the furnace operating conditions and coke bed structure. Gas break-through time decreases with (a) increasing draining rate; (b) decreasing slag and iron levels in the hearth; and (c) increasing slag viscosity. It increases with an increase in the coke-free layer depth and coke-free space width. Under certain conditions, the gas-liquid interface in the region directly above the taphole becomes unstable, leading to viscous finger formation and subsequently early blast gas discharge from the taphole. The amount of blast gas entrained into the taphole due to viscous fingering, when it occurs, is sufficient to cause a splashy taphole stream.

KEY WORDS: blast gas discharge; splashy taphole; viscous fingering; hearth drainage; blast furnace; ironmaking.

1. Introduction

Effective drainage of molten metal and slag from the hearth is important for a stable and efficient ironmaking blast furnace (BF) operation. It has been extensively studied both theoretically and experimentally.[1–5] Ideally, the molten metal and/or slag are continuously tapped from the furnace as a coherent stream with minimal splashing, as shown in **Fig. 1**(a), until the gas-slag (G-L) interface reaches the taphole. At this point the tapping process is terminated to prevent blast gas from exiting the taphole. However, in some instances blast gas unexpectedly exits the taphole very early in the tapping process, causing excessive splashing (see Fig. 1(b)) and fume emissions. When this situation occurs often the only action is to terminate the tapping process by plugging the taphole. Experience at Bluescope Steel's Port Kembla Steelworks has shown that the premature plugging of the taphole can have a significant impact on furnace operation, leading to a high liquid level in the hearth and in many cases, decreased stability, productivity and/or overall efficiency of the ironmaking process.

The splashy taphole stream in the early stage of casting is caused by the entrainment of the blast gas into the taphole.[6] One possible mechanism for the unexpected blast gas entrainment is the formation of "viscous fingers" at the G-L interface, penetrating the packed bed and then into the taphole, due to Saffman-Taylor instabilities.[9] Viscous fingering can occur at the interface when a viscous fluid is displaced by a less viscous fluid through a porous medium. It has been extensively studied in a variety of contexts, with particular emphasis on petroleum recovery applications,[10–13] but few studies associated with the BF hearth draining process.[7,8]



(a) (b)

Fig. 1. Images of casting streams taken from BlueScope Steel's No. 6 blast furnace.

In the course of the hearth drainage, the liquid phase (slag) is displaced by the less viscous gas phase. The descending velocity of the G-L interface varies with distance from the taphole, with its highest value occurring in the region directly above the taphole. When the local descending velocity exceeds the critical value, the G-L interface becomes unstable, leading to the formation of viscous fingers, as shown in **Fig. 2**. In our previous studies,[7,8] it was demonstrated that viscous fingering is likely cause for blast gas discharge in the early stage of the hearth drainage. From these studies, it was also found that the G-L interface stability was greatly influenced by bed packing characteristics, in particular, bed heterogeneity.

In this work, the behavior of the G-L interface was studied, with the aim of further understanding the conditions that may cause instability of the G-L interface and subsequently early blast gas discharge from the taphole during the hearth drainage. In particular, it focused on the G-L interface stability as a function of draining rate, slag viscosity, slag and metal levels and the presence of a coke free layer.

2. Experimental

This study involved experimentally simulating the BF drainage process in a packed bed model. The experimental apparatus is schematically shown in **Fig. 3**. The model was constructed of perspex and consisted of a cylindrical vessel with an internal diameter of 300 mm and a height of 400 mm. The taphole was 3 mm in diameter and 100 mm long, located at 75 mm from the bottom of the model and inclined 10° upwards. The taphole was attached to a sealed chamber, which was connected to a vacuum pump via a flask. The setup made it possible to simultaneously observe both the G-L interface movement near the wall of the model and the taphole stream behavior during draining. There was a ball valve between the taphole and model for on/off control of the draining process.

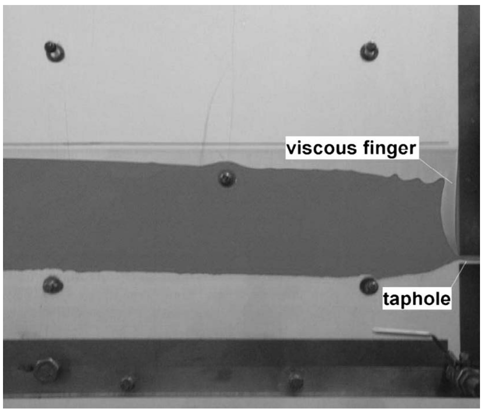


Fig. 2. Image showing viscous finger formation at a high draining rate (taken from a Hele-Shaw viscous flow model[8]).

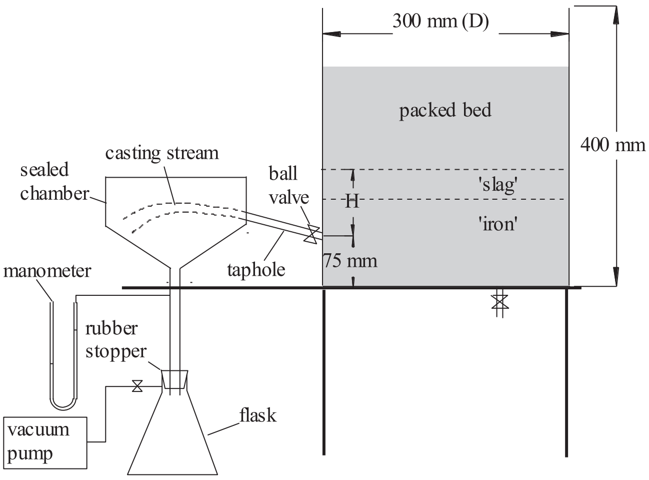


Fig. 3. Schematic of experimental apparatus.

The model was packed with expanded polystyrene beads. The expanded polystyrene beads had a size range 4.5–7.5 mm, which gave a bed porosity of 0.36. The expanded polystyrene bead bed floated in the test liquids due to its lower density, and was held in position by a restraining mesh plate.

The test fluids were air, mineral oil and 70 wt% $ZnCl_2$ aqueous solution, simulating blast gas, liquid slag and iron, respectively. The test fluids were chosen to match as closely as possible the viscosity ratio for the gas-slag system, although other factors such as iron-slag density and viscosity ratios were also considered. The liquid physical properties, as well as those in the real system, are given in **Table 1**.

The molten iron and slag flow into the hearth from the zone above was not considered in this study, *i.e.* no liquid was added to the model during draining. In the experiments, the drainage was controlled by suction applied to the taphole exit, rather than by pressurization inside the model, which is the case in ironmaking blast furnaces. It is believed that applying either suction or pressurization to affect the drainage should not influence the test results, provided that the pressure difference across the bed is the same in both cases. For each test, the pressure difference was set at a constant predetermined value throughout the draining process. The draining process was terminated when gas escaped from the taphole. The period from the start of drainage to the time when gas escapes from the taphole, referred to as the gas break-through time, was recorded. As demonstrated in previous studies,[7,8] the gas break-through time dramatically

Table 1. Physical properties of fluids for blast furnace and model.

Properties	Values
Blast Furnace:	
Gas viscosity, Pa.s	1.86×10^{-5}
Gas density, kg/m^3	1.25
Slag viscosity, Pa.s	0.25
Slag density, kg/m^3	2 600
Iron viscosity, Pa.s	0.0045
Iron density, kg/m^3	6 700
Viscosity ratio, gas/slag	7.14×10^{-5}
Viscosity ratio, slag/iron	5.56
Density ratio, slag/iron	0.39
Model:	
Air viscosity, Pa.s	1.8×10^{-5}
Air density, kg/m^3	1.2
Mineral oil viscosity, Pa.s	0.08–0.225
Mineral oil density, kg/m^3	854
70% $ZnCl_2$ solution viscosity, Pa.s	0.0108
70% $ZnCl_2$ solution density, kg/m^3	1 690
Viscosity ratio, air/oil	8.0×10^{-5}–2.27×10^{-4}
Viscosity ratio, oil/70% $ZnCl_2$ solution	7.4–20.8
Density ratio, oil/70% $ZnCl_2$ solution	0.51

decreases when viscous fingering takes places. Therefore, it was used as an indicator for the occurrence of viscous fingering.

The total volume of liquids drained during this time was measured. The average draining rate was then calculated at the end of each test. Note that the draining rate varies with time during the process due to two reasons. Firstly, the drop of liquid level in the model as a result of the drainage leads to a decrease in the driving force for drainage and consequently draining rate. Secondly, the volume ratio of oil to $ZnCl_2$ solution in the drained mixture changes during draining, which affects the average viscosity of the mixture, and subsequently the draining rate. Unless specified, the initial liquid-liquid (L-L) and G-L interface levels were at the taphole and 80 mm above it, respectively.

In order that the results from this study could be applied to the real system, some experimental results are presented in a dimensionless format, *i.e.* dimensionless gas break-through time versus flow-out coefficient. The dimensionless gas break-through time, τ, is defined as:

$$\tau = \frac{t}{t_{ave}} = \frac{4Qt}{\pi D^2 H} \quad \text{.........................} (1)$$

and, the flow-out coefficient, F_L, is:[14)]

$$F_L = 180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{1}{\phi^2 d^2}\frac{\mu}{\rho g}V_o\left(\frac{D}{H}\right)^{1.4} \quad \text{...........} (2)$$

where, t: gas break-through time; t_{ave}: time taken to completely drain the oil at the average draining rate, Q; D: diameter of the model; H: liquid height above the taphole; ε: bed porosity; ϕ: shape factor of particle (ϕ=1 for sphere); d: particle diameter; μ: oil viscosity; ρ: oil density; g: gravitational acceleration; and V_o: superficial velocity.

3. Results and Discussion

3.1. Effect of Initial G-L and L-L Interface Level

Slag and iron levels in the blast furnace at the start of the hearth drainage may vary from cast to cast. Their effect on stability of the G-L interface was examined using the packed bed model. The results are shown in **Fig. 4**. In these experiments, the pressure difference across the bed was kept constant at 100 mmH_2O. For a given initial L-L interface level, the gas break-through time decreased linearly as the initial G-L interface level decreased. This is simply due to a decreasing distance between the initial G-L interface and the taphole. For a given initial G-L interface level, it decreased with decreasing the initial L-L interface level. In the latter case, decreasing the initial L-L level meant that the taphole was more exposed to the upper liquid phase. Due to its high viscosity, the oil phase could not flow quickly enough across the packed bed towards the taphole to supplement the volume being drained, resulting in an increase in the G-L interface descending velocity in the region near the taphole and thus a reduction in the gas break-through time.

Gas break-through time is presented in **Fig. 5** as a function of draining rate for different initial G-L and L-L interface levels. It is seen that gas break-through time decreased rapidly and then gradually approached near-zero as draining rate increased. According to the findings from previous studies using a two dimensional model,[7,8)] where the relationship between the formation of viscous finger and gas break-through time was established, the near-zero gas break-through time shown in the figure indicates that viscous fingering occurred at a high draining rate.

The experimental results shown in Figs. 4 and 5 were replotted in **Fig. 6** in the dimensionless format. It is seen that all the experimental data fell into three groups according to the initial L-L interface level, *i.e.* 20 mm below, at and 20 mm above the taphole. This highlights the significance of the initial L-L interface level in destabilising the G-L interface. The result implies that an increase in the initial metal level in the BF hearth would reduce the likelihood of viscous fingering in the early stage of draining.

3.2. Effect of Slag Viscosity

Slag viscosity is a function of slag composition and temperature, which may vary from time to time. **Figure 7** shows its effect on gas break-through time, in which the results were plotted in the dimensionless format. Light and heavy mineral oils were used in the experiments. Their viscosity was 0.08 and 0.225 Pa.s, respectively. In these tests, the experimental conditions were kept the same otherwise. It was found that for a given flow-out coefficient, the dimensionless gas break-through time decreased with increasing slag viscosity. Viscous fingering occurred at a lower flow-

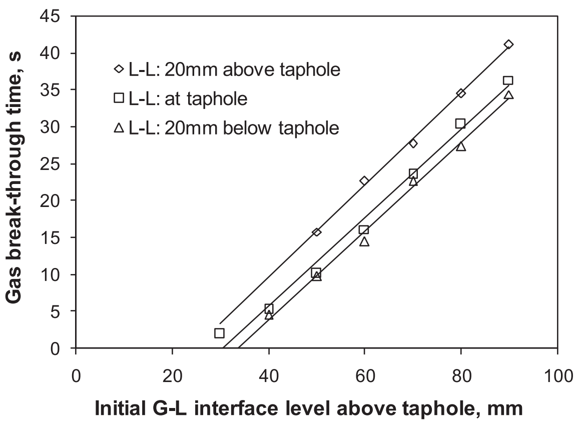


Fig. 4. Effect of G-L and L-L interface levels on gas break-through time.

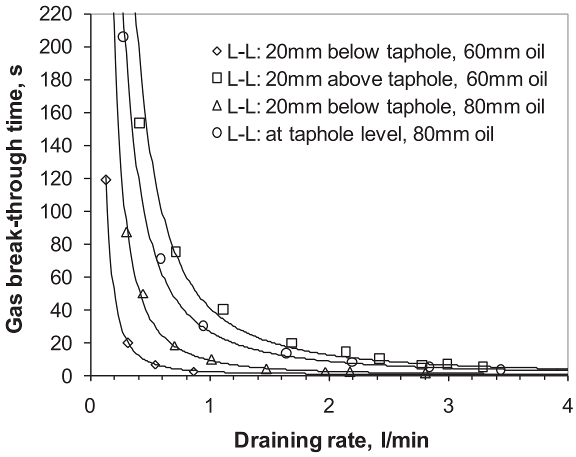


Fig. 5. Effect of draining rate on gas break-through time at different L-L and G-L interface levels.

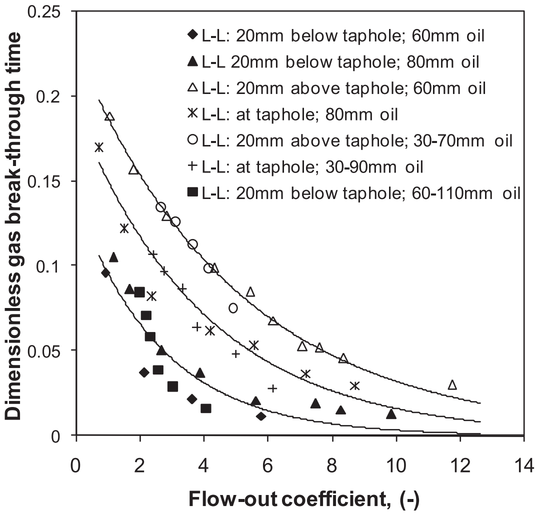


Fig. 6. Correlation of dimensionless break-through time and flow-out coefficient at different initial L-L interface levels.

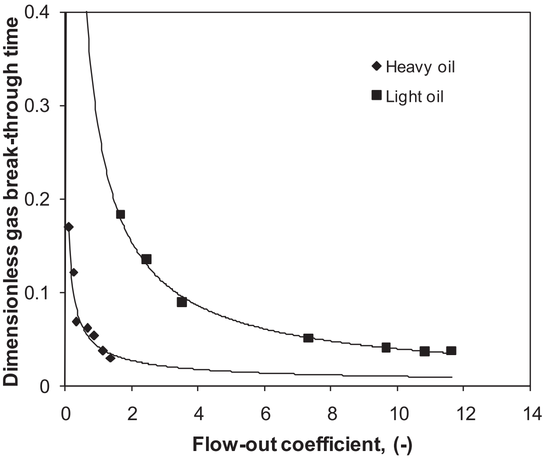


Fig. 7. Effect of oil viscosity on gas break-through time.

out coefficient for heavy mineral oil, in comparison to light oil. This is consistent with the result by Saffman and Taylor,[9] who reported that the critical displacing velocity for viscous finger formation decreased with increasing viscosity of the displaced fluid. This is because the liquid flow through a packed bed is greatly influenced by its viscosity. For a given draining rate, an increase in the liquid viscosity means a slower flow across the bed supplementing the liquid being drained. As a result, the descending velocity of the G-L interface in the region near the taphole increased, and subsequently the gas break-through time decreased. This implies that the likelihood of viscous fingering would increase when blast furnace slag viscosity increases.

3.3. Effect of Coke-free Zone

Based on the findings from a previous study[7] that viscous fingering is more likely to take place in a non-uniform bed than in a uniform one, it is expected that the existence of a coke-free zone in the BF hearth, which has been widely reported,[16–19] would influence the G-L interface stability. This was examined uring the packed bed model. The location of coke-free zone was either at the hearth bottom (**Fig. 8**(a)), or, in some experiments, next to the wall (Fig. 8(b)), referred as to coke-free layer and coke-free space, respectively.

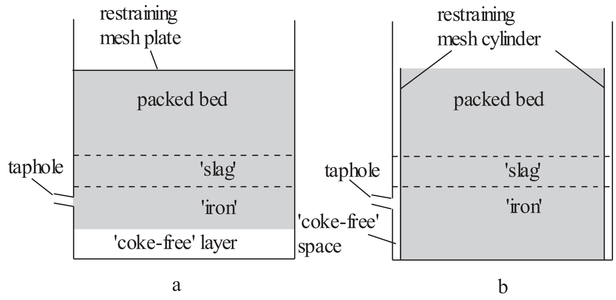


Fig. 8. Schematic of coke-free layer in the hearth and coke-free space near the wall.

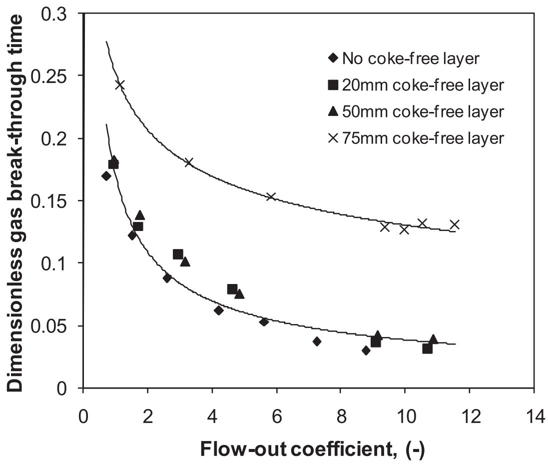


Fig. 9. Effect of coke-free layer on gas break-through time.

3.3.1. Coke-free Layer

The depth of the "coke-free" layer was controlled by varying the restraining mesh plate height. "Coke-free" layer of 20, 50, and 75 mm were considered.

The experimental results are presented in **Fig. 9** in the dimensionless format. It can be seen that gas break-through time dramatically increased when the "coke-free" layer depth was 75 mm, in comparison to the case of no "coke-free" layer (Note that the taphole was positioned at 75 mm from the model bottom). This can be explained as follows.

When "coke-free" layer was not present the liquids (oil and $ZnCl_2$ solution) were drawn into the taphole from all directions in the course of the hearth drainage, as shown in **Fig. 10**(a). This would result in a short gas break-through time, especially at a high draining rate. The upper liquid (oil) could not flow rapidly enough towards the taphole to supplement the volume being drained due to its high viscosity and flowing through the packed bed of high flow resistance. As discussed earlier, this would lead to a high descending velocity of the G-L interface in the region near the taphole. Viscous fingering occurs when the G-L interface descending velocity is greater than the critical value.[8]

When the bottom of the packed bed coincided with the level of the taphole the liquids in the hearth were primarily drained through the "coke-free" layer due to its resistance to the flow being much lower than that of the packed bed. The liquids in the packed bed flowed into the "coke-free" zone to supplement the volume being drained and then towards the taphole, rather than flowing through the packed bed

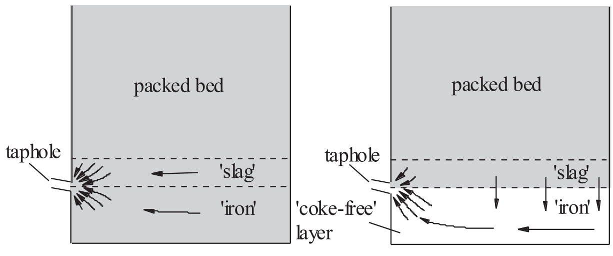


Fig. 10. Illustration of the effect of coke-free layer on draining flow path.

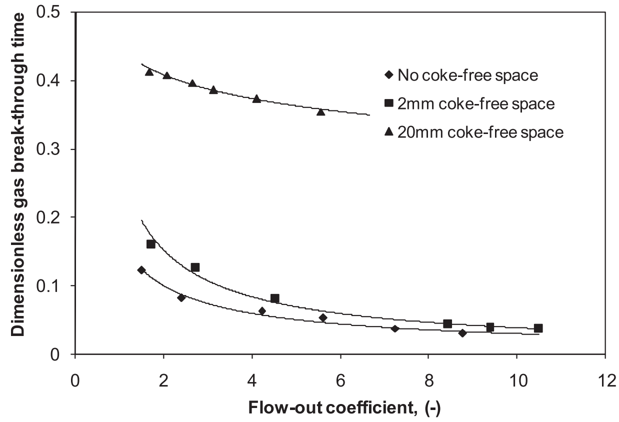


Fig. 11. Effect of coke-free space on gas break-through time.

directly towards the taphole (see Fig. 10(b)). In this case, the G-L interface descended more uniformly across the bed, leading to an increase in gas break-through time. However, in the cases of less than 75 mm, the "coke-free" layer had very little effect on gas break-through time, as seen in Fig. 9, because the upper liquid still had to flow through the porous bed.

3.3.2. Coke-free Space

Figure 11 shows dimensionless gas break-through time as a function of flow-out coefficient for different "coke-free" space widths (0, 2 and 20 mm). The "coke-free" space was created by using a restraining mesh cylinder with a diameter smaller than that of the model. The mesh cylinder was packed with expanded polystyrene beads. There were no packing materials in the space between the mesh cylinder and the model. The "coke-free" space influenced the behavior of the G-L interface in the same way as the 75 mm "coke-free" layer did. The liquids first flowed into the "coke-free" space and then towards the taphole within the region. But, its effect reduced dramatically when the width of the "coke-free" space was decreased to 2 mm.

3.4. Effect of Viscous Fingering on Casting Stream Characteristics

In a previous study,[6] it was reported that the entrainment of blast gas into the taphole may cause break-up of the casting stream, but depending on the amount of gas entrained, may not necessarily result in a splashy casting stream,. A splashy taphole stream occurs only when entrained gas is above the critical value. Therefore, in the context of the present study, the question is whether the amount of entrained gas due to the occurrence of viscous fingers is sufficient to cause a splashy taphole stream. Splashy casting streams are a serious concern in the ironmaking blast furnace operation as it can cause excessive refractory consumption on the taphole and the trough/trough cover, increased dust and fume generation and increased risk for the furnace operators.[6,15]

Observations of casting stream characteristics were carried out during hearth drainage under conditions where viscous fingering occurred. It was found that there was a direct correlation between viscous fingering and splashy casting streams, indicating that the entrained gas due to viscous fingering was above the critical value for splashy casting stream.

4. Conclusions

Gas break-through time in the course of the BF hearth drainage is strongly influenced by the furnace operating conditions and coke bed structure. Gas break-through time decreases with (a) increasing draining rate; (b) decreasing slag and iron levels in the hearth; and (c) increasing slag viscosity. It increases with an increase in the coke-free layer depth and coke-free space width. Under certain conditions, the G-L interface in the region directly above the taphole becomes unstable, leading to viscous finger formation and subsequently early blast gas discharge from the taphole. The amount of blast gas entrained into the taphole due to viscous fingering, when it occurs, is sufficient to cause a splashy taphole stream.

REFERENCES

1) W. B. U. Tanzil, P. Zulli, J. M. Burgess and W. V. Pinczewski: *Trans. Iron Steel Inst. Jpn.*, **24** (1984), 197.
2) W. B. U. Tanzil and W. V. Pinczewski: *Chem. Eng. Sci.*, **42** (1987), 2557.
3) T. Fukutake and K. Okabe: *Trans. Iron Steel Inst. Jpn.*, **16** (1976), 309.
4) T. Fukutake and K. Okabe: *Trans. Iron Steel Inst. Jpn.*, **16** (1976), 317.
5) T. Fukutake, H. Shikata, I. Ichihara, T. Yamiya, K. Okumura and H. Kawarada: Proc. of 42nd Ironmaking Conf., Iron and Steel Society, USA, (1983), 567.
6) Q. He, P. Zulli, F. Tanzil, B. Lee, J. Dunning and G. Evans: *ISIJ Int.*, **42** (2002), No. 3, 235.
7) Q. He, P. Zulli, G. Evans and F. Tanzil: *Dev. Chem. Eng. Mineral Process*, **14** (2006), 1.
8) Q. He, G. Evans, P. Zulli and F. Tanzil: Proc. of The 5th Int. Cong. on Sci. and Tech. of Ironmaking, Chinese Society for Metal, Beijing, (2009), 1126.
9) P. G. Saffman and G. I. Taylor: *Proc. R. Soc. (London) Sect. A*, **245** (1958), 312.
10) S. Hill: *Chem. Eng. Sci.*, **1** (1952), 247.
11) R. A. Wooding and H. A. Morel-Seytoux: *Annu. Rev. Fluid Mech.*, **8** (1976), 233.
12) G. M. Homsy: *Annu. Rev. Fluid Mech.*, **19** (1987), 271.
13) P. Tabeling, G. Zocchi and A. Libchaber: *J. Fluid Mech.*, **177** (1987), 67.
14) P. Zulli: "Blast furnace hearth drainage with and without a coke-free layer", PhD Dissertation, University of New South Wales, Sydney, (1991).
15) Q. He, G. Evans, P. Zulli, F. Tanzil and B. Lee: *ISIJ Int.*, **42** (2002), No. 8, 844.
16) J. M. Luomala, J. O. Mattila and J. J. Harkki: *Scand. J. Metall.*, **30** (2001), No. 4, 225.
17) K. Takatani, T. Inada and K. Takata: *ISIJ Int.*, **41** (2001), No. 10, 1139.
18) K. Yamaguchi, H. Ueno and K. Tamura: *ISIJ Int.*, **32** (1992), No. 6, 716.
19) F. Yan, C. Zhou, D. Huang, P. Chaubal and Y. Zhao: *Iron Steel Technol.*, **1** (2005), No. 1, 48.