Flow Patterns of Iron and Slag in the Blast Furnace Taphole

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The drainage of molten iron and slag is of considerable significance for the ironmaking blast furnace (BF). The draining process is in principle driven by the in-furnace overpressure that balances the pressure drops induced by liquid flows through the dead man and taphole. The two-liquid flow in the taphole has not received much attention, even though some investigators have mentioned the key role of taphole operation in BF drainage. In this paper, the taphole flow pattern, i.e., separated or dispersed flow, is predicted by utilizing a model of zero real characteristic which is based on the stability analysis of two immiscible liquids flowing through an upwards inclined tube. The model is firstly validated by comparison with a set of physical modeling results from the open literature and the experimental system is believed to represent that of an industrial BF taphole, according to similarity laws. Simulations with the model are applied to demonstrate how different factors affect the taphole flow pattern. In a more detailed application short-term tapping data from the commercial BF is evaluated by the model. The calculated results show that separated flow of iron and slag is more likely to occur in the taphole of the studied BF.

KEY WORDS: blast furnace; hearth drainage; taphole flow; iron and slag tap rates.

1. Introduction

An efficient drainage is necessary for the ironmaking blast furnace (BF) since it ensures smooth operation which is a prerequisite of high productivity and long campaign life. The draining process is mainly driven by the in-furnace overpressure that balances pressure drops induced by iron and slag flows in furnace hearth (i.e., through the dead man) and taphole. The taphole load has significantly raised along with the construction of larger BFs with higher production rates. Tapping problems will in general be encountered if the dead man permeability and/or the durability of taphole refractories (taphole mud) become deteriorated, which would cause abnormal variations in the taphole flows and drainage rates. It is therefore of considerable importance for furnace operators to understand the behavior of liquid-liquid flow in taphole and its effect on BF drainage.

The issues on BF drainage have been experimentally and numerically investigated over the years.1–10 Most investigators were concerned about the effect of various in-furnace conditions, including coke size, dead man porosity and coke-free zone on multiphase (gas, iron and slag) flow in the BF hearth. The taphole flow, however, has been given very little attention and was usually ignored or strongly simplified. Nishioka et al.7,8) developed a three-dimensional computational fluid dynamics (CFD) model to predict the slag residual ratio and drainage rates of iron and slag for industrial BFs. The facial shapes were computed with the volume of fluid (VOF) method. The effect of the pressure drop caused by taphole flow was taken into account by subtracting a term given by a simple expression from the total in-furnace pressure in every computational time-step. A similar treatment was later adopted by Iida et al.,9,10) who studied the deviations of tapping time (or liquid drainage rates) under different operation conditions. Based on the pressure balance in the BF hearth, the drainage rates of iron and slag, which are implicitly contained in the pressure drop expressions of flows in the coke-particle bed (dead man) and the taphole, were iteratively computed. The expression employed to calculate the pressure drop essentially assumes that iron and slag be perfectly mixed and that fully dispersed flow occurs in the taphole. As a result, the average liquid quantities, i.e., density and viscosity, were applied. In practice, there exist no direct ways to measure or observe the taphole flow due to the hostile conditions with high temperature and chemically aggressive liquids. The assumption of fully dispersed flow in the taphole was presumably made by simply considering the high drainage rates and the small taphole size compared to the hearth dimensions. Nevertheless, the use of an average viscosity of two immiscible liquids can be questioned and the large density difference between iron and slag would make it more natural to assume separated flow in the BF taphole.

To the best of the present authors’ knowledge, the only two-phase flow studies of BF taphole were focused on the simultaneous flow of gas and liquid (i.e., iron). He et al.11,12) noted that a splashy taphole stream can increase the consumption of trough refractories and thus affect the BF total operation costs. These investigators carried out physical modeling on the basis of geometric and dynamic similarities, and concluded that the occurrence of gas entrainment in the liquid, i.e., dispersed flow of gas and liquid in the taphole, is the root cause. The experiments...
revealed that the dispersed flow takes place when the gas/liquid flow rate ratio exceeds a specific threshold. Also, the packed bed (i.e., dead man) in the vicinity of the taphole acts as a buffer medium and only delays the occurrence of the dispersed flow. From a theoretical standpoint, such gas-liquid system represents a very particular extreme that makes it easier to be dispersed compared to the liquid-liquid (e.g., slag-iron) flow. However, even for this gas-liquid system, the authors pointed out that slug flow (not fully dispersed flow) is more likely to occur in the taphole under the typical BF operation conditions. In addition, clear interfaces of iron and slag at the taphole exit have been observed from time to time in some commercial BFs, which is contradictory to the assumption of iron and slag mixing.

The present paper aims to shed some light on and deepen the understanding of two-liquid flow in BF taphole. A theoretical model is presented to determine the transitional boundary between separated and dispersed flow. The model is validated with a set of results from an experimental oil-water system reported in the open literature. The experimental system is believed to correspond well to the real taphole flow of an industrial BF according to similarity laws. The theoretical model is illustrated by some examples and it is finally evaluated on short-term tapping data from the industrial BF.

2. Model Description

Iron and slag flow in the taphole is essentially an issue of two immiscible liquids flowing through an inclined tube. This issue has been studied especially in the petroleum industries where water and oil have been used as the two liquids in experiments. Depending on the physical properties of the liquid, flow rates, tube inclination angle and tube diameter, a number of flow patterns may be encountered and can be generally classified into two categories.

Separated flow: This flow pattern occurs if the liquid flow rates are comparable. Each phase retains its continuity with the upper layer and the heavier one the lower. The interface can be smooth, wavy or even contain some mixing of liquid droplets. More details of the derivation will not be shown, but the governing equations and main features of the ZRC criterion are illustrated here.

Dispersed flow: This flow pattern emerges if the difference between the liquid flow rates is large or both flow rates are sufficiently high to break the stability of separated flow. The relative movement between the two phases becomes substantial as the liquid flow rates differ greatly, giving rise to vortexes at the interface. The faster phase could, in general, penetrate and disperse the slower phase, leaving a continuous fast phase layer containing droplets of the slower phase, i.e., oil-in-water dispersion or water-in-oil dispersion. The cross-section of the tube can also be occupied by dispersed droplets of the two phases (fully dispersed flow) as the liquid flow rates are further increased.

The transition from separated to dispersed flow has been extensively studied and a variety of methods have been proposed to determine the transition, with different simplifications and assumptions. The concept of zero real characteristic (ZRC) proposed by Brauner et al. is adopted in this work as it is elementary but fundamental with very few assumptions.

2.1. Two-Fluid Model (TFM) of Separated Flow

The ZRC criterion is derived on the basis of analyzing transient differential equations of continuity and momentum for two immiscible liquids flowing through a slightly inclined tube. The equations set would have real characteristic if there exists an interface between the two liquids. The interface can be smooth, wavy or even contain some mixing of liquid droplets. More details of the derivation will not be shown, but the governing equations and main features of the ZRC criterion are illustrated here.

Since the condition of separated flow is central to this work, the initial step is the development of a generalized relationship for separated flow. The two-fluid model (TFM) of separated flow presented in our previous paper is employed. Figure 1 shows the flow configuration and symbols used in the equations of the TFM. The lighter liquid forms the upper layer and the heavier one the lower. The pressure balance equations for the two phases are given as

\[ A_s \frac{\Delta P}{l} - \tau_s S_s - \tau_i S_i - \rho_s A_s g \sin \beta = 0 \quad \text{(1a)} \]

\[ A_b \frac{\Delta P}{l} - \tau_b S_b + \tau_i S_i - \rho_b A_b g \sin \beta = 0 \quad \text{(1b)} \]

where subscripts “a”, “b” and “i” stand for light liquid, heavy liquid and interface, respectively. The geometric parameters in Fig. 1 are given by

\[ A_s = \left[ \pi - \phi_0 + 0.5 \sin(2\phi_0) \right] D^2 / 4 \quad \text{(2a)} \]

\[ A_b = \left[ \phi_0 - 0.5 \sin(2\phi_0) \right] D^2 / 4 \quad \text{(2b)} \]
\[ S_\lambda = (\pi - \varphi_b)D; S_b = \varphi_b D; S_l = \sin \varphi_b D \quad \text{...(2c,d,e)} \]
\[ h = 0.5(1 - \cos \varphi_b)D \quad \text{.........................(2f)} \]

The shear stress reads
\[
\tau_i = \begin{cases} 
\frac{\lambda}{4} \rho_i \left( w_i - w_b \right) & \text{if } w_i \geq w_b \\
\frac{\lambda}{4} \rho_i \left( w_i - w_b \right) & \text{if } w_i < w_b
\end{cases} \quad \text{.....}(3a)
\]
\[
\tau_{liq} = \frac{\lambda_{liq}}{4} \rho_{liq} w_i^2 \quad \text{.........................(3b)}
\]

where \( w \) is the physical velocity of the liquid. Subscript “liq” denotes “a” or “b” depending on which phase is under consideration. The friction factor is for turbulent flow calculated according to Colebrook equation
\[
\frac{1}{\sqrt{\lambda_{liq}}} = -2 \log \left( \frac{2.51}{Re \sqrt{\lambda_{liq}}} + \frac{\delta}{3.7D} \right) \quad \text{............(3c)}
\]
where \( \delta \) is the roughness of the tube inner surface. For laminar flow the friction factor is
\[
\lambda_{liq} = \frac{64}{Re} \quad \text{....................(3d)}
\]

Note that the Reynolds number (Re) is calculated using the physical velocity and hydraulic diameter of each liquid.
\[
\begin{aligned}
D_a &= \frac{4A_a}{(S_a + S_i)} \\
D_b &= \frac{4A_b}{S_b} & \text{if } w_a > w_b \\
D_i &= \frac{4A_i}{S_i} \quad \text{if } w_i < w_b
\end{aligned} \quad \text{.....}(3e)
\]

2.2. The ZRC Criterion

The ZRC criterion applies if the liquid wettability has minor influence on the flow system, i.e., the Eötvös number (Eo) is much larger than unity
\[
\text{Eo} = \frac{\Delta \rho g D^2 \cos \beta}{8\sigma} \quad \text{.....................(4)}
\]

where \( \sigma \) is the surface tension between the two liquids. The ZRC criterion is given by
\[
C = \gamma' (\gamma' - 1) \rho_a w_a^2 + \gamma' (\gamma' - 1) \rho_b w_b^2 - (\gamma' w_a - \gamma' w_b)^2 + \rho_a \Delta \rho g \cos \beta \quad \text{.....}(5a)
\]

where
\[
\rho_a = 1 + \frac{\rho_a A_a}{\rho_b A_b} \quad \text{; } \rho_b = 1 + \frac{\rho_b A_b}{\rho_a A_a} \quad \text{; } \rho_{liq} = \frac{\rho_a A_a}{\rho_a dA_a / dh} \quad \text{...................(5b,c,d)}
\]

The shape factor \( \gamma \) in the criterion accounts for the velocity distribution over each liquid layer. Here, \( \gamma = 1.0 \) for turbulent flow and \( \gamma = 1.1 \) for laminar flow.

According to Brauner et al.,16,17 the real characteristic can be obtained (i.e., no complex root) for the transient differential equations of continuity and momentum if \( C < 0 \). Then, any finite waves at the liquid interface upstream will
decay and separated flow will be established in the tube. If \( C > 0 \), there is no real characteristic and any finite waves can disturb the liquid continuity, leading to the emergence of dispersed flow. Inspection of Eq. (5a) reveals that the shape factor acts as a stabilizing term only in the laminar regime and the density difference can also stabilize the liquid-liquid flow, i.e., lower flow rates and larger density difference both promote separated flow. One the other hand, velocity difference and tube inclination angle are destabilizing terms. Either high velocity difference or steep tube inclination could break the stability of separated flow.

The transition boundary from separated to dispersed flow can be determined by setting \( C_{liq} = 0 \) and solving for any combinations of \( w_a \) and \( w_b \) which satisfy the equality. However, Eq. (5a) is an implicit function of \( w_a \) and \( w_b \), and, furthermore, is not closed because the crucial parameter, the phase configuration angle \( \varphi_b \) (cf. Fig. 1), is unknown. In order to close the set of equations, the TFM is rearranged by equating pressure drop in each liquid (cf. Eq. (1a, b)),
\[
-r_a \frac{S_a}{A_a} + r_b \frac{S_b}{A_b} = -\left( \frac{S_a}{A_a} + \frac{S_b}{A_b} \right) (\rho_a - \rho_b) \lg \sin \beta = 0 \quad \text{.....}(6)
\]

3. Results and Discussion

The ZRC model is next developed for and evaluated on short-term tapping data from a medium-size BF with one taphole. The hearth diameter is 8 m and the hot metal production rate is about 3 500 metric tons per day. The furnace is tapped 12 times daily and, according to the operation practice, the taphole is generally kept plugged for 20–30 min to let the injected taphole mud solidify properly after the previous tap. Each tap usually starts with iron-only flow and slag appears in the outflow after a delay (i.e., slag delay). During each tap, iron flows through the runner to ladles that are transported to the steel plant and slag goes to a granulation unit. The instantaneous (5-minute average) outflow rates of iron is measured with radar facilities installed above the ladles and the slag flow rate is estimated either from the mass and heat balances of the water used in the granulation unit or from the variations in hydraulic pressure in the bearings of the granulation drum.19,20

3.1. Model Validation on Water-Oil Data

In the lack of available physical modeling particularly related to slag-iron flow in the BF taphole in the open literature, a set of experimental results reported by Lum et al.15 was studied to verify the ZRC model. The system studied by these authors is believed to represent the taphole flow of the BF considered in this study on the basis of similarity laws. A comparison of liquid properties and main operation conditions between the physical model and the industrial BF is given in Table 1, where the influential dimensionless numbers are also shown. The superficial Reynolds (Re) and Froude (Fr) number in Table 1 are
\[
\text{Re}_i = \frac{\rho U}{\eta} \quad \text{; } \text{Fr}_i = \frac{\rho U^2}{\Delta \rho g \cos \beta} \quad \text{; } U = \frac{4Q}{\pi D^2} \quad \text{.....}(7a,b,c)
\]

where \( Q \) is the liquid flow rate.

It can be seen in Table 1 that the Eo of the two systems

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are very close and are both larger than unity, suggesting that gravity plays a more important role than surface tension and the ZRC criterion is applicable to the systems. The other dimensionless numbers (Re and Fr) of the systems are generally of same magnitudes except that the lowest Re of iron is beyond the experimental range. This is because iron density is much larger than that of water used in the experiments. Nevertheless, similarity is still expected since the values of Re,b (cf. Table 1) imply both systems to be in turbulent regime. It should be noted that in the experimental facility there was no packed bed in front of the tube. As a consequence, the effect of the dead man is ignored in this study. In this respect, the experimental system is equivalent to the case where the coke-free zone extends above the taphole level, which can be caused by excessively high liquid levels in the BF hearth.5,6) Even though a coke bed in the hearth could have an influence on the flow patterns in the taphole, it would be almost impossible to consider the effect in an appropriate way since the exact configuration of the coke particles next to the taphole is unknown. The observed flow patterns in the experiments undertaken by Lum et al.15) under various combinations of liquid flow rates are shown in Fig. 2, where the corresponding transition boundary predicted by ZRC model is also plotted. The ZRC transition boundary consists of two branches, an upper and a lower branch, which correspond to \( w_a < w_b \) and \( w_a > w_b \), respectively. The gap between the two branches mainly depends on the density difference (cf. the gravity term in Eq. (5a)) and the two branches gradually approach each other as the liquid flow rates are raised. As can be seen in Fig. 2, most of the observed separated (wavy stratified or dual continuous) patterns locate either below the upper branch or above the lower one. The in-situ velocity of water is much higher than that of oil above the upper branch and as a result, oil droplets are formed in a continuous water layer (i.e., oil-in-water dispersion). Conversely, water-in-oil dispersion occurs below the lower branch if the in-situ oil velocity is much higher than the one of water. Deviations are seen to exist, particularly below the lower branch (cf. Fig. 2). This is probably attributed to the emergence of local backflow and increase of in-situ water holdup due to the upwards inclination of the pipe, which could postpone the dispersion of water layer at low water velocity. Nevertheless, the branches of the ZRC boundary demarcate the flow patterns relatively well. Therefore, the ZRC model was seen as a promising theoretical tool that could help shed some light on the liquid-liquid flow characteristics of BF taphole in lack of practical observations and measurements.

3.2. Theoretical Analysis of Slag and Iron Flow Patterns

Some examples were conducted to investigate the effect of main BF operation conditions on the taphole flow as outlined in Table 2, where the perturbed variables have been written in boldface. For all cases in the table, the roughness of the taphole inner surface was set to \( \delta = 0.001 \) m, and the density of slag and viscosity of iron to 2 800 kg/m³ and 0.007 Pa·s, respectively. The taphole was assumed to be an upwards inclined tube with constant diameter, \( D_{th} \).

The taphole diameter and inclination angle greatly depend on the quality of taphole clay and hearth drilling practice on the casthouse floor. High quality taphole clay can resist the taphole expansion/erosion induced by liquid flow during tapping. It has been reported that the taphole diameter (or taphole expansion rate during tapping) can significantly influence the slag residual ratio and casting duration.5,8) Also, steeper taphole inclination could lead to higher productivity and longer casting duration since more iron can be drained out below the taphole level. However, the effect of taphole diameter and inclination angle on the taphole flow patterns has, to the best of our knowledge, not been reported. Figure 3 illustrates the effect of taphole diameter on the taphole flow patterns. Clearly, the region of separated flow (confined by the two branches of each case in the figure) is extended with growing taphole diameter. As

**Table 1.** Comparison of liquid properties and main operation conditions between the physical model used by Lum et al.15) and the BF studied by the present authors.

|                         | Physical model | Actual BF |
|-------------------------|----------------|-----------|
| Density of light liquid (kg/m³) | 828            | 2 800     |
| Density of heavy liquid (kg/m³)  | 998            | 6 800     |
| Viscosity of light liquid (Pa·s)   | 0.0055         | 0.435     |
| Viscosity of heavy liquid (Pa·s)    | 0.001          | 0.007     |
| Surface tension (N/m)           | 0.04           | 1.18      |
| Tube/eroded taphole diameter (mm) | 38             | 45        |
| Tube/taphole inclination angle (°)| 5              | 8         |
| Flow rate of heavy/light phase (m³/min) | 0.01–0.136 | 0.3–0.8  |

Eo (–) 7.5 8.3
Re,×10³ (–) 0.8–11.4 0.9–2.4
Re,×10³ (–) 5.31–75.8 137–366
Fr,×10³ (–) 0.257–52.5 15.8–113
Fr,×10³ (–) 0.31–63.2 38.4–273
the taphole cross-section becomes bigger, the liquid velocities are reduced and higher liquid flow rates are required for transition from separated to dispersed flow.

The effect of taphole inclination angle is illustrated in Fig. 4. The inclination angle has a marginal impact on the taphole flow patterns and the effect of the inclination angle is further reduced at high liquid flow rates, where the inertial force overcomes gravity and becomes dominant in the flow system. At low liquid flow rates, the lower branch of the ZRC boundary slightly rises as the inclination angle increases from $4^\circ$ to $12^\circ$ (cf. Fig. 4). This could be attributed to the normal component of gravity, which promotes the segregation of the liquids for an upwards inclined tube. However, the normal component decreases as the inclination angle increases, reducing the region of separated flow in the figure.

The physical properties (i.e., density and viscosity) of iron and slag vary according to their respective compositions and temperature. In this work, only slag viscosity and iron density were perturbed to elucidate the effect of the density/viscosity difference on the taphole flow patterns. The effect of viscosity is illustrated in Fig. 5, where the two branches of ZRC boundary consistently move slightly to the right. This suggests that as slag becomes more viscous the

### Table 2. Taphole diameter and inclination, slag viscosity and iron density in the cases studied.

| Case | $D_{th}$ (mm) | $\beta_{th}$ (°) | $\eta_{sl}$ (Pa·s) | $\rho_{ir}$ (kg/m³) |
|------|---------------|------------------|--------------------|--------------------|
| 1.   | 40            | 8                | 0.435              | 6800               |
| 2.   | 45            | 8                | 0.435              | 6800               |
| 3.   | 50            | 8                | 0.435              | 6800               |
| 4.   | 40            | 12               | 0.435              | 6800               |
| 5.   | 40            | 8                | 0.400              | 6800               |
| 6.   | 40            | 8                | 0.47               | 6800               |
| 7.   | 40            | 8                | 0.435              | 6500               |
| 8.   | 40            | 8                | 0.435              | 6300               |
| 9.   | 40            | 8                | 0.435              | 6300               |

Fig. 3. Effect of taphole diameter on ZRC boundaries.

Fig. 4. Effect of taphole inclination angle on ZRC boundaries.

Fig. 5. Effect of viscosity difference on ZRC boundaries.

Fig. 6. Effect of density difference on ZRC boundaries.
departure from separated flow emerges at higher slag flow ratio: slag flow rate increases for a given iron rate along the lower branch and iron flow rate decreases for a given slag rate along the upper branch. This is because high viscosity can keep the continuity of slag layer from being disturbed by turbulence and separated flow could exist at high slag flow rate. However, the overall effect must be considered marginal. Similarly, as depicted in Fig. 6, the branches move to the right side of the figure and the critical slag flow ratio increases as iron density becomes smaller: The velocity difference (destabilizing term in Eq. (5a)) is reduced as the liquid flow rates gradually approach each other, which could compensate for the decrease in the stabilizing term of density gap.

In conclusion, among the investigated variables only tap-hole diameter has a marked effect of the boundaries for the flow patterns.

3.3. Interpretation of BF Liquid Flow-out

Figure 7 shows the instantaneous outflow rates of iron and slag for four different taps of an industrial BF. The drilled taphole diameter ($D_{th,0}$) and slag delay ($t_{sd}$), i.e., the duration of the iron-only outflow period, are also depicted in the figure. In order to predict the slag-iron flow pattern in the taphole, the ZRC model was applied to the tapping data of the two-phase flow period of each tap. The taphole diameter was estimated by

$$D_{th} = D_{th,0} + \varepsilon$$ .......................... (8)

where the taphole expansion rate was here set to $\varepsilon = 10^{-6}$ m/s.

The predicted flow patterns for the four taps are depicted in Fig. 8, where the calculated ZRC criterion for all combinations of the measured liquid flow rates is plotted. Both the ZRC criterion and the tapping time were normalized to make it possible to depict the results in one figure. It can be seen that most $C_{zrc}$ values are positive, which suggests that the taphole flow is separated. The reasons for some of the points showing negative $C_{zrc}$ values indicating dispersed flow, are the large occasionally appearing sudden decreases in the liquid flow rates (cf. Fig. 7), where possibly loose coke particles temporary choke the taphole during tapping.20)

5. Conclusions and Prospective Work

The iron and slag flows in the BF taphole have been investigated using the ZRC model, which is based on the stability analysis of two immiscible liquids flowing through an upwards inclined tube. The model, which is here applied to predict the two-liquid flow pattern (i.e., separated or dispersed flow) in the taphole of an industrial BF, was first validated on a set of physical modeling results taken from the open literature. The experimental system for which the experiments were available was believed to represent the BF taphole conditions according to similarity laws. The ZRC model was next evaluated on short-term tapping data and the calculated results showed that separated flow of iron and slag more likely occurs in the taphole of the BF studied. The proposed method has thus been demonstrated to be able to shed some light on and deepen the understanding of the BF
taphole flow. Still, a number of issues need further consideration. The inaccuracies in the measurements of iron and slag outflow rates, and the “real” taphole shape would be important factors with an impact on the taphole flow patterns. A filtering of the measured flow rates, particularly in cases where there are large sudden changes in them, should be studied. Furthermore, both experimental work in laboratory scale and analysis by CFD will be undertaken to assess the effect of taphole shape and the dead man state in front of the taphole.

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Nomenclature
Roman letters

\( A \): Cross-sectional area (m²)
\( C \): Criterion (–)
\( D \): Diameter (m)
\( E_o \): Eotvös number (–)
\( Fr \): Froude number (–)
\( g \): Acceleration of gravity (m/s²)
\( h \): Gap of heavy liquid (m)
\( l \): Length (m)
\( P \): Pressure (Pa)
\( Q \): Flow rate (m³/s)
\( Re \): Reynolds number (–)
\( S \): Perimeter (m)
\( t \): Tapping time (min)
\( U \): Superficial velocity (m/s)
\( w \): Physical velocity (m/s)

Greek

\( \beta \): Inclined angle (°)
\( \delta \): Roughness (–)
\( \Delta \): Difference operator (–)
\( \varepsilon \): Taphole expansion rate (m/s)

\( \lambda \): Friction factor (–)
\( \eta \): Viscosity (Pa·s)
\( \rho \): Density (kg/m³)
\( \sigma \): Surface tension (N/m)
\( \tau \): Shear stress (N/m²)
\( \phi_0 \): Configuration angle (°)
\( \gamma \): Shape factor (–)

Subscripts

0: Initial state
a: Light liquid
b: Heavy liquid
i: Interface
liq: Liquid index (a or b)
s: Superficial
d: Slag delay
th: Taphole
zrc: Zero real characteristic

A tilde above a symbol denotes a dimensionless value.

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