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Slug flow in a blast furnace taphole

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Abstract

Excessive splashiness of a blast furnace taphole stream, which is caused by entrained blast air, can result in premature trough refractory wear. This splashiness has been found to occur when the gas–liquid flow regime of slug flow is present in the taphole tube. The taphole stream trajectories reported by He et al. [Q. He, P. Zulli, F. Tanzil, B. Lee, J. Dunning, G.M. Evans, Flow characteristics of a blast furnace taphole stream and its effects on trough refractory wear, ISIJ Int. 42 (2002) 235–242] can be predicted by the theory proposed herein that recognises that the average velocity in the liquid slug is equal to the sum of gas and liquid superficial velocities. The splashy flow observed by He et al. [Q. He, P. Zulli, F. Tanzil, B. Lee, J. Dunning, G.M. Evans, Flow characteristics of a blast furnace taphole stream and its effects on trough refractory wear, ISIJ Int. 42 (2002) 235–242] may be simply predicted by reference to a two-phase flow regime map. It is suggested that a splashy taphole stream will be avoided if the taphole points downwards or if the cast rate is above around 5 m s^{-1}.

Keywords: Taphole; Slug flow; Dispersed flow; Refractory wear; Blast furnace

1. Introduction

Trough refractory wear can be exacerbated by a splashy blast furnace taphole stream. This effect was studied by He et al. [1] who conducted plant trials at BHP Steel's No. 5 and No. 6 Blast Furnace at Port Kembla, Australia, as well as laboratory tests on a water/air model system with a plant scale taphole. It was found that the consumption of refractory on No. 6 Blast Furnace was 0.65 hg per tonne of hot metal, which was deemed unacceptable.

The plant taphole is approximately 3.5 m long (2.9 m for taphole itself plus 0.6 m taphole clay build-up), has an upward inclination of 10°. The flows observed by He et al. [1] were sometimes 'splashy' and showed periodic pulsating characteristics. The intermittent characteristic of the stream was identified by He et al. as being the cause of premature wear of refractory on the trough, and the splashiness was thought to be due to the entrainment of gas that originated from the tuyeres by the falling molten metal and slag into the taphole stream. In particular, it was thought that entrained blast air in the taphole caused increased taphole stream velocity because the finite gas hold-up led to a greater liquid velocity at constant superficial velocity, the pressure gradient caused gas expansion that led to liquid acceleration and an acceleration effect at the taphole exit due to the release of entrained air. The validity of these hypotheses will be discussed herein in the context of recent work conducted on multiphase mixtures in near-horizontal tubes. It will be shown, by comparing the data of He et al. [1] to objective tests for the liquid–gas flow regime of slug flow, that the observed splashiness was in fact due to the presence of the slug flow and the condition for the onset of a splashy taphole stream will be demonstrated.

In order to illuminate the fluid mechanics that lay behind the phenomenon of splashy taphole streams, He et al. constructed a model experimental rig, shown schematically in Fig. 1, to conduct experiments on an air/water system. The equipment consisted of a cylindrical section tank (height 0.6 m, i.d. 0.39 m) that was supplied with water and compressed air at known rates and discharged through a pipe

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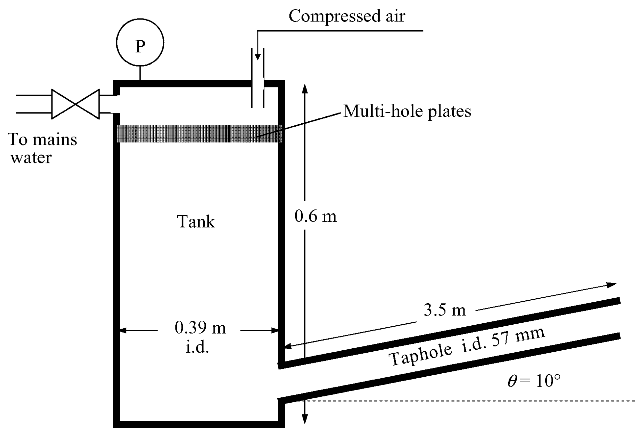

Fig. 1. Schematic diagram of the experimental apparatus of He et al. [1]. The tank arrangement was elevated so that the taphole outlet was located 0.8 m above ground.

Table 1
Liquid and system properties and pertinent dimensionless groups for Blast Furnace No. 6 and the experimental system of He et al. [1]

	Plant	Model system
Maximum cast rate, j_f (m s^{-1})	5.85	5.60
Minimum cast rate, j_f (m s^{-1})	3.90	3.73
Dynamic viscosity, μ (Pa s)	0.0045	0.001
Liquid density, ρ (kg m^{-3})	6700	1000
Surface tension, σ (N/m)	1.36	0.073
Taphole diameter, D (mm)	57	57
Reynolds number, $Re = j_f D\rho/\mu$	$3.3–5.0 \times 10^6$	$2.2–3.2 \times 10^6$
Froude number, $Fr = j_f^2/gD$	27–61	25–61
Weber number, $We = j_f^2 D\rho/\sigma$	4300–9600	11000–25000

The maximum and minimum plant cast rates correspond to 6 and 4 t/min, respectively, hot metal production and the rates are calculated assuming that no slag enters the taphole. Also the 'plant' material properties are estimated on the assumption of no slag in the stream.

(taphole) near the bottom of the tank after the air and water had passed through a multi-holed plate in order to disperse the phases. The pipe had the same dimensions and inclination as the industrial taphole and was constructed from Perspex to allow easy visualisation of the flow. A comparison of plant and experimental parameters can be seen in Table 1.

In order to understand the cause of the splashiness, He et al. [1] took high-speed video footage of the taphole stream. Five sequential still images were taken over a total time of 0.03 s. The multiphase flow regime is clearly identifiable as 'slug flow' from their still images. In slug flow, gas bubbles travel above relatively slow moving liquid films interspersed with plugs of aerated liquid that travel at high velocity. The slug nose is very turbulent and scoops up liquid that has been travelling in the film section into the slug body. A schematic of slug/intermittent flow is shown in Fig. 2 that shows the above-mentioned flow features. It should be noted that hot metal and molten slag are the two liquid phases in a blast furnace; as a simplification, in this work only one liquid phase is considered.

The fact that the regime is truly slug flow may be confirmed by comparing the velocity of the slug nose (i.e. the velocity at which the nose travels relative to the stationary observer), V_n, calculated with reference to the still photographs of He et al. [1], with the established correlations of Bendiksen [2] for horizontal and inclined tubes. He et al. [1] took photographs with a total mixture superficial velocity (i.e. the sum of the gas and liquid superficial velocities) ($j_g + j_f$), of 5.7 m s^{-1} corresponding to a Froude number of 7.6. Therefore, the following correlation of Bendiksen [2] is appropriate:

$$V_n = 1.2(j_g + j_f), \qquad Fr > 3.5 \tag{1}$$

where the Froude number, $Fr = (j_g + j_f)(gD)^{-0.5}$. The term ($j_g + j_f$) is, in fact, equal to the average velocity of elements of fluid within the slug section. The slug nose velocity, calculated by reference to the still images of the model taphole stream presented by He et al. [1], is 5.97 m s^{-1} versus 6.83 m s^{-1} predicted by Eq. (1). This is in good agreement; the slight discrepancy is probably due to the fact that correlation 1 is for established slug flow whereas the nose of immature slug needs to accelerate to its mature velocity. Thus, the predictions of correlation 1 should be considered an upper bound to slug nose velocity. It is worth stressing again that the velocity of the slug nose is dissimilar to the velocity of the fluid elements within the slug body; the velocity of these elements will be calculated in the following section in the prediction of the taphole stream trajectory.

Slug flow is common in subsea flowlines (see [3] for a description of such flows). In this article, we present some results of He et al. [1] and compare them to predictions that are enabled through recognition of the fluid mechanics that actually occur within the taphole stream.

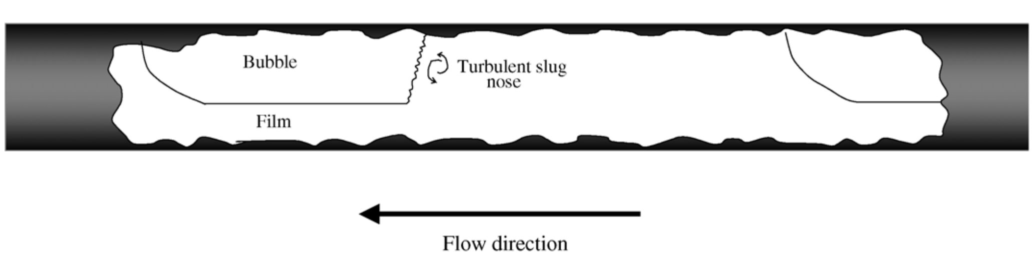

Fig. 2. A schematic cut-away representation of slug flow in a horizontal tube. The aeration of the slug body, which can be significant at superficial velocities that occur in the taphole, is not represented (after [11]).