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SLAG-METAL FLOW OVER A WEIR

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ABSTRACT

Experimental investigation of the entrainment of a heavy fluid into a light fluid in a two-layer fluid system was achieved by physical modelling. The main thrust behind this study was to investigate the entrainment of copper matte with the slag during the skimming of slag from a Peirce-Smith converter. Several combinations of fluid pairs were used in a series of transient experiments, covering a range of densities and viscosities, where the light fluid was allowed to overflow a weir and the amount of entrained heavy fluid was measured. Moreover, the initial height of the light fluid above the weir crest and the initial depth of the fluid-fluid interface were also varied to study their effect on entrainment. The resulting entrainment is measured as the ratio of the withdrawn heavy fluid to the withdrawn light fluid. The Keulegan number, K, has been found to correlate with the entrainment. Keulegan number takes into account the effect of the density difference of the two fluids and the viscosity of the heavy fluid.

INTRODUCTION

During the skimming of slag from a Peirce-Smith converter, copper/nickel matte (heavy fluid) is entrained in the slag layer (light fluid). Copper mattes for example, consisting of a copper and iron sulphides mixture, are converted in order to remove the iron content. This involves adding silica flux and blowing air through submerged tuyeres to selectively oxidise the iron and sulphur in the matte. A layer of slag (iron silicate), which gradually forms on top of the matte layer, is skimmed by rotating the converter to pour the slag out of the mouth. Skimming results in valuable matte being entrained and lost with the slag.

Biswas and Davenport (1994) have estimated that 2 to 8 % of the copper (as metal) may be lost in the slag. Although modern smelters usually employ a copper-from-slag recovery step, this may not be always feasible due to the large volume of skimmed slag. A better understanding of the mechanisms of entrainment is important for keeping the loss due to entrainment at an economic level.

Investigation of interfacial entrainment in metallurgical applications has concentrated on entrainment due to gas bubbling in bottom gas injection systems, or entrainment due to vortex formation in bottom tapping systems.

In bottom gas injection systems, Minto and Davenport (1972) have identified three distinct patterns of entrainment: filming, flotation and dispersion, where a gas bubble acts as a transport medium.

As for bottom tapping, such is the case in steel tapping from ladles, a vortex may form causing the light phase (slag) to be entrained by the steel. Mazumdar *et al.* (1995) studied this phenomenon and found out that entrainment can be reduced by increasing the waiting time before tapping and by increasing the viscosity of the light phase. Entrainment resulting from the above two situations has little relevance to the entrainment due to the skimming of slag, which is best described by the entrainment that results in horizontally accelerating flows of a two-layer fluid system.

In the case of horizontally accelerating flows, three types of flows have been identified and they are counterflows, surface stress flows and buoyant overflows. Huppert and Simpson (1980) studied the counterflows (density currents) experimentally and reported that entrainment occurred as a result of the Kelvin-Helmholtz instabilities. Kantha *et al.* (1977) studied the phenomenon of surface stress flows and observed that an intermediate layer was formed between the two layers as a result of the interfacial mixing. Buoyant overflows apply when the fluids overflow an obstacle such as a weir. Thus, in addition to the interfacial entrainment due to a surface stress flow, the heavy fluid is also entrained in the light fluid as the light fluid overflows the weir. Ellison and Turner's (1959) work is considered classic for buoyant overflows, however their investigation was restricted to the entrainment that occurred before the fluids overflowed the weir. The authors are not aware of any work that has been done to evaluate entrainment as a result of overflowing an obstacle especially in relation to the skimming of slag. This article presents a basic analysis for this kind of entrainment.

EXPERIMENTAL METHOD

Experiments were conducted using a rig that was made of Perspex, which was 400 mm in width, 500 mm in height and 2500 mm in length. Several combinations of two liquids, which were initially stratified, were used in each experiment. The liquids were retained behind a wall that consisted of a fixed section (weir) and a moving section (gate). Once the gate was opened both the light liquid and the heavy liquid overflowed the weir simultaneously. Overflowing of the heavy liquid continued until the liquid-liquid interface reached the weir crest. At this point the heavy liquid stopped overflowing and only the light liquid continued to flow. Figure 1 is a schematic showing the experimental rig and the two liquids before an experiment.

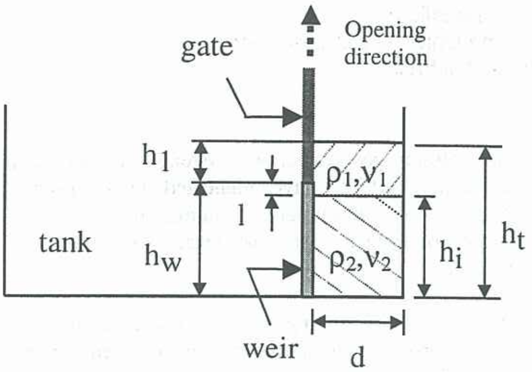

Figure 1. A schematic of the experimental rig and two liquids before an experiment.

The flow was recorded using a standard VHS video camera where the initial and final positions of the free surface and the liquid-liquid interface were clearly determined using a ruler that was fixed to the external wall of the tank. Entrainment was measured as the ratio of the withdrawn heavy liquid to the withdrawn light liquid. The liquids that were used consisted of fresh water, salt-water (using cooking salt), vegetable oil and glycerin. Physical properties of selected experimental liquids, matte and slag are outlined in Table 1. Furthermore, the initial height above the weir crest ranged from 25 mm to 100 mm, and the depth of the liquid-liquid interface below the weir crest ranged from zero to 20 mm. The experimental variables (physical properties and geometrical aspects) were chosen so that dynamic and geometric similarities, between the physical model and the real case, were achieved.

Liquid	Density (ρ) kg/m^3	Dynamic Viscosity (μ) kg/ms
Water (20° C)	998.2	1.005×10^{-3}
Salt water (cooking salt)	1150	1.75×10^{-3}
Vegetable oil	910	60×10^{-3}
Glycerin	1260	1500×10^{-3}
Matte 50% Cu (1200°C)	4600	10×10^{-3}
Slag (1200°C)	3300	350×10^{-3}

Table 1. Physical properties of experimental liquids, slag and matte.

A record of a typical experiment, showing how both liquids overflow the weir, 0.5 seconds after opening the gate can be seen in Figure 2. The liquid-liquid interface appears to be smooth which suggests that entrainment between the two liquids did not occur as result of the Kelvin-Helmholtz instabilities.

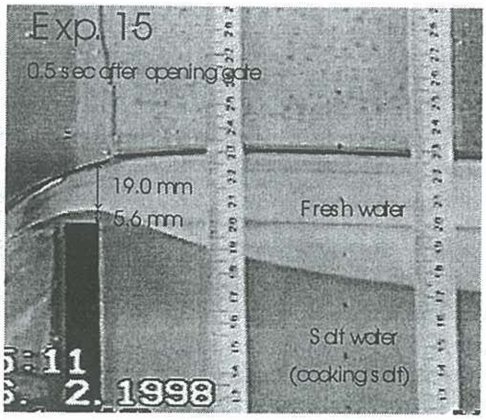

Figure 2. A snapshot from a typical experiment.

RESULTS

Non-dimensional entrainment, E, is expressed as the volumetric ratio of the withdrawn heavy liquid to the withdrawn light liquid

$$E = V_2/V_l \, . \qquad (1)$$

V_l is the volume of the light liquid that overflowed the weir and V_2 is the volume of the heavy liquid that was entrained with the light liquid.

Interfacial mixing or entrainment for inviscid steady-state flows has also been traditionally expressed as a function of the non-dimensional overall Richardson number, Ri_o, where

$$Ri_o = \frac{g' h_l}{u_l^2} \, . \qquad (2)$$

h_l is the initial height of the light liquid, u_l is the mean horizontal velocity of the light liquid and g', the reduced acceleration of gravity = $g\ (\rho_2 - \rho_l/\rho_l\ )$, ρ_l is the density of the light liquid and ρ_2 is the density of the heavy liquid.

Since the applications where the Richardson number is used involve mainly fresh water and salt water as the working pair of liquids, the effect of viscosity has been neglected. Keulegan (1949) however, derived a non-dimensional number from the continuity equation and the equation of motion that takes into account the effect of the viscosity of the heavy liquid. Later, Turner (1973) re-examined Keulegan's findings and expressed the number that was suggested by the latter as

$$K = \frac{u_l^2}{g' h_l}\left(\frac{u_l d}{\nu_2}\right)^{1/2} = \frac{\sqrt{Re}}{Ri_o} \, . \qquad (3)$$

d is the length of the interface and v_2 is the kinematic viscosity of the heavy fluid. Keulegan number, K, is in fact the product of the inverse of Richardson number and the square root of the Reynolds number, Re. Since the flow is transient, the velocity u_l was averaged based on the discharge height of the liquid. u_l was calculated as the volume of the discharged liquid divided by the averaged cross sectional area and the time required for the liquid to be discharged.

It follows from the above analysis that the non-dimensional overall entrainment of the heavy liquid into the light liquid for horizontally accelerating flows can then be expressed as

$$E = f(K) . \qquad (4)$$

Figure 3 shows the scatter of the data points that were obtained from the experiments that were undertaken in the present work.

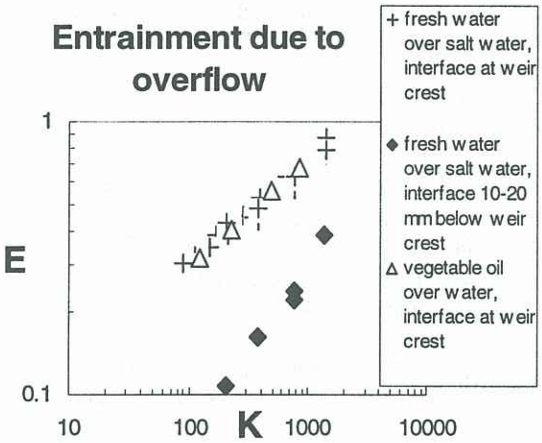

Figure 3. Entrainment versus Keulegan number.

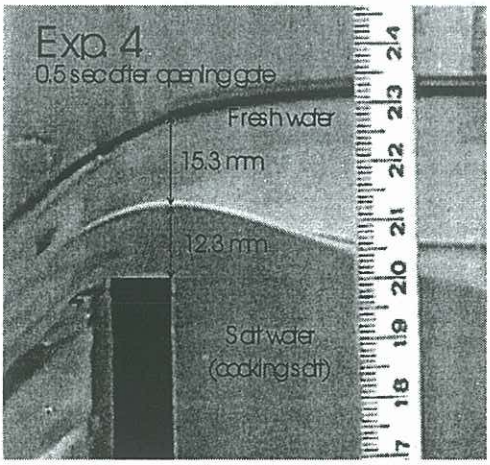

Figure 4. Experiment with a density difference of 50 kg/m^3 and initial depth of liquid-liquid interface below weir of zero mm. K=770, E=0.63.

Effect of Density

Figures 4 and 5 correspond to two experiments that were conducted under similar conditions except for the density difference between the two liquids. The density difference in the experiment corresponding to Figure 4 was 50 kg/m^3 while that corresponding to Figure 5 was 150 kg/m^3 . The discharge height of the heavy liquid in the latter was less than the former by 1 mm, half a second after opening the gate. This suggests that the flow of the heavy liquid in the experiment corresponding to Figure 5 was more restricted and consequently, less overall entrainment of the heavy liquid occurred. This was confirmed at the end of the experiments.

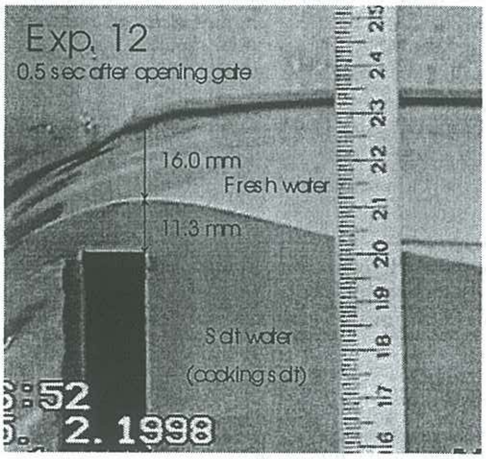

Figure 5. Experiment with a density difference of 150 kg/m^3 and initial depth of liquid-liquid interface below weir of zero mm. K=205, E=0.43.

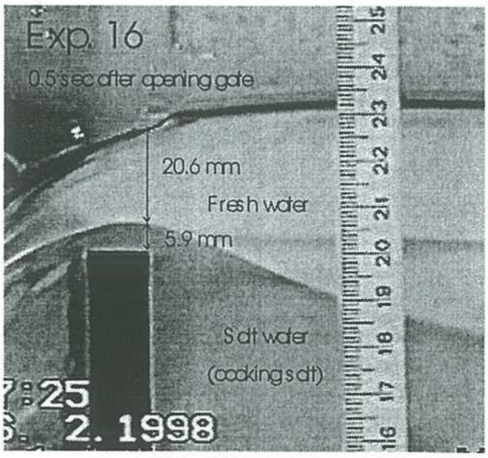

Figure 6. Experiment with a density difference of 50 kg/m^3 and initial depth of liquid-liquid interface below weir of 20 mm. K=206, E=0.107.

Effect of Interface Below Weir Crest

Figures 5 and 6 correspond to two experiments, having the same Keulegan number, that were conducted under similar conditions except for the initial depth of the liquid-liquid interface below the weir crest. In the experiment corresponding to

Figure 5 the initial depth was zero while in the experiment corresponding to Figure 6 the initial depth was 20 mm . Half a second from the opening of the gate, the discharge height of the experiment corresponding to Figure 6 is nearly half of that corresponding to Figure 5, again suggesting restricted flow of the heavy liquid and consequently, less overall entrainment of the latter with the light liquid. This was confirmed at the end of the experiments and is shown in Figure 3.

CONCLUSION

The two-layer system that was used in the present study simulates the slag and the copper matte layers in a Peirce-Smith converter. Pouring of the slag, which is achieved by rotating the converter, was simulated by the flow of the liquid above the weir crest after the removal of the retaining gate. Entrainment of matte in the slag during the skimming of slag from a Peirce-Smith converter can thus be evaluated using the non-dimensional analysis that was presented in this article. Entrainment occurs as a result of a "lifting motion" of the heavy liquid as the light liquid overflows the converter mouth. This may be due to the fact that when the gate is opened, a pressure gradient exists along the length 'd' (refer Figure 1) that pushes the heavy liquid over the weir.

Entrainment due to the Kelvin-Helmholtz instabilities along the liquid-liquid interface was absent throughout all the experiments that were undertaken in the present work.

Entrainment can be reduced, depending on their practical feasibility, by

- Increasing the density difference between the two liquids.
- Maintaining the liquid-liquid interface at a considerable depth below the converter mouth during the skim.

NOTATION

d	interfacial length between two liquids, m
E	net entrainment
f	function coefficient
g	acceleration of gravity, m/s^2
g'	reduced acceleration of gravity $= g(\rho_2-\rho_1)/\rho_1$, m/s^2
h_l	initial height of light liquid above weir crest, m
h_i	initial height of liquid-liquid interface, m
h_t	initial total height of liquids, m
h_w	height of weir, m
K	Keulegan number
l	initial depth of interface below weir crest, m
Re	Reynolds number
Ri_0	overall Richardson number
u_l	mean horizontal velocity of the light liquid, m/s
V_1	volume of the withdrawn light liquid, m^3
V_2	volume of the withdrawn heavy liquid, m^3
ρ_1	density of the light liquid, kg/m^3
ρ_2	density of the heavy liquid, kg/m^3
ν_1	kinematic viscosity of the light liquid, m^2/s
ν_2	kinematic viscosity of the heavy liquid, m^2/s

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