



Multiphase flow modelling of lancing of furnace tap-holes: validation of multiphase flow simulated in OpenFOAM®

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Synopsis

Pyrometallurgical furnaces are tapped through tap-holes that are opened with drills and oxygen lances. The lance is often used on its own or as the last step of opening the tap-hole. Interaction of oxygen with molten material inside the tap-hole can occur, and is a phenomenon that is not well understood.

As part of a study that focuses on the effect of lancing on flow inside and around the furnace tap-hole, a cold-model validation was done. The validation study focuses on validating the MULTIPHASEINTERFOAM multiphase flow solver in OpenFOAM® for the problem involved. The sensitivity of the model to different materials properties (viscosity and density in particular) is presented with both cold models and the results from flow simulations in OpenFOAM®.

Keywords

tapping, lancing, OpenFOAM, pyrometallurgy, multiphase flow.

Introduction

Many pyrometallurgical operations are carried out in furnaces where molten material accumulates continuously. Once enough material has accumulated and is ready to be removed from the furnace, material is tapped through one or more tap-holes in the furnace. Tap-holes differ significantly in both geometry and materials of construction, depending on the process involved – examples of different types of tap-hole configurations can be found in, for example, Nelson and Hundermark (2014). Tap-holes all share one common feature: they are high, wear areas of the furnace. Molten material at high temperature flows through these areas, after which the tap-hole is sealed, usually using tap-hole clay. The purpose of the tap-hole clay is to harden inside the tap-hole and seal it until the next tap.

Once ready to tap, a pneumatic drill and/or oxygen lance is used to open the tap-hole. The extent of lancing a furnace tap-hole depends strongly on the type of furnace. In, for example, many blast furnace operations lancing is limited as much as possible, and done only if drilling was not effective. In other operations, such as on small-scale pilot furnaces with short tap-holes, only lancing is used to open the tap-hole.

Lancing involves using a long metal pipe (usually steel), approximately 15 mm in diameter and varying in length, as an oxygen cutting torch. Oxygen flows through the lance and reacts with iron in the steel to form iron oxide, releasing heat.

Despite significant advances in technology to enhance the safe of opening of tap-holes, lancing remains part of the process, and can be quite dangerous if not done properly. The danger stems from the fact that the process is largely manual, *i.e.* done by furnace staff. Both novice and expert furnace tappers can make mistakes when lancing, risking a highly focused amount of thermal energy being concentrated in the tap-hole. Aside from damage to the tap-hole, unwanted oxidation of the material inside of the furnace can occur. As well as the possible thermal disturbance, which may or may not be significant, flow around the entrance to the tap-hole inside the furnace may be affected and could contribute to wear.

The work described in this paper was aimed at validating modelling work related to safer tapping practices, with a focus on oxygen lancing of furnace tap-holes. Since such a study would be virtually impossible from inside a furnace, multiphase modelling is used to study the problem in as much detail as possible. The emphasis is on some validation work done to ensure that the strengths and limitations of the model(s) can be identified for the specific problem involved – flow of gas into two fluids, which could serve as potential fluids to emulate slag and metal/alloy in real pyrometallurgical processes,

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Table I
Dimensionless groups pertinent to injection of gas into two fluids (from Erwee, Reynolds, and Zietsman, 2016b)

Dimensionless number	Description / purpose of the number
$\frac{\sigma_{tf-bf}}{\sigma_{gas-tf}}$ $\frac{\sigma_{gas-bf}}{\sigma_{gas-tf}}$	Interfacial surface tension (σ) ratios between the top and bottom fluids as well as the gas (the fluids would represent slag, metal, and gas)
$\frac{h_{bf}}{h_{tf}}$ $\frac{l_{lance}}{h_{tf}}$ $\frac{h_{lance}}{h_{tf}}$	Geometry: the relative heights (h) of the top fluid (tf , e.g. slag) and bottom fluid (bf , e.g. metal) as well as the relative position of the lance with respect to the top fluid)
$\frac{\mu_{tf}}{\mu_{bf}}$	The ratio of viscosity (μ) of the top fluid and bottom fluid
$\frac{\rho_{tf}}{\rho_{bf}}$	The ratio of density (ρ) of the top fluid and bottom fluid
$Mo = \frac{g\mu_{tf}^4}{\rho_{tf}\sigma_{gas-tf}^3}$	Morton number (Mo): Ratio of viscous forces to surface tension forces
$Re = \frac{\dot{V}_{gas}\rho_{tf}}{(h_{tf} - h_{lance})\mu_{tf}}$	Reynolds number (Re): Ratio of inertial forces to viscous forces
$Eo = \frac{g(h_{tf} - h_{lance})^2\rho_{tf}}{\sigma_{gas-tf}}$	Eötvös number (Eo): Ratio of buoyancy to surface tension forces

and also to validate the model over a large range of parameters (density, viscosity, *etc.*).

Dimensional groups pertinent to the lancing problem

Previous work by the authors (Erwee, Reynolds, and Zietsman, 2016b) revealed, by dimensional analysis, the most pertinent dimensionless groups that describe the lancing problem. These parameters allow for matching, at least in part, computational modelling work that can be done in a laboratory to the actual furnace problem. Ten dimensional groups that were identified are listed in Table I (see also Figure 1). The exact details of these groups are given elsewhere (Erwee, Reynolds, and Zietsman, 2016a, 2016b). However, they are listed here to allude to which parameters are important to the lancing problem.

From the dimensional analysis, it was very clear that the physical properties of the materials involved play an important role in describing the problem, as does the level of the bottom and top fluids relative to the lance. This might seem obvious to any pyrometallurgist, but also prompts the reader to recall how

difficult it is to both measure and/or model the said physical properties. Furthermore, finding materials that could be used at room temperature that would satisfy the dimensionless groups involved in order to validate a computational model is equally difficult, since so many groups were identified. One group, the surface (and hence interfacial) tension ratios, is very important. For most metals and slags, the surface tension values are quite high, in the order of 0.4–1.0 N/m (Guthrie, 1989), whereas for fluids at room temperature such as oil and water, these values are quite low, e.g. the surface tension for water is approximately 7.2×10^{-2} N/m. This is just one example of differences that often make matching properties difficult. The Morton and Eötvös numbers are of importance, as they describe the shapes of bubbles/drops moving in a fluid. This would seem somewhat superficial to consider for opening a furnace tap-hole; however, when oxygen reacts with metal inside a furnace during lancing, the reaction rate is often, for example, dependent on the shape and size of the surface – *i.e.* to better understand this behaviour in future models (not this work), it would be important to incorporate this aspect of the physics for the fluids involved.

The dimensionless numbers can be calculated for a particular furnace, using the dimensions of the lance, the slag and metal/alloy levels, as well as the density, viscosity, and surface tension. Using this as a baseline, one can potentially source fluids at room temperature that could emulate slag and metal if some of the dimensionless groups match up. Perfect matching is not always possible, but if many different materials are used at room temperature, one can build a set of validated data for the model. Even if these do not match the real furnace fluids perfectly, if the model fits a validated data-set over a range of dimensionless numbers, it could provide insight into the limitations of the model results and allow for more confidence in extrapolations of the model parameters.

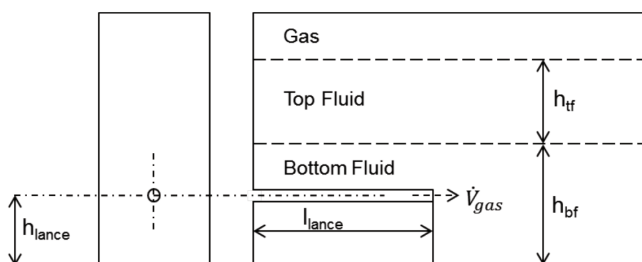


Figure 1—Parameters to consider for the lancing problem (geometry not accurate or to scale, just shown for simple orientation of fluids relative to lance) (Erwee, Reynolds, and Zietsman, 2016b)

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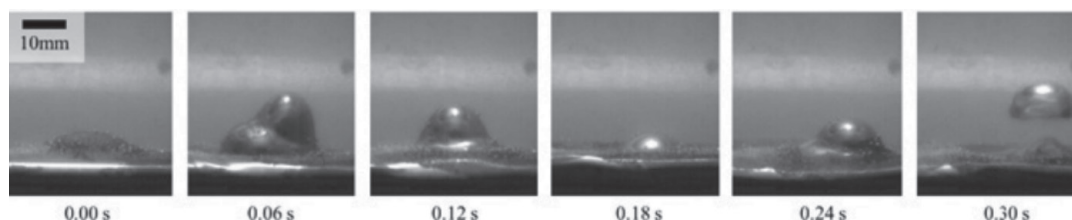


Figure 2—Example footage from the Natsui experiment (Natsui *et al.*, 2016)

The Natsui case

Many computational fluid flow studies have been conducted and validated against, for example, water-based cold models. For brevity, these studies are not repeated in this paper. An excellent study that resembles a metal-slag-gas system quite closely is that by Natsui *et al.*, (2016). The authors used a mixture of molten chloride salts, metallic tin, and argon gas to verify a smoothed particle hydrodynamics model of interfacial flow of two immiscible melts. Argon gas was bubbled through a small Pyrex beaker containing the molten material and filmed for validation of the model. An example of the behaviour observed is shown in Figure 2. Of note is the fact that a significant amount of effort went into setting up the experiment, with visual observations being crucial to match the computational model to the high-temperature model. The authors of this paper are currently setting up a similar experiment to make more observations to validate the model described later in the paper.

Cold model for this study

While the set-up of a similar model to that of Natsui *et al.* is under way, the authors opted to conduct similar tests using a rectangular tank of 50 × 50 × 150 mm with a gas inlet at the bottom. The gas inlet had a diameter of 5 mm and was mounted flush against the bottom of the tank. Mercury, silicone oil, and water were used as fluids. Mercury was chosen since it has a high surface tension, which is important for this problem, as described earlier. The work with mercury, silicone oil (in this case a viscosity standard), and water is meant to complement work like that of Natsui *et al.*, such that the computational model can be validated across a wide range of materials properties. The materials properties for the fluids involved in this study are given in Table II.

For the cold model experiments, technical grade nitrogen gas was used and injected at flow rates between 0.2 and 0.8 L/min. The level of the top fluid (oil or water) was kept constant at 30 mm, and that of mercury at 10 mm. An Olympus i3 high-speed video camera was used to film the behaviour of the interface between the two fluids as gas bubbles rose through the tank.

Computational model

OpenFOAM® (openfoam.org, 2018) is an open-source framework, based in C++, in which fluid flow can be simulated using the volume-of-fluid (VOF) method (Hirt and Nichols, 1981). The specific method involves locating and tracking the fluid-fluid interface ('free surface') on a mesh, while fluid flow is described using the Navier-Stokes equation.

The computational domain was set up on the same scale as the rectangular tank for cold model experiments, except for the total height, which was limited to 75 mm since the total fluid height was only 40 mm.

The domain was meshed using the open-source tool gmsh (Geuzaine and Remacle, 2009) version 3.0.6 and then imported into OpenFOAM® version 6. The mesh was converted to a polyhedral mesh with approximately 952 000 equisized elements of 0.5 mm each.

A standard solver exists in OpenFOAM® for multiphase flow problems and was used for this work. The specific solver is called 'MUTIPHASEINTERFOAM'. The solver or model consists of an incompressible flow solver based on the Navier-Stokes and continuity equations. Furthermore, a phase separation model is included. A detailed description of the model and governing equations, with an example of their use, is given in Andersson (2010). The nature of the problem leans towards a special interface capturing scheme, developed by Ubbink and Issa (1999).

The simulations were decomposed to run in parallel on the Lengau supercomputer at the Centre for High Performance Computing in Cape Town, South Africa. In this case, the simulations were run across 480 processors (30 nodes with 16 cores each and 16 MPI processes per core). On average, a case ran for approximately 6000 core hours to solve a model of 2.5 seconds in real time (time-step = 0.01 seconds). Results were processed using Paraview 5.4.1.

Results and discussion

Several cases were set up and run, but only two cases are presented in this paper. These cases showed the most salient

Table II

Materials properties at 20°C

Material	Density (kg/m ³)	Viscosity (Pa.s)	Surface tension (N/m, with air)
Mercury	13560	0.0015	0.485
Silicone oil	978	0.498	0.04
Water	997	8.90 × 10 ⁻⁴	0.07

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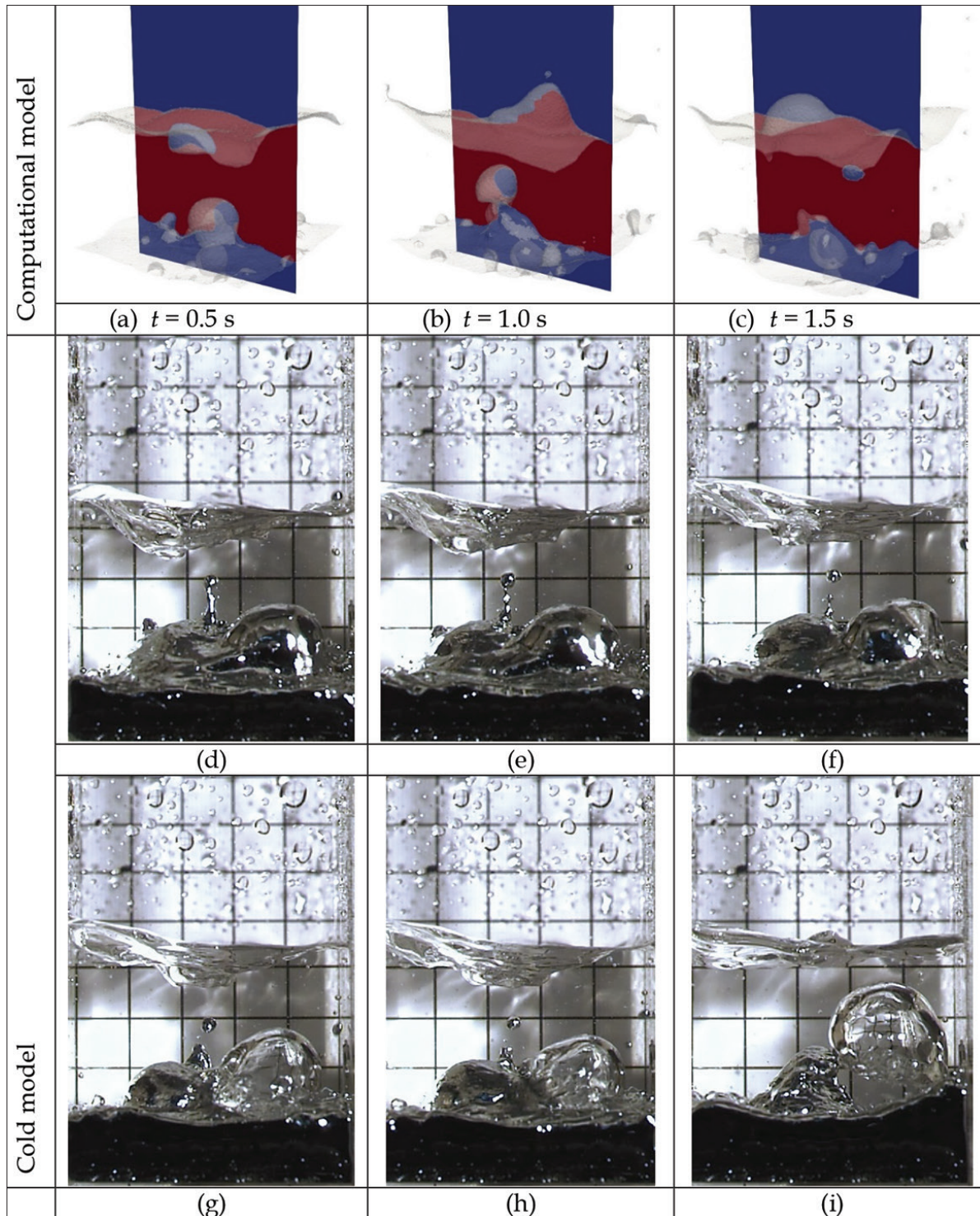


Figure 3—Mercury-water experiment (gas flow rate 0.8 L/min)
 (The time scale for the photographs is not shown, as these are snapshots of high-speed camera footage after reaching a steady state, frames are extracted from 2 seconds of real time. Each block in the background of the photographs is 10 × 10 mm)

differences between the cold model and the computational model. For this paper, the focus is on visual comparison of the behaviour of the interface and movement of the bubbles. This is because there are few other parameters that can be measured against output from the model. Previous work (Erwee, Reynolds, and Zietsman, 2016a) involved measuring pressure signals against the wall of the tank, but when fluids other than water

are involved, this proves difficult. This is, however, still being explored by the authors.

Figures 3 and 4 show the behaviour of the computational model and physical cold models for mercury-water and mercury-oil respectively. When played as video files (only frames are shown in this paper), the general behaviour of both cases seems, at first glance, to agree. When comparing, for example the case

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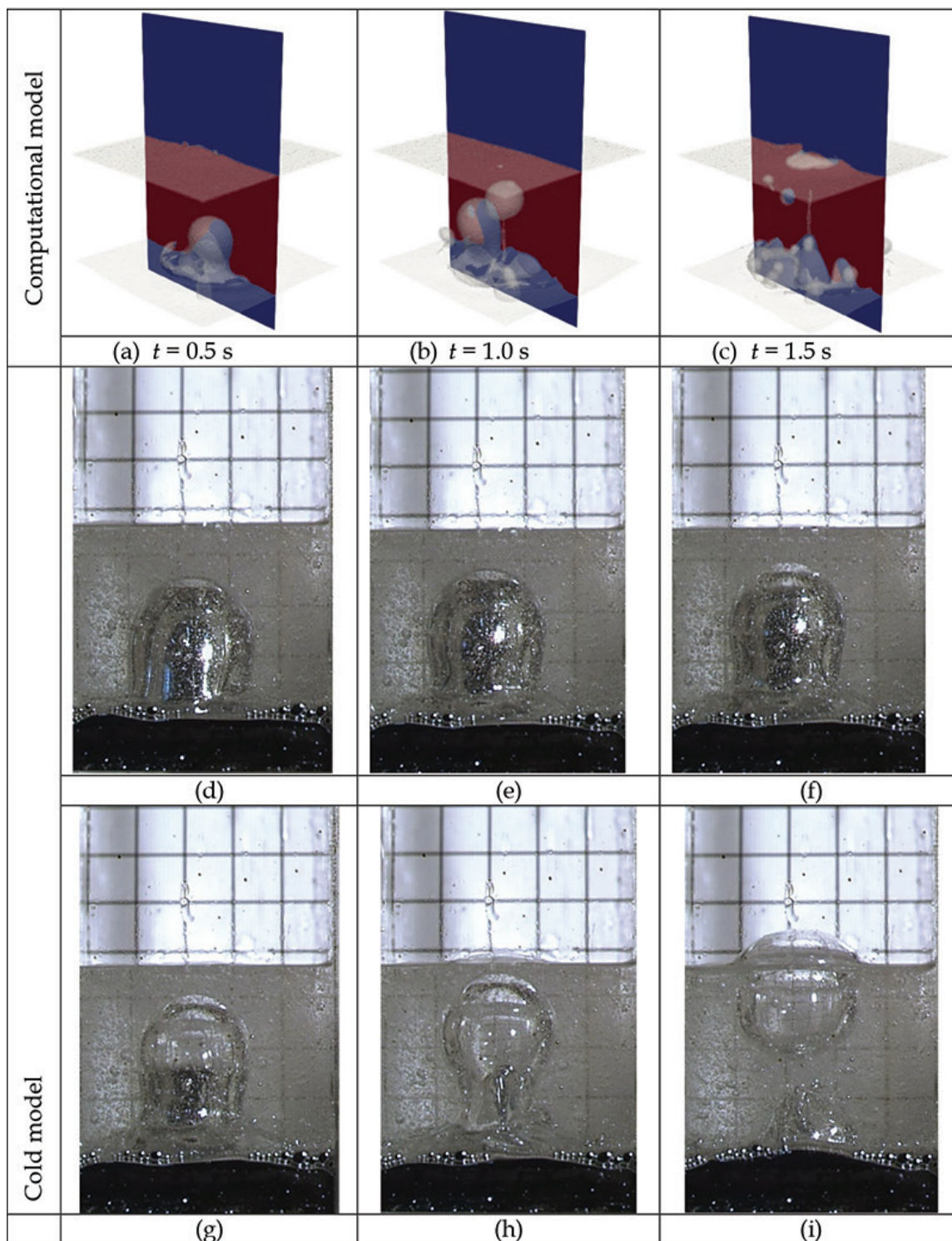


Figure 4—Mercury-silicone oil experiment (gas flow rate 0.8 L/min)

(The time scale for the photographs is not shown, as these are snapshots of high-speed camera footage after reaching a steady state, frames are extracted from 2 seconds of real time. Each block in the background of the photographs are 10 × 10 mm)

with water (Figure 3) to that with oil (Figure 4), deformation of the mercury-water interface and water-air interface is significantly higher than in the mercury-oil case. This is despite very small differences in both density and surface tension of the water and oil. Notably, the high viscosity of the silicone oil seems to play an important role in this phenomenon, which is somewhat counterintuitive when compared to some of the cases run by

Natsui *et al.*, (2016).

What was noteworthy when comparing the cases was the shape of the bubbles. In the mercury-water experiments, the bubbles wobbled significantly more and did not retain a spherical shape, as they did in the water-silicone cases. The same behaviour was observed in the computational model. A noticeable difference between the computational models and experiments

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was the behaviour of the mercury films on the interface between gas and fluid (water or oil). This difference is due to the fact that film drainage is not accounted for in the computational model. This, however, does not seem to influence, at least visually, the interfacial deformation, but will need to be explored further, along with interfacial energy, in future studies.

In the experimental model it was observed that film drainage was significantly faster in the mercury-water case than in the mercury-oil case. For the mercury-oil case, it was found that the mercury film around the gas film drains off when the bubble has already left the interface, while in the water case it drained off before the bubble leaves the interface. This behaviour can be observed by comparing the bursting/drainage of the mercury bubble in Figures 3f and 3g to that in Figures 3f through 3h. Similar results were obtained by Natsui *et al.*, (2016).

Another difference between the computational model and experiments is that of gas entrapment in the silicone oil. Small bubbles remained suspended in the silicone oil in the experiments, but not in the computational model. Similarly, many small beads of mercury remain on the surface of the mercury-oil interface in the experiments, but this is not observed in the computational model. This, again, is attributed to the fact that film drainage is not accounted for in the computational model.

Although film drainage is not accounted for in the computational model, the bulk behaviour, especially interfacial deformation behaviour, is modelled well. Film drainage models are inherently difficult to incorporate in computational models, but are being developed by others, at Mintek as well as the CSIR.

Interfacial deformation, however, is important for the case of lancing. When oxygen gas moves through a metal or slag phase, there is potential for mixing between slag and metal. This is somewhat quantifiable by interfacial deformation, *i.e.* a certain degree of deformation could lead to more mixing between metal and slag and metal droplets can be entrained in the slag. Entrained metal in the slag is a direct loss to the economics of the process as metal is lost and not necessarily recovered from the slag in subsequent processes. Aside from metal entrainment, metal oxidation could also occur.

Notably, no oxidation of the material is accounted for in the computational model, as it is beyond the scope of the project. This is an extremely important point, since most metals oxidize when contacted with oxygen. Metal oxidation is exothermic, which could lead to localized heating around the tap-hole area, which can be detrimental to the tap-hole and furnace. Oxidation of metal is also usually accompanied with some release of gas (highly dependent on the system), which could lead to uncontrolled tapping. Coupling CFD simulations to oxidation of metal is inherently complex (Zietsman, 2016) and will be studied in future outside of this project.

Conclusions

To validate a multiphase fluid flow model for the case where gas is injected into a metal-slag mixture, cold model experiments with water, oil, and mercury were conducted. These experiments form part of a larger project on the validation of computational models in OpenFOAM®.

Reasonable agreement was found between the computational models and the experiments conducted as far as bulk flow behaviour and interfacial deformation are concerned. However,

film drainage behaviour in the experimental model is not captured in the computational model. This is expected, as film drainage models are quite complex, but for the lancing problem film drainage is not necessarily as important as interfacial deformation. The behaviour matches work done by previous authors in which molten salt-tin mixtures were used as fluids. It was found that viscosity plays a significant role in the way in which bubbles behave in the system.

Further work is ongoing. Significant effort is being made to obtain more quantitative data from the experiments as well as the computational model. Furthermore, an experimental rig like the one used by Natsui *et al.*, (2016) (molten slag-tin mixture) is being built to run more experiments.

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