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Droplet formation mechanisms in metallurgical processes

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1. Introduction

Background

In some metallurgical processes, the stream of tapped metals can be observed to disintegrate into multiple droplets or smaller streams. The understanding of such phenomena is of great importance, not only due to the hazardous consequences when liquid metals react with certain materials such as water, but also for economic reasons regarding loss of product. Therefore, the ability to minimise the volume of droplet formation is of particular interest in industry.

One such process of interest is the formation of metal droplets during the production of ferromanganese. The metal is created from raw materials which undergo chemical processes in a large furnace. The main products after the reactions have finished are liquid slag and liquid metal (ferromanganese). The metal is about twice as dense as the slag and therefore sinks to the bottom of the furnace.

Metal droplets can be observed in the slag layer in the first ladle. We wish to know what material properties control the formation of these droplets.

Once a certain amount of metal has collected at the bottom of the furnace, it is ready to be 'tapped' for further processing into the final stages of production. A schematic of this process is shown in Figure 1. The tapping process begins at a tap-hole near the bottom of the furnace. When the tap-hole is opened, the fluid in the furnace flows freely down a runner and is collected in a ladle placed approximately a metre beneath the end of the runner. 'Overflow' pipes transfer the liquid from the first ladle into another once it is full, and so on. The volume of liquid metal is small compared to that of slag, and the metal is predicted to collect mostly within the first ladle, so that the remaining ladles should contain mostly slag.

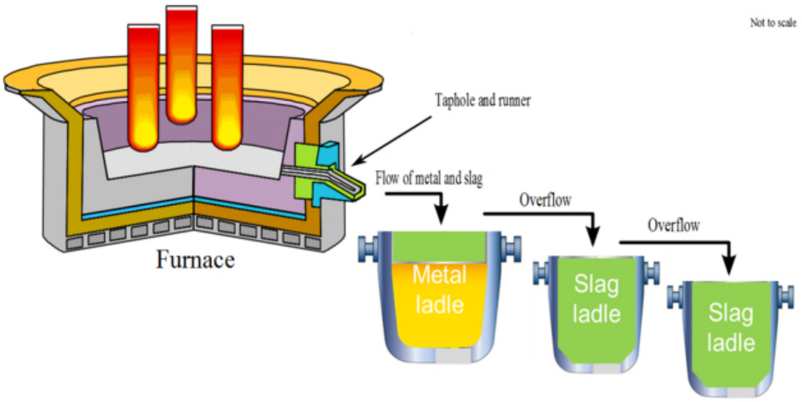


Figure 1: A schematic of the tapping process in ferromanganese production, from [1].

During the tapping process, some metal is lost to its surroundings. It is here that we are able to see some disintegration of the flow before the liquid metal collects in the ladle, and droplets are also seen to protrude into the air from splashing upon impact with the fluid already in the first ladle. The surface of any metal droplets formed by splashing will react very quickly with the air, and the metal will be irrecoverable. Furthermore, metal droplets can be observed trapped in the slag in the first 'metal' ladle. This contributes towards unnecessary loss of the precious metal, with obvious process efficiency, and hence economic, consequences. Hence, we are motivated to discover the mechanisms underlying these droplet formation phenomena and thus investigate potential methods of minimising the volume of metal lost.

2. Mechanisms underlying the phenomenon of droplet formation

In this section, we review the phenomenon of fluid breakup at different stages during the tapping process of ferromanganese production. We consider three distinct stages:

- the flow from the end of the runner into the first ladle;
- the flow of a continuous jet or a broken up jet into the first ladle where air entrainment or further disintegration can occur;
- the flow through the contents of the first ladle which mainly consists of slag.

In each of these stages, we describe the phenomena that can make the liquid jet break up into droplets, or cause further droplet disintegration.

Jet flow from the runner towards the ladle

First, we discuss the flow between the end of the runner and the ladle. Note that along the runner, previous studies [1] show that there is good separation between the slag and the metal, with a metal layer flowing beneath the slag. The radius of the jet as it falls from the runner is around the same radius of the taphole, i.e. 5cm. The jet of metal and slag can be modeled as a cylindrical jet, although there exist circumstances where this is not possible (for example, when the taphole is small and the fluid velocity is large). The dynamics of such a turbulent jet (rather than a laminar jet) can lead to atomization or disintegration of the stream into multiple 'micro'-droplets at the point of fluid exit. Information on different breakup regimes in various fluid models can be found in [3], in which different breakup characteristics and the underlying physical mechanisms are reviewed and discussed for multiple flow parameters and configurations.

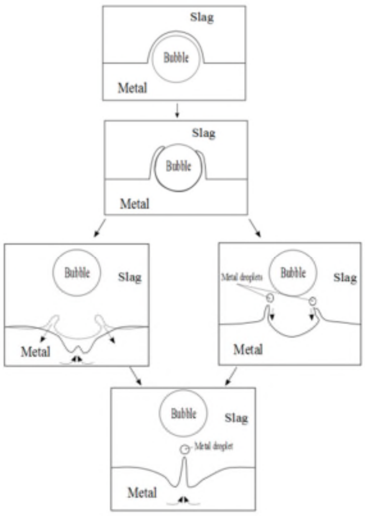
Disintegration at the surface of the liquid in the ladle

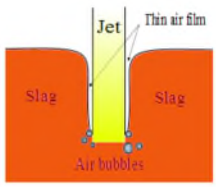
We progress our discussion of droplet generation to the region where the jet reaches the top of the liquid in the ladle (we do not consider a jet or droplets hitting the solid base surface of the first ladle). We suppose that the jet does not breakup in the region between the runner and the ladle and that it impacts and penetrates the liquid in the ladle as a continuous column of fluid. At and around the point of impact, the jet will drag down some of the adjacent air. The film of air around the penetrating jet then breaks into air bubbles which are subsequently trapped in the liquid in the ladle before rising to the surface (see Figure 2b). If the bubbles reach the metal layer near the bottom of the ladle, they may also induce the formation of metal droplets as they burst at the interface between the metal and slag, as seen in Figure 2a.

We also consider the situation where the jet undergoes breakup before impact and droplets hit the surface of the fluid in the ladle. This will initiate the splashing of smaller droplets on the surface or inside the collecting fluid depending on the impact velocity (see Figure 2c). At impact, the 'splatting' of the droplet and its consequent motion contribute to the generation of numerous smaller droplets. It is possible to determine the size distribution of each of these smaller droplets, as well as to deduce the distribution of the number of droplets formed [2].

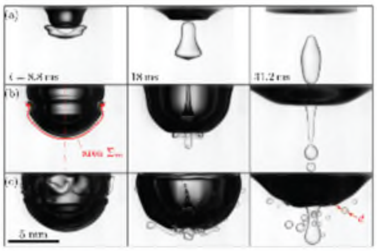
Fluid flow inside the first ladle (two-fluid model)

The final stages of breakup involve the dynamics of a cylindrical jet flowing through the slag in the first ladle. The instabilities at the interface between the jet and the slag in the ladle can cause the formation of droplets. Lastly, we consider the interaction between a preexisting metal droplet in the first ladle and the surrounding slag. Supposing that droplets are already present in the slag layer due to the mechanisms explained thus far, we expect the droplets to experience further fragmentation. This depends on the material properties of each fluid. The droplets may also be subject to body forces which deform by flattening or thinning the droplets, leading to fragmentation with time.





b) Air entrainment schematic.



a) Diagram showing how metal droplets can be formed by rising air bubbles.

c) Schemes of droplet breakup as a droplet impacts another fluid at different velocities. Credited to [2].

Figure 2: Diagrams showing the different mechanisms leading to further droplet formation and fragmentation.

Glossary of terms

- Material properties: This is a collective term for the physical properties of a fluid. They include viscosity, density, and surface tension, as well as interfacial tension in the case of a two-fluid configuration.
- Breakup time and length: This is the critical time and length at which a jet will undergo breakup. The breakup time can be estimated directly from the growth rate of perturbations, and the breakup length is simply the breakup time multiplied by the jet's initial velocity.
- Growth rate: This determines the rate at which perturbations to the jet's radius grow. A negative growth rate means that the jet is stable, so that it does not experience breakup. A positive growth rate means the jet is unstable, and that the perturbations will grow with time, leading to jet breakup.

Mathematical model

We focus on the jet flow region between the end of the runner and before impact with the fluid collected in the ladle. For both configurations, we assume the cylindrical jet to be axisymmetric, and to be travelling vertically downwards from the end of the runner with a constant velocity, U. The material properties are assumed to be constant for both metal and slag, and we also assume that the tapping process takes place at a constant temperature. For our mathematical analyses, we restrict our attention to a small portion of each jet, such that the unperturbed radii in both models can be considered to be constant and gravitational effects negligible.

The Navier-Stokes equations govern viscous fluid motion and describe the conservation of mass and momentum.

We assume that the metal and slag satisfy the Navier-Stokes equations, in a regime where the Reynolds number, *Re,* is within the range of $O(10^4) \leq Re \leq O(10^6)$. The stability analysis proceeds as follows for the one- and two-fluid models:

1. Steady solutions to the governing equations are found. These are called the 'base states'.
2. Small perturbations are added to the base state solution.
3. The time-dependent amplitude of the perturbations is investigated.
4. We either find that the amplitude grows or subsides with time.

3. Breakup of one- and two-fluid jets

Results for the one-fluid model

We predict that breakup is likely to first occur in the falling jet.

For the one-fluid model where we consider the jet to be comprised of only metal, we find from our investigations that the jet begins to break up after $O(10^{-1})$ seconds (assuming that the surface tension value, γ, is around O(1) N/m). Hence, we predict that the metal jet will breakup into droplets before reaching the fluid in the ladles with the current available data. However, there are controllable properties which can increase the breakup time and therefore length. For example, we find that increasing the initial jet radius reduces the growth rate of perturbations, allowing for a much larger breakup time. Additionally, increasing surface tension significantly reduces the breakup time and, therefore, the length that the jet can fall.

Results for the two-fluid model

Using our stability analysis, we predict that the breakup time of a metal jet travelling with a surrounding slag layer (at an approximate value of interfacial tension value of $O(10^{-1})$ N/m between the metal and the slag) is of O(1) seconds. Simply by surrounding the metal jet with slag, the breakup time is significantly increased.

The introduction of an outer core of a different fluid stabilises the jet.

Similar to the role of surface tension in the one-fluid model, we find that the interfacial tension between the metal and slag has a significant influence on the growth rate, and therefore the breakup times and lengths. However, unlike in the one-fluid case, the radius of the unperturbed metal jet does not greatly affect the breakup times and lengths.

Expanding the model

- Our model describes the mechanisms underlying the breakup of a one- or two-fluid jet travelling through air.

- It may be of interest to consider a metal layer travelling adjacent to a slag layer, rather than a metal jet being completely surrounded by slag. This would be a better representation of the actual flow in the runner, where there is good separation between the two fluids, with the metal travelling beneath the slag. However, we suspect that other interfacial instability mechanisms, such as the Rayleigh-Taylor instability, may also influence the behaviour of the jet in this case. This requires a much more complicated analysis.

- We have also neglected gravitational effects in our model. In practice, this would have some effect on the shape of the jet, and the base state solutions must be chosen carefully if the configuration is to take the whole jet into account.

- Another obvious extension from our mathematical formulation is that of a jet travelling through a stationary fluid. This will then represent the fluid behaviour of the jet through the fluid in the first ladle. We may then be able to conclude whether a continuous jet can breakup as it penetrates a receiving fluid of slow or zero velocity.

- Additionally, since we now know the breakup lengths within an appropriate range of surface and interfacial tension values, we can proceed to form some models which describe some of the other mechanisms discussed previously.

4. Discussions and Future Work

Discussions

We have carried out a stability analysis of the solution to the Navier-Stokes equations and appropriate boundary conditions. We find that an increase in surface or interfacial tension reduces the breakup time and length. We also find that a metal jet will break up much slower and over a longer distance if it is surrounded by slag, rather than travelling alone through air. For verification of the results, simple experiments could be performed. Water and silicone or vegetable oil are often used to represent metal and slag, respectively. However, we must note that the validity of such comparisons must be thoroughly determined since, although the density and viscosity ratios may be similar, water and oil may not interact on the size and temperature scales that the tapping process is operated on. Keeping the Reynolds, capillary, Stokes and Weber numbers the same will be key to validating the model with such experiments. We have also thus far presented our drop formation analyses at different stages during the tapping process, in addition to our one- and two-fluid models. For further details of each stage of breakup and our detailed mathematical analyses, we refer the reader to our accompanying technical report.

Future work

Since in reality it is difficult to alter the material properties in the production process, it may be of interest to explore external factors which can affect the fluid behaviour and act on the flow. An example of such a factor would be to subject the slag and metal to an electric field. Also, the presence of a magnetic field around or near a ladle may induce some separating qualities and may be possible to implement in practice.

A key task is to explore whether there is the opportunity for technology transfer from other metallurgical processes. For example, the literature involving the impact of a liquid tin droplet on steel surfaces [4], or the ejection of steel and slag droplets from bubble bursting and splashing in melts [5], may be useful in determining similar fluid behaviours in the metal-slag case. In addition, there are preexisting studies of the volume of droplets entrained in another fluid layer as well as a more general study on the distribution of metal droplets in slag in ladles [6]. Though most of these papers do not deal with a similar physical system to ours, analogies may certainly be made in order to progress this research further.

5. Potential Impact

Svenn Anton Halvorsen, Chief Scientist, Teknova, reported: *"Metal-slag separation is a general issue for many metallurgical processes. In some cases, there can be serious problems separating metal droplets in slag. The project has focused on how metal droplets can be formed during the tapping process for FeMn, and has provided valuable insight. This insight will be combined with metallurgical competence and* *operational experience to improve the tapping process. …. The mathematical analysis has provided valuable, new, insight to handle practical problems for the metallurgical industry."*

Mehdi Kadkhodabeigi, Process Metallurgist, Eramet, commented on this project that*: 'I think the report explains the industrial problem very well. Dividing the investigations into different areas and using fundamental mathematical modeling for every individual area, depending on its governing condition, is very interesting. The work has been summarized very well and the suggestions for future work are quite interesting'*

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