Liquid Steel at Low Pressure: Experimental Investigation of a Downward Water Air Flow

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Abstract. In the continuous casting of steel controlling the steel flow rate to the mould is critical because a well-defined flow field at the mould level is essential for a good quality of the cast product. The stopper rod is a commonly used device to control this flow rate. Agglomeration of solid material near the stopper rod can lead to a reduced cross section and thus to a decreased casting speed or even total blockage (“clogging”). The mechanisms causing clogging are still not fully understood. Single phase considerations of the flow in the region of the stopper rod result in a low or even negative pressure at the smallest cross section. This can cause degassing of dissolved gases from the melt, evaporation of alloys and entrainment of air through the porous refractory material. It can be shown that the degassing process in liquid steel is taking place mainly at the stopper rod tip and its surrounding.

The steel flow around the stopper rod tip is highly turbulent. In addition refractory material has a low wettability to liquid steel. So the first step to understand the flow situation and transport phenomena which occur near the stopper is to understand the behaviour of this two phase (steel, gas) flow. To simulate the flow situation near the stopper rod tip, water experiments are conducted using a convergent divergent nozzle with three different wall materials and three different contact angles respectively. These experiments show the high impact of the wettability of the wall material on the actual flow structure at a constant gas flow rate.

1. Introduction
In the continuous casting process a stopper rod is a commonly used device to control the steel flow from the tundish to the mould. The stopper characteristic (throughput to stopper lift) is a critical parameter in the mould level controller design. In addition the flow field within the submerged entry nozzle (SEN) strongly influences the flow field in the mould and accordingly the quality of the cast product. The most important parameters which influence this flow field in the SEN are clogging and the structure of the two phase flow (gas - liquid).

Clogging is the result of a wide range of complex mechanisms such as chemical reactions, heat transfer, particle transport and deposition, degassing, diffusion and gas formation and transport [1], [2], which all influence one another. The chemical reactions can produce gas bubbles and inclusions. Interfaces between the liquid and the gas phase can trigger chemical reactions, collect inclusions and change global flow characteristics. Inclusions can nucleate bubbles or agglomerate at the walls and thus change their properties and shape. Accordingly the distribution of the gas phase in the SEN plays a key role.

The gas distribution and hence the flow structure depends on the source of the gas phase, the liquid flow velocity and the wetting characteristics of the bounding walls. Milan et al. [3] have shown that in case of a concurrent downward flow in a tube (8.8 mm diameter) it takes up to 130 tube diameters to
establish a developed flow regime. In addition they could show the influence of the phase distribution at the inlet on the flow structure in their whole tube with a length of 227.3 diameters. Accordingly the flow situation right at the stopper rod tip determines the phase distribution in the whole SEN.

In the SEN single phase calculation result in a negative absolute pressure in the stopper rod gap. For a more detailed discussion refer to [4] and [5]. This low pressure leads to gas nucleation at the refractory walls which defines the inlet boundary condition for the gas liquid flow in the SEN. So this paper focuses on the starting point of the two phase flow, the gap between the stopper rod tip and the bottom of the tundish.

2. Experimental setup

The experiments presented in this paper were done with compressed air (gas phase) and desalted water (liquid phase). Desalted water was chosen as a liquid because it is the transparent liquid with the largest surface tension. Liquid metals provide a significantly larger surface tension but they are opaque which makes the detection of the flow structure more challenging.

2.1. Geometry

Figure 1 (a) shows a sketch of the water circuit. From the reservoir the water flows through a flow meter (Bio-Tech FCH-C-PA), a valve, a pump (Grundfos UPS 20-15 N 150), a flow conditioner and a transition piece to change from circular to rectangular cross section before it reaches the actual measurement section which is depicted in detail in figure 1 (b).

![Figure 1](image-url)

**Figure 1.** Experimental setup: (a) Water circuit: Starting in the storage reservoir the water flows through a flow meter (1) and a valve (2) to the pump (3). The right part of the circuit consists of a flow conditioner (4), followed by 100 mm of circular pipe, a transition from circular to rectangular (19 x 20 mm²) (5) and the measurement section (6). The measurement sections outflow is situated 35 mm below the free surface of the tank. (b) The measurement section consists of three Plexiglas walls and an exchangeable back plate. The channel depth is 19 mm. Its width changes from 20 mm to 6 mm and back to 20 mm. Through the hole in the back plate air is injected.
The flow conditioner consists of small pipes with a diameter of 2 mm and has a length of 50 mm. The transition from circular to rectangular has a length of 60 mm.

The measurement section (figure 1 (b)) has a constant depth of 19 mm. Its width changes from 20 mm to 6 mm and back to 20 mm. The back plate (right part in the sketch) can be exchanged. The other three sides of the channel consist of Plexiglas. Through the hole in the back plate air is injected. It is connected to a mass flow controller (Bronkhorst F-201CV -1K0) via a pipe with an inner diameter of 2 mm and a length of 1 m. The hole in the back plate has a diameter of 1 mm.

2.2. Contact angle
For the experiments presented in this paper three different test plates have been used. All three of them have the same thickness. Thus the geometry of the measurement section is exactly the same. The only difference between the back plates is the surface material resulting in different contact angles (see table 1).

| Contact angle | Example picture drop |
|---------------|----------------------|
| Plexiglas     | 79°                  |
| PTFE oiled    | 94°                  |
| PTFE clean    | 105°                 |

The contact angle was measured after conducting the flow experiments using the sessile drop method. The drop diameter ranged from 2 mm to 4 mm. The values in table 1 are an average of ten drops at different positions at the surface. The contact angle between commonly used refractory material and liquid steel ranges from approximately 80° to 140° ([6], [7]). So the tested materials are well within the range of contact angles found in steel casters.

2.3. Measured quantities
The measurements presented in this paper focus on the flow regime hence the special distribution of water and air in the measurement section. The measured quantities are the water flow rate \( \dot{V}_w \) and the air flow rate \( \dot{V}_a \).

The flow structure is recorded using a high speed camera using background light as shown in figure 2. The camera recording rate was set to either 250 or 2000 fps depending on the dynamic of the flow. The exposure time was 1/5000 s. The resulting pictures were used to determine the flow regime.
3. Results

Depending on the water and air flow rate \( (\dot{V}_w, \dot{V}_a) \) and on the contact angle of the back plate different flow structures were observed. The three different water flow rates used for the results presented in this paper are listed in table 2. The Reynolds number in table 2 is calculated for the single phase flow using the hydraulic diameter of the smallest cross section of the measurement section as the length scale.

Table 2. Water flow rates and Reynolds numbers

| Water flow rate \( \dot{V}_w \) in l/s | Reynolds number |
|--------------------------------------|----------------|
| 0.08                                 | 6150           |
| 0.13                                 | 10100          |
| 0.17                                 | 12800          |

3.1. Contact angle 79° (Plexiglas)

Figure 4 shows a selection of the main flow structures observed using the Plexiglas back plate. Three flow regimes were observed (see figure 3):

- Singular bubbles: From the air nozzle single bubbles detach which are significantly smaller than the channel width. So they remain almost spherical (figures 4 (a), (f)). This flow regime occurs at low air flow rates. As the water flow rate increases it can be observed that a cone shaped bubble stays attached to the air nozzle and the necking takes place slightly below the air nozzle (figures 4 (f)).
- Elongated bubbles: This flow regime occurs at a medium air flow rate. The bubble volume is too big to form a sphere in the channel so the bubbles elongate (figures 4 (b), (d), (g)). With an increased water flow rate the bubbles become longer and thinner.
- Intermediate level: In this case a large bubble is attached to the air nozzle. This bubble reaches below the water level in the reservoir. Its bottom end is horizontal. The water still completely wets the bounding walls. Small bubbles are ripped off the big bubble at the bottom and transported down the last part of the channel.
The air and water flow rates necessary for the transition between those three flow regimes are listed in table 3. Figure 5 illustrates the regions of the different flow regimes and the relative location of the examples of figure 4.

**Figure 4.** Results of the Plexiglas back plate.
(a) $V_w = 0.08 \text{ l/s}, V_a = 0.05 \text{ l/min}$, (b) $V_w = 0.08 \text{ l/s}, V_a = 0.60 \text{ l/min}$,
(c) $V_w = 0.08 \text{ l/s}, V_a = 0.65 \text{ l/min}$, (d) $V_w = 0.13 \text{ l/s}, V_a = 0.80 \text{ l/min}$,
(e) $V_w = 0.13 \text{ l/s}, V_a = 1.00 \text{ l/min}$, (f) $V_w = 0.17 \text{ l/s}, V_a = 0.80 \text{ l/min}$,
(g) $V_w = 0.17 \text{ l/s}, V_a = 1.00 \text{ l/min}$,

At a water flow rate of 0.08 l/s the bubbling regime can be observed up to an air flow rate of 0.4 l/min. At this air flow rate the bubbles do not simply detach from the nozzle. Several bubbles are formed at the nozzle, which coalesce right beneath it to form a bigger bubble. Additionally bubbles are collected in the channels diffusor section in the recirculation area. With an increase of the air flow rate these bubbles start to coalesce and form a big bubble which stays there.

At a water flow rate of 0.08 l/s and an air flow rate of 0.50 l/min there are no longer circular bubbles formed as they are constrained by the channel walls. Instead they form elongated shapes. Directly at the nozzle there stays conical bubble which grows till its lower part detaches to form a new bubble. This mode stays stable up to an air flow rate of 0.60 l/min (figure 4 (b)).
After increasing the air flow rate to 0.65 l/min the bubbles in the measurement section coalesce and form an intermediate level which is located below the storage tank water level. This single gas bubble only touches the wall at the lower left end. The rest of the walls are fully wetted.

At an increased water flow rate of 0.13 l/s the bubbles are smaller compared to the same air flow rate at a water flow rate of 0.08 l/s due to the difference in the shear forces. At this water flow rate a cone shaped bubble is attached to the air nozzle which breaks up in the middle to form a new bubble. So the bubble formation does not take place directly at the nozzle but some millimetres below it.

The transition from the formation of single bubbles to elongated bubbles is shifted to an air flow rate of 0.50 l/min. The resulting bubbles are now thinner as can be seen in figure 4 (d). This flow regime stays stable up to an air flow rate of 0.90 l/min. At an air flow rate of 0.95 l/min the transition to an intermediate level takes place (figure 4 (e)). It can be observed that especially the upper part of the gas volume is narrower compared to the water flow rate of 0.08 l/s.

Increasing the water flow rate to 0.17 l/s results in an even bigger drop shaped bubble (figure 4 (f)) attached to the air nozzle. The transition to elongated bubbles takes place at an air flow rate of 0.90 l/min. The transition to an intermediate level cannot be reached with the current setup as the air flow rate is limited to 1.00 l/min.

**Table 3.** Air flow rate $V_g$ at transition of the flow structure using the Plexiglas back plate (contact angle 79°).

| Water flow rate in l/s | Circular to elongated bubbles in l/min | Elongated bubbles to intermediate level in l/min |
|------------------------|----------------------------------------|-------------------------------------------------|
| 0.08                   | 0.45                                   | 0.62                                            |
| 0.13                   | 0.50                                   | 0.90                                            |
| 0.17                   | 0.90                                   | >1.00                                           |

**Figure 5.** Flow chart of the Plexiglas back plate. The blue dashed line shows the transition from single bubble formation to elongated bubbles. The green dotdashed line the transition from elongated bubbles to an intermediate level. The black dots show the positions of the examples listed in figure 4.
3.2. Contact angle 94° (Oil coated PTFE)
The oiled PTFE back plate was tested using a water flow rate of 0.13 l/s and 0.17 l/s. The air flow rate was set from 0.01 l/min to 0.20 l/min. Within this range of parameters only two different flow structures were observed (see figure 6):

- Elongated bubbles: In this case a long bubble attached to the air nozzle and to the back plate forms. Waves traveling down the bubble can be observed. They become larger as the bubble becomes longer. At some point the air water interface touches the back plate due to the surface wave, which causes the bubble to break up. The upper part stays attached to the air nozzle while the lower part accelerates and becomes shorter. While it is moving down, it stays attached to the back plate. Two examples are shown in figure 7 (a) + (b) and (d) + (e).

- Intermediate level: At higher air flow rates a large air bubble is attached to the air nozzle which reaches below the reservoir water level 7 (c). In the upper part the bubble forms a half cone which is attached to the back plate. Again the lower end of the bubble is almost horizontal and a source of small bubbles.

![Figure 6](image1.png)  
**Figure 6.** Overview of the basic flow structures observed using the oiled PTFE back plate; The top shows the phase distribution in a cross section in the middle of the shown channel. The grey colour indicates water, white colour air. (a) elongated bubbles, (b) intermediate level.

The border between those two flow regimes is illustrated in figure 8. The air flow necessary to change to an intermediate level can be seen in table 4.

![Figure 7](image2.png)  
**Figure 7.** Results of the oiled PTFE back plate.  
(a) \( \dot{V}_w = 0.13 \) l/s, \( \dot{V}_a = 0.03 \) l/min, \( t = 0 \) ms,  
(b) \( \dot{V}_w = 0.13 \) l/s, \( \dot{V}_a = 0.03 \) l/min, \( t = 44 \) ms,  
(c) \( \dot{V}_w = 0.13 \) l/s, \( \dot{V}_a = 0.11 \) l/min,  
(d) \( \dot{V}_w = 0.17 \) l/s, \( \dot{V}_a = 0.03 \) l/min, \( t = 0 \) ms,  
(e) \( \dot{V}_w = 0.17 \) l/s, \( \dot{V}_a = 0.03 \) l/min, \( t = 24 \) ms,
An example of elongated bubbles can be seen in figure 7 (a) and (b). Figure 7 (b) was taken 44 ms after (a). First a long bubble forms, which is attached to the air nozzle. This bubble is also attached to the wall and has an approximately conical shape. As this bubble becomes longer waves form at its surface (figure 7 (a)). When this wave touches the wall the bubble breaks apart. The upper part retreats (figure 7 (b)) while the top end of the lower part starts to accelerate down. The lower part is then transported down still attached to the wall. The upper part slowly starts growing again losing some of its air volume by forming small bubbles at its lower end. As the gas flow rate increases the length of the bubble attached to the air nozzle increases.

An intermediate level occurs if the air flow rate is increased further. For the air flow rates see table 4. As in case of the Plexiglas plate this is a very stable flow field and the intermediate level is below the water level in the storage tank. Nevertheless the air volume is now attached to the wall forming a half cone in the upper part.

An increase of the water flow rate leads to significantly smaller bubbles (figure 7 (d) and (e)). Accordingly the transition from elongated bubbles to intermediate level takes place at a higher air flow rate.

| Water flow rate in l/s | Elongated bubbles to intermediate level on l/min |
|------------------------|-------------------------------------------------|
| 0.13                   | 0.10                                            |
| 0.17                   | 0.20                                            |

**Table 4.** Air flow rate $\dot{V}_a$ at transition of the flow structure using the oiled PTFE back plate (contact angle 94°).

**Figure 8.** Flow chart of the oiled PTFE back plate. The green dot-dashed line marks the transition from elongated bubbles to an intermediate level. The black dots show the positions of the examples listed in figure 7.
3.3. Contact angle 105° (PTFE)

The clean PTFE back plate was tested using water flow rates of 0.08 l/s, 0.13 l/s and 0.17 l/s. The air flow rate was chosen between 0.01 l/min and 0.25 l/min. Within this range three different flow regimes could be observed (figure 9):

- Singular bubbles: They are no longer spherical as in case of the Plexiglas back plate. After separating from the air nozzle they slide down the wall (figure 10 (a)). These bubbles can detach from the wall if the receding contact angle\(^1\) reaches 0°. This results in flow structures where the bigger bubbles depart halfway down the channel while the smaller bubbles slide down to feed the recirculation bubble. This big bubble in the recirculation area is in this case attached to the PTFE wall (figure 10 (b), (c) and (e)).

- Elongated bubbles: As the air flow rate increases elongated bubbles form (figure 10 (d)). This flow structure is quite similar to the case of the oiled PTFE back plate but the bubble diameter is smaller now. Accordingly the transition to the intermediate level takes place at a slightly higher air flow rate compared to the oiled PTFE back plate.

- Intermediate level: This flow structure is quite similar to the oil coated PTFE back plate. Again the gas volume is attached to the back plate.

![Figure 9. Overview of the basic flow structures observed using the clean PTFE back plate; The top shows the phase distribution in a cross section in the middle of the shown channel. The grey colour indicates water, white colour air. (a) single bubbles, (b) elongated bubbles, (c) intermediate level.](image)

The dividing lines between the observed flow regimes are listed in table 5 and illustrated in figure 11. Note that the air flow rates for both transitions are a factor of six smaller compared to the experiments with the Plexiglas back plate.

The single bubble regime at high water flow rates shows a long bubble attached to the air nozzle which breaks up approximately in the middle. The lower part slides down or even detaches from the back plate while the upper part stays attached to the air nozzle. This behavior is quite similar to the Plexiglas back plate but now the feeding bubble is also attached to the wall.

\(^1\) The receding contact angle can be observed if the liquid phase moves away from the gas phase, for example if a solid object is pulled out of a water pool.
Figure 10. Results of the clean PTFE back plate.
(a) $\dot{V}_w = 0.08 \text{ l/s}, \dot{V}_\alpha = 0.05 \text{ l/min}$,  
(b) $\dot{V}_w = 0.13 \text{ l/s}, \dot{V}_\alpha = 0.05 \text{ l/min}$, $t = 0 \text{ ms}$,  
(c) $\dot{V}_w = 0.13 \text{ l/s}, \dot{V}_\alpha = 0.05 \text{ l/min}$, $t = 8.5 \text{ ms}$,  
(d) $\dot{V}_w = 0.13 \text{ l/s}, \dot{V}_\alpha = 0.10 \text{ l/min}$,  
(e) $\dot{V}_w = 0.17 \text{ l/s}, \dot{V}_\alpha = 0.05 \text{ l/min}$,  
(f) $\dot{V}_w = 0.17 \text{ l/s}, \dot{V}_\alpha = 0.25 \text{ l/min}$,

Table 5. Air flow rate $\dot{V}_\alpha$ at transition of the flow structure using the PTFE back plate (contact angle 105°).

| Water flow rate in l/s | Singular bubbles to elongated bubbles in l/min | Elongated bubbles to intermediate level in l/min |
|------------------------|-----------------------------------------------|-----------------------------------------------|
| 0.08                   | 0.07                                          | 0.09                                          |
| 0.13                   | 0.08                                          | 0.14                                          |
| 0.17                   | 0.13                                          | 0.24                                          |

Figure 11. Flow chart of the PTFE back plate. The blue dashed line shows the transition from single bubble formation to elongated bubbles. The green dotdashed line the transition from elongated bubbles to an intermediate level. The black dots show the positions of the examples listed in figure 10.
4. Conclusion
The experiments presented in this paper clearly show that the contact angle strongly influences the flow regime. The major differences observed are the distribution of the air phase in the cross section of the channel, the air flow rate necessary to sustain an intermediate level and the bubble size in the bubbling regime at the same air and water flow rate.

With a contact angle of 94° and 105° the air to moves down along the back plate while in better wetting conditions (contact angle 79°) it is transported in the middle of the channel.

The air flow rate necessary to generate an intermediate level depends on the wetting conditions. With the Plexiglas back plate (79°) the required air flow rate is six times higher as in the case of the PTFE back plate (105°).

The bubble size is larger in case of the PTFE back plate compared to the Plexiglas back plate. As the transition to an intermediate level occurs at a much smaller air flow rate in case of the PTFE back plate, there is a limited number of water and air flow rates where both the Plexiglas and the PTFE back plates both show bubbling.

These differences in the flow regime will clearly influence all other transport phenomena mentioned in section 1. Inclusions can only agglomerate at the refractory walls if the liquid steel wets the wall. The amount of inclusions collected by the gas liquid interface depends on its size. The bubble size distribution generated strongly depends on the contact angle which affects the bubble size distribution and the velocity field in the SEN and the mold.

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