ADVANCES IN PURGING PLUG DESIGN FOR SOFT PURGING: A WATER MODELING STUDY

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Abstract

Water modelling has shown that gas bubble formation characteristics such as the number of bubbles and bubble size differ significantly according to the purging plug design (i.e., hybrid, porous, or slot) as well as the specific flow rate. In contrast, the width of an open eye, which can form at the fluid surface as a result of gas purging, is controlled by the size of the gas injection area and the flow rate only. Regardless of the plug design, an increase in flow rate always increases the open eye whereas an increase of the size of the gas injection area always retards and shifts its formation to higher flow rates. The growth of the open eye follows a root function law depending on the flow rate. For optimum soft bubbling this has consequences regarding plug selection. The best results can be achieved with plugs having maximum sized gas injection areas generating a large number of small bubbles at a given flow rate like specially designed “clean steel”hybrid or porous plugs.

Introduction

Soft bubbling at low flow rates with inert gases is the final process step in steel secondary metallurgy in order to achieve maximum steel cleanliness. During soft bubbling nonmetallic inclusions (NMIs) are floated up by inert gas bubbles from the steel bath into the slag layer. As an important precondition the opening of the slag layer – the so called open eye formation – has to be avoided in order to prevent slag entrainment into the melt and reactions of the melt with air. Finely distributed gas bubbles are desired. A brief introduction to this topic with further references is available in the literature [1–4].

Mathematical and experimental modelling of the processes taking place at the steel/slag interface during argon bubbling, which also consider open eye formation in the slag, have been published [5, 6]. It was shown that the opening behaviour and the opening width of the slag were influenced by both the flow rate and by the number of gas inlets that were investigated (i.e., 1 or 2 gas inlets). However, no investigation was carried out regarding the influence of the plug design and the plug size on the slag opening behaviour.

A large number of different purging plug types is available on the market and there is a comprehensive overview of this topic [7]. These plugs differ significantly in design and properties and not all of these plugs are optimized for soft bubbling performance. In order to evaluate the influence of plug design and plug size on soft purging behaviour, water modelling comparisons were carried out at the Technology Center Leoben (Austria). The first results regarding the bubble number, size, and size distributions generated from a hybrid versus a porous and a slot design have been published [1]. It was demonstrated that at a given flow rate the number of bubbles released from a hybrid and a porous plug significantly exceeded those generated by a slot plug. Consequently, the predominant bubble size produced by a hybrid and a porous plug was considerably smaller than from a slot plug. In addition, the bubble size distribution was extremely narrow for the hybrid and the porous plug while the slot plug showed a much broader size distribution. Based on these observations it can be concluded that during soft bubbling the hybrid and the porous plug would be beneficial for floating NMIs up into the slag layer.

This paper describes an extension of these water modelling studies, focusing on the influence of plug design (i.e., hybrid, porous, and slot), plug size and flow rate on a modelled slag layer and open eye formation.

Experimental Procedure

Investigations were carried out in two steps. In a first step the influence of the plug design was investigated by testing a hybrid plug, a porous plug, and a standard slot plug with gas injection areas of the same magnitude in the water model. Details of these plugs are given in Table I.

Table I: Geometric and physical characteristics of the hybrid, porous, and slot plugs examined in the water modelling investigation.

	Hybrid plug	Porous plug	Slot plug
Slot number	-	-	24
Slot dimensions (mm)	-	-	16 x 0.25
Open porosity (vol.%)	27	27	12
Bulk density (g cm^{-3})	2.7	2.6	3.1
Gas injection area (mm^2)	3600	11300	7200

In a second step the influence of the plug size was investigated by testing three sizes of porous plugs with increasing gas injection areas. Details of these plugs are given in Table II.

Table II: Geometric and physical characteristics of porous plugs with increasing gas injection area examined in the water modelling investigation.

	Porous plug small	Porous plug medium	Porous plug large
Open porosity (vol.%)	27	27	27
Bulk density (g cm^{-3})	2.7	2.6	2.7
Gas injection area (mm^2)	3600	11300	35000

The basin of the water model had a water volume of 1000 litres and a height of 1000 mm. Sufficient height of the basin was necessary in order to observe the behaviour of the gas permeating through the water.

The water was covered with a 20 mm thick layer of coloured oil to simulate a slag layer. This rather thin oil layer was selected in order to be able to investigate the formation of an open eye at very low flow rates. The thickness of the oil layer was kept constant for all plug types and flow rates. A summary of the fluid properties of the water/oil system [5, 8] and the steel/slag system [5] are given in Table III.

Table III: Fluid properties of water, oil, steel, and slag.

	Viscosity (kg m^{-1} s^{-1})	Density (kg m^{-3})
Water (20 °C)	0.001	998.2
Oil (Paraffinum liquidum, 20 °C)	0.032	846
Steel (liquid)	0.006	7020
Slag (liquid)	0.2664	3500

As the viscosity ratio of water to oil (0.031) is within the same order of magnitude as the viscosity ratio of steel to slag (0.023) the water/oil system is considered to be suitable to model a

steel/slag surface [5]. Due to the difference in the density ratio water to oil (1.18) compared to steel to slag (2.00) influences on the flow behaviour can be expected. As a result of the buoyancy difference the open eye in the water model will form earlier and will grow faster compared to real slag covering a steel bath [10].
The plugs were fed with compressed air at ambient temperature with a mass flow controller (range 0–10 NL/min), which allowed precise adjustment and a constant gas flow in the range of 0 NL/min up to 10 NL/min [8]. The basin was illuminated from the bottom on the left and right sides. A digital camera was used to take images of the water surface at a rate of 30 frames/second to observe open eye formation. Digital image processing was carried out the gain data on the geometrical extensions of the forming open eyes. A surface view of the water model is given in Figure 2 showing the formation of an open eye at a flow rate of 5 NL/min in the dark oil floating on top of the water.

Figure 1: Open eye formation in the dark oil layer covering the water (flow rate: 5 NL/min)

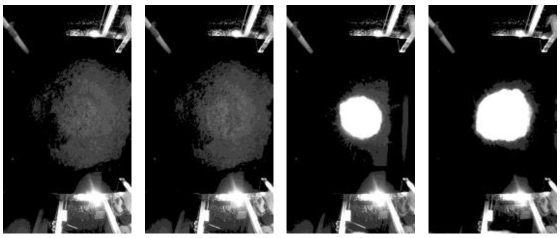
Water Modelling Results

Water modelling was carried out in two steps. First plugs with different designs but similar sized gas injection areas were investigated. In a second step plugs with identical design but increasing size of gas injection areas were tested.

Comparison of plugs with different plug designs

Hybrid Plug

At extremely low flow rates (e.g., 0.5 NL/min) the oil layer remained intact and purging gas bubbles penetrated the oil layer without opening it. However, at 1 NL/min first tiny openings in the dark oil layer were observed. A further increase of the flow rate resulted in a rapid opening of the oil layer and the formation of an open eye. A continuous increase of the flow rates resulted in a further growth of the open eye size. Figure 3 shows the development of the open eye at flow rates of 0.5 NL/min, 1 NL/min, 5 NL/min, and 10 NL/min.

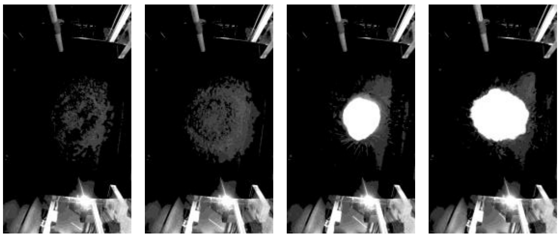


(a) (b) (c) (d)

Figure 2: Open eye formation with a hybrid plug at flow rates of (a) 0.5, (b) 1, (c) 5, and (d) 10 NL/min.

Porous Plug

The porous plug behaved in a similar manner to the hybrid plug. Again at very low flow rates the oil layer remained intact and with increasing flow rates the formation of an open eye was observed. Increasing flow rates resulted in a continuous growth of the open eye (Figure 4).

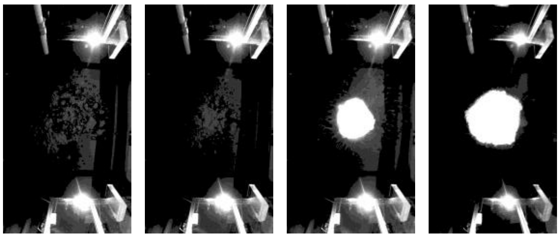


(a) (b) (c) (d)

Figure 3: Open eye formation with a porous plug at flow rates of (a) 0.5, (b) 1, (c) 5, and (d) 10 NL/min.

Slot Plug

Again at very low flow rates the oil layer stayed intact and the purging gas penetrated the oil layer without opening it. Increasing the flow rates resulted in the opening of the oil layer and the formation of an open eye. Rising flow rates resulted in a continuous growth of the open eye (Figure 5).



(a) (b) (c) (d)

Figure 4: Open eye formation with a slot plug at flow rates of (a) 0.5, (b) 1, (c) 5, and (d) 10 NL/min.

Comparison of plugs with increasing gas injection areas

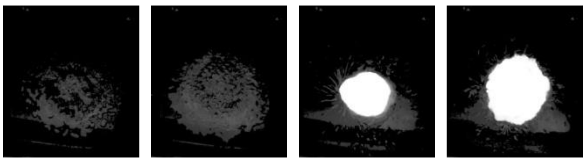
Three porous plugs with increasing hot face diameters, i.e., increasing gas injection areas were investigated in the water model.

Small sized porous plug

Results have been presented in Figure 3 demonstrating the effect of different plug designs. In this comparison the porous element of the hybrid plug was taken as smallest porous plug.
First open eye formation was observed at flow rates as low as approximately 0.8 NL/min.

Medium sized porous plug

The gas injection area of this plug was about 3 times larger than the small sized porous plug. Compared to the porous plug with smaller gas injection area higher flow rates were necessary to open the oil layer. At 0.5 NL/min and 1 NL/min the oil layer stayed intact, first open eye formation was observed at a flow rate of 1.9 NL/min. With increasing flow rates the open eye grew continuously (Figure 6).

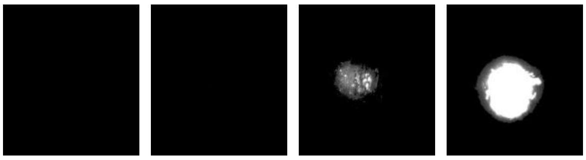


(a) (b) (c) (d)

Figure 5: Open eye formation with a medium sized porous plug at flow rates of (a) 0.5, (b) 1, (c) 5, and (d) 10 NL/min.

Large sized porous plug

The gas injection area of this plug was about 10 times larger than the small sized plug and about 3 times larger than the medium sized plug. Compared to smaller plugs of similar design significantly higher flow rates were required to open the oil layer covering the water model. Up to 5 NL/min the oil layer stayed completely intact. Starting with 5 NL/min the oil layer was thinning out and first small spots started to open. A further increase of the flow rates resulted in a full opening and subsequent expansion of the open eye (Figure 7).



(a) (b) (c) (d)

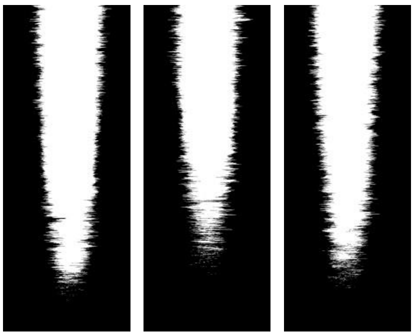
Figure 6: Open eye formation with a large porous plug at flow rates of (a) 0.5, (b) 1, (c) 5, and (d) 10 NL/min.

Comparison of open eye development and flow rate

In order to enable a quantitative evaluation of the water modelling results a compilation of images was prepared covering a 30 minute period where the flow rate was continuously increased from 0 to 10 NL/min. Every 0.03 seconds images of the oil layer were taken and the open eye formation was observed. The diameters of open eye and surrounding oil were determined and projected into the compilation image. By applying this diagram the size of the open eye can be determined at every given flow rate.

Plugs with different designs but similar gas injection areas

The development of the open eye for a hybrid, porous, and slot plug with similar sized gas injection areas is shown in Figure 8. The bottom line of each picture represented a flow rate of 0 NL/min, the top line 10 NL/min.



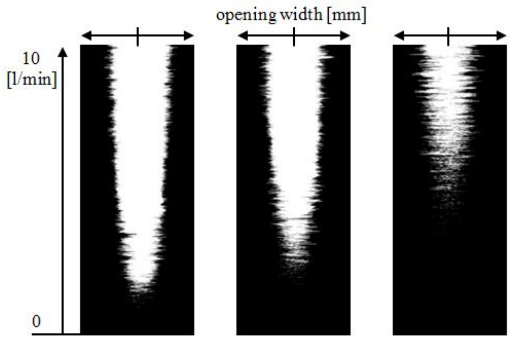
(a) (b) (c)

Figure 7: Development of the open eye diameter versus flow rate for the (a) hybrid plug, (b) porous plug, and (c) slot plug.

The compiled images for hybrid plug, porous plug, and slot plug were quite similar regarding size and opening velocity of the oil layer. A central bright zone representing the full open eye was surrounded by a shaded area representing a zone with a fluctuating oil layer and a black outermost area representing the intact oil layer.
The total width of the open eye grew with increasing flow rates. A detailed comparison of the diagrams revealed some minor differences among the three plug types: The hybrid plug (8a) and the slot plug (8c) opened the oil layer a little earlier at lower flow rates compared to the porous plug (8b).
Concluding from these observations the plug design seems to have only minor influence on the opening of the oil layer.

Porous plugs with increasing gas injection areas

The development of the open eye formation for porous plugs with increasing size of gas injection areas is shown in Figure 9. Again the bottom line of each picture represented a flow rate of 0 NL/min, the top line 10 NL/min.



(a) (b) (c)

Figure 8: Development of the open eye diameter versus flow rate for the (a) small sized, (b) medium sized, and (c) large sized porous plug.

Contrary to the plug design a clear linear dependence of the oil layer opening upon the size of the gas injection area (plug size) and the flow rates was observed. Whereas the small sized porous plug started to open the oil layer at flow rates as low as 0.8 NL/min, the medium sized and the large sized porous plugs preserved the oil layer up to 1.9 NL/min and 5.5 NL/min, respectively. Figure 10 shows the dependence between size of gas injection area and the flow rate required for opening the oil layer.
For the given experimental configuration the following relation was found:

$$Q = 2 * 10^{-3} * A + 0.235 \quad (1)$$

where Q is the flow rate in NL/min and A is the size of the gas injection area in mm^2. The confidence interval R^2 for this linear regression has been found to be 0.9999 .

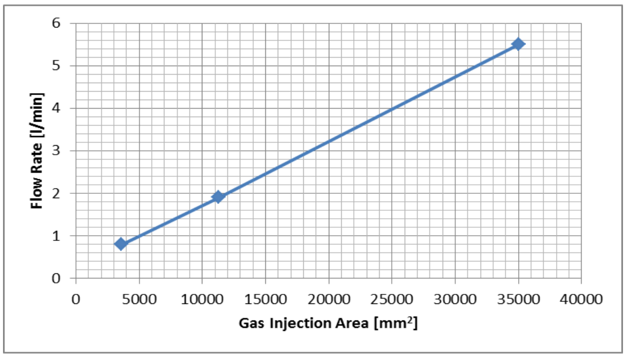


Figure 9: Flow rates required to open the oil layer and form an open eye versus effective gas injection area.

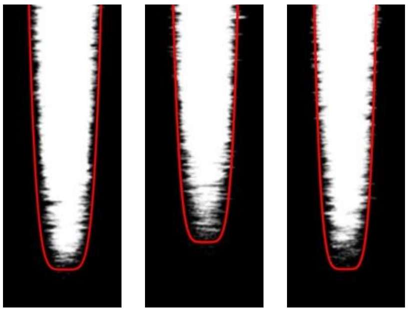
Summary and Discussion

As shown above the open eye formation clearly depended on the size of the gas injection area and the flow rate. There seemed to be a linear correlation between these parameters. When increasing the size of the gas injection areas higher flow rates were necessary to open the oil layer, or in other words: Plugs with larger gas injection areas allowed higher flow rates before the oil layer opened.

At a given size of the gas injection area the size of the open eye grew following a root function law depending on the flow rate. The opening width of the open eye could be described by the following equation:

$$R(Q) = 3.4 * Q^{0.2} \quad (2)$$

Where R is the radius of the open eye (cm) and Q is the flow rate (NL/min). This correlation is illustrated for hybrid, porous, and slot plugs in Figure 11.



(a) (b) (c)

Figure 10: Mathematical modelling of the open eye formation for the (a) hybrid plug, (b) porous, and (c) slot plug.

Good accordance to [9] was found where the relationship is described by:

$$R = 0.38 * Q^{0.15} * H^{0.62} \quad (3)$$

where H is the bath height. Since the bath height was kept constant in all investigations, the equation can be simplified to:

$$R \sim k * Q^{0.15} \quad (4)$$

The results found were in good accordance with this relationship.

Contrary to the beneficial effect of hybrid and porous plug design upon bubble size and amount of bubbles no correlation was found between plug design and open eye formation. Hybrid, porous and slot plug generated open eyes of the same size at a given flow rate, provided that the gas injection areas which were in contact with the water were of the same size.

Conclusion

Soft bubbling is a process step carried out to remove NMIs from the melt. The interaction of the slag with the steel bath during purging has a substantial influence on the finished steel quality. An opening of the slag layer has to be avoided in this process step in order to prevent reoxidation or nitrogen pick-up of the steel from the surrounding air as well as an entrainment of slag into the steel bath. Low flow rates in combination with a high number of bubbles and large bubble surfaces are beneficial for this process [10]. Constant low flow rates will prevent the formation of such an open eye, namely opening of the slag layer. The water model investigations have shown that the geometry of the purging plug has considerable influence on the formation of an open eye. By increasing the gas injection area the opening of the slag layer can be retarded and shifted to higher flow rates. Plugs with larger purging surface or plugs especially designed with larger gas injection areas should be considered for this purpose. The plug type itself had no direct influence on the opening of the slag layer. However, in order to achieve best NMI flotation as many small bubbles as possible are required. Considering previous water modelling results [1] and combining them with the results of this study best results are to be expected with hybrid plugs, possibly also with porous plugs with maximized gas injection areas. Optimum NMI removal is an ongoing technological challenge. Such special plugs in combination with a gas control system designed for precise, low gas flows [11, 12] provide the current optimum solution for NMI removal by soft purging. Considering ongoing developments in plug and flow control equipment as well as research in steel plant operations substantial improvements in future NMI removal may be expected. Based on the results of this study for optimum NMI removal the whole ladle bottom should be considered as gas interface.

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