

## **TUNDISH NOZZLE CLOGGING – APPLICATION OF COMPUTATIONAL MODELS**

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### **INTRODUCTION**

Clogging of the tundish nozzle is a major castability problem in continuous casting of steel for several reasons. Firstly, clogging increases the frequency of operation disruptions to change nozzles or tundishes or even to stop casting. These extra transitions increase operating cost, decrease productivity, and lower quality. Secondly, clogging can lead directly to a variety of quality problems. Clogs change the nozzle flow pattern and jet characteristics exiting the ports, which can disrupt flow in the mold, leading to surface defects in the steel product and even breakouts. Dislodged clogs also disturb the flow and either become trapped in the steel or change the flux composition, leading to defects in either case. Quality problems also arise from the mold level transients which occur as the flow control device compensates for the clogging.

Clogging is a complex problem which has received a great deal of past study. Two comprehensive reviews of current understanding are given by Rackers<sup>[1]</sup> and by Kemeny, who recently summarized the many different causes and remedies with practical operation guidelines.<sup>[2]</sup> This paper provides a summary of the formation mechanisms, detection methods, and prevention of tundish nozzle clogging, focussing on the role of computational models in quantifying the non-composition-related aspects.

### **TYPES OF CLOGS**

Tundish nozzle clogging problems take many different forms, and can occur anywhere inside the nozzle, including the upper well, bore, and ports (See Fig. A1 for terminology). They are classified here into four different types according to their formation mechanism: the transport of oxides present in the steel to the nozzle wall, air aspiration into the nozzle, chemical reaction between the nozzle refractory and the steel, and steel solidified in the nozzle. In practice, a given nozzle clog is often a combination of two or more of these types, and its exact cause(s) can be difficult to identify.

**1. Transport of oxides present in the steel** – The most important cause of nozzle clogging is the deposition of solid inclusions already present in the steel entering the nozzle. These may arise from many sources:

- 1.1) deoxidation products from steelmaking and refining processes
- 1.2) reoxidation products from exposure of the molten steel to air
- 1.3) slag entrapment
- 1.4) exogenous inclusions from other sources
- 1.5) chemical reactions such as the products of inclusion modification

Rackers calculates that a typical clogged nozzle contains 16% of the oxide inclusions that pass through the nozzle <sup>[3]</sup>. Thus, it is beneficial both to reduce the number of inclusions, as well as to limit their transport and attachment to the nozzle walls. The transport of inclusions to the nozzle walls can be lessened by streamlining the flow pattern within the nozzle to minimize the frequency of contact of inclusions with the walls. In particular, slight misalignment <sup>[4]</sup>, separation points in the flow pattern <sup>[4]</sup>, turbulence <sup>[5]</sup>, and fluctuations in casting speed <sup>[6]</sup> are all very detrimental and should be avoided. Nozzle walls should be smooth to increase the thickness of the laminar boundary layer and discourage contact. Once oxide particles touch the nozzle wall, they attach due to surface tension forces, and eventually sinter to form a strong bond. Nozzle wall coatings may help to reduce attachment <sup>[1]</sup>.

The best way to avoid this source of clogging is to minimize the number of solid inclusions passing through the nozzle. Inclusions making up a clog would otherwise end up in the final product, where they often have the same composition and structure <sup>[7]</sup>.

1.1) Careful refining practices can minimize the quantity of deoxidation products. For example, vacuum degassing greatly lowers average inclusion levels, relative to conventional argon bubbling. In addition, ladle and tundish slag composition should be designed to have a low enough oxygen potential to absorb inclusions, while not being so reactive that steel composition is altered. Late aluminum additions are dangerous because the small inclusions which form will not have sufficient time to agglomerate and be removed. Luyckx suggests that aluminum should only be added at tap when the oxygen content is high and the inclusion morphology enables easy flotation <sup>[8]</sup>.

After the last alloy additions, it is suggested to first stir vigorously for a brief time in order to encourage mixing and collisions for the inclusions to agglomerate (Fig. 1) <sup>[9]</sup>. Argon bubbles are better than electromagnetic stirring <sup>[2]</sup> because they contribute greatly to the attachment, agglomeration, and flotation removal of the inclusions <sup>[9]</sup>. Then, a long period of gentle stirring or simple natural convection should follow, to allow time for the inclusions transport to the slag or wall surfaces and be removed (See Fig. 2 <sup>[9]</sup>). Without enough of this gentle “rinse” time, further collisions would generate more detrimental large clusters to be sent into the tundish. Finally, an optimized tundish flow pattern with a basic slag is helpful as the final refining step prior to entering the tundish nozzle.

1.2) Reoxidation products are caused by the exposure of the molten steel to air. Reoxidation during ladle treatment can be avoided by providing an adequate slag composition and thickness and then avoiding excessive stirring that opens up “eyes” in that slag cover. Reoxidation during steady tundish operation is easy to avoid with a non-porous slag cover and with ladle nozzles and baffles to avoid excessive surface turbulence. Reoxidation during ladle opening and tundish filling is a much greater problem that requires great operational care, as discussed elsewhere <sup>[2, 10]</sup>. In particular, it is important to use a submerged ladle shroud (preferably bell shaped) throughout, maintain minimal turbulence during tundish filling, add a tundish slag that quickly forms a continuous liquid layer, use a tight sealing tundish cover, and even purge the tundish with argon prior to filling.

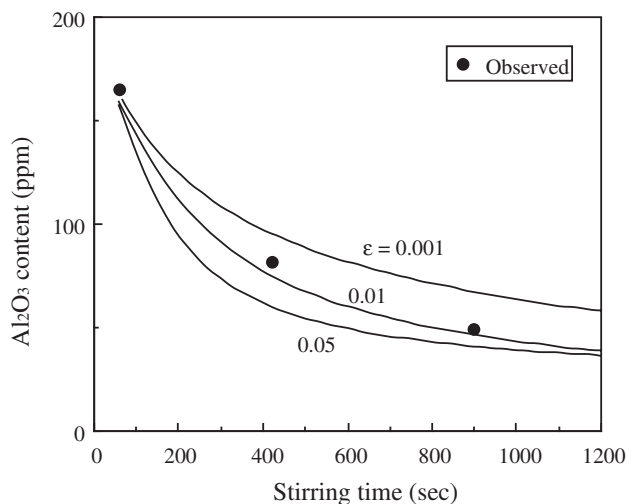


Fig. 1 Decrease in alumina content with stirring time in an RH degasser (calculations and measurements) [9]. Increasing stirring intensity (indicated by turbulence dissipation rate  $\epsilon$ ) encourages faster inclusion removal.

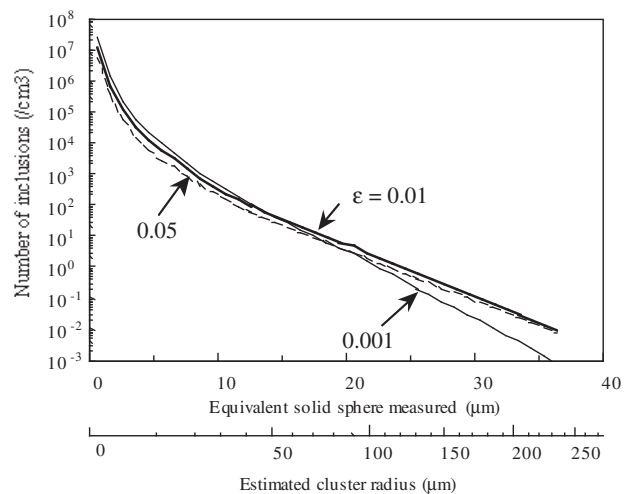


Fig. 2 Inclusion size distributions calculated after 900s stirring in an RH degasser. Lowering stirring intensity  $\epsilon$  decreases collision rates, so fewer large inclusions form and removal processes can lower their numbers [9].

1.3) Slag entrapment is avoided firstly by minimizing slag carryover [2, 7, 10]. A sensor to consistently detect the presence of slag is essential in this regard. Care is required during ladle exchanges when slag may become entrapped in the tundish in several ways, including stream impingement on the slag layer and vortexing [11]. Tundish flow control using baffles and weirs, a pour box or impact pad is important to give any entrained and emulsified slag a chance to float out. Finally, it is important to maintain adequate submergence of the tundish nozzle because mold slag can be drawn into the top of the ports due to the recirculation flow pattern in the upper part of the mold and due to the tendency of the flux to coat the nozzle [10]. Once it is deposited on the nozzle walls, entrapped slag collects other inclusions, thereby exacerbating clogging [7]. Clogs caused by slag entrapment are easy to identify by matching the average composition of the inclusion particles with either the ladle, tundish, or mold slag compositions.

1.4) Exogenous inclusions come from many sources apart from slag entrapment [7]. Loose ceramic material, mortar, and dirt can be picked up when steel first flows over the refractory surfaces. Ladle packing sand can become entrained in the flowing steel. Ladle, nozzle, and tundish wall refractory material, and existing oxide deposits can become dislodged and entrained also. These particles are identifiable from their large size and unusual shapes. Great care must be given to refractory preparation, assembly, maintenance, and cleanup. Filtration [12, 13] and electromagnetics [14] are also effective solutions, but are costly and catch only a limited number of particles.

1.5) Chemical reactions generate solid inclusions in many different ways [2]. For example, ladle slags with high FeO or MnO content often have sufficient oxygen potential to react with aluminum in the steel to form alumina. This is correlated with increased clogging. Magnesium residuals in the steel, in the aluminum alloy additions, or in the tundish liner can react to form magnesium aluminate spinels. Titanium reacts to form inclusions which are particularly prone to clogging, perhaps due to their effect on surface tension. Calcium is often added to avoid clogging by keeping the inclusions liquified in the molten steel. Improper calcium treatment can worsen clogging, however, by producing solid inclusions if the calcia content does not almost match the alumina mass. Too little calcia causes clogs with calcium-aluminates (eg.  $\text{CaO} \cdot 6\text{Al}_2\text{O}_3$ ), while too much calcium produces calcium sulfides, even in low S steel. Calcium treatment is best after alumina and especially sulfur have already been minimized. It is also important to control the slag composition (eg. maintain 2% FeO) and to rinse stir

both before and after Ca addition [2]. Finally, it is important to choose refractory compositions which are compatible with the steel, or they may be eroded to form inclusions [15].

**2. Air aspiration into the nozzle** - Air aspiration into the nozzle through cracks and joints leads to reoxidation, which is an important cause of inclusions and clogging [4, 16]. While regulating the liquid steel flow, the flow control device creates a local flow restriction which generates a large pressure drop, (Fig. 3). This “venturi effect” creates a low-pressure region just below the slide gate or stopper rod. This minimum pressure region can fall below 1 atm (zero gauge pressure) according to both water model measurements [16, 17] and calculations [18]. This allows air to be drawn into the nozzle. The rate of air ingress can be huge, approaching that of the steel flow rate for a pressure of  $-0.30$  atm ( $-30$  kPa) [19]. The minimum pressure is affected by argon injection, tundish bath depth, casting speed, gate opening, shape of the surfaces, and clogging, which will be discussed later.

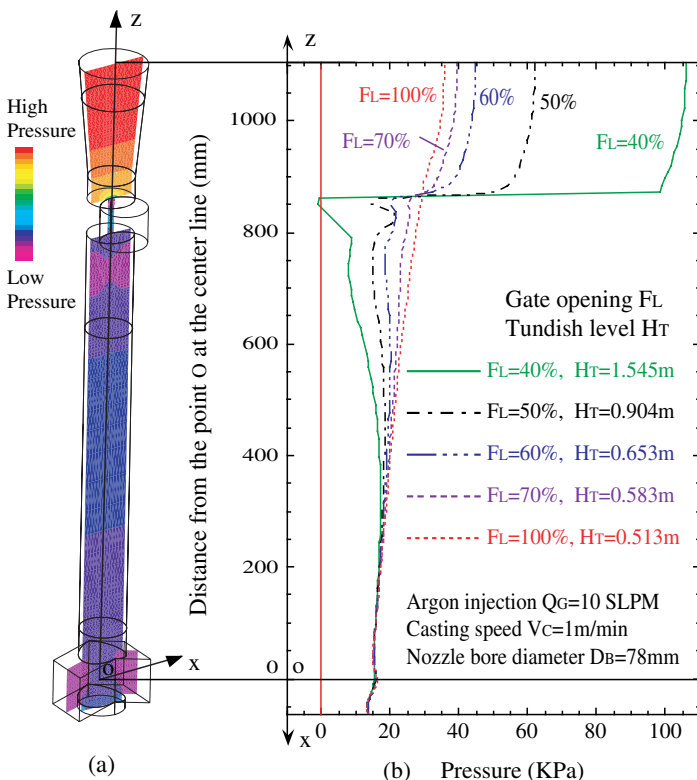


Fig. 3. Pressure distribution in a standard tundish nozzle calculated by the computational flow model described in Appendix I for conditions in Table A1 [20] a) shaded contour plot; b) pressure profile along the nozzle centerline. Note that increasing tundish height causes the gate opening to restrict, which decreases the minimum pressure found just below the sliding plate.

Clogs caused by air aspiration can be identified in several ways. Firstly, if the inclusions are large and dendritic in structure, this indicates that they formed in a high oxygen environment, such as found near an air leak in the nozzle. Secondly, an erratic or low argon back pressure during casting likely indicates a crack, leak, or short circuiting problem that could allow air aspiration. Finally, nitrogen pickup in the steel between the tundish and mold indicates exposure to air. Rackers calculates that 5ppm nitrogen pickup is accompanied by enough oxygen to clog a typical nozzle (1-m long and 20-mm thick alumina clog) in seven 250-ton heats [3].

If air enters the nozzle, the oxygen will react with aluminum in the steel locally to form alumina inclusions. The aspirated oxygen also may create a surface tension gradient in the steel near the wall. This can generate surprisingly large forces attracting particles towards the nozzle walls. Rackers calculates that even the small oxygen concentration gradient accompanying a 0.3 ppm nitrogen pickup could generate surface tension forces that could accelerate a 10 micron inclusion particle to a velocity of 0.9 m/s towards the nozzle wall [3]. This is likely the dominant clogging mechanism in regions of low turbulence and nonrecirculating flow. Thus, it is critical to avoid air aspiration.

Air aspiration can be addressed through several nozzle design and operating practices. The nozzle refractory must maintain a stable nonporous barrier that does not allow air to diffuse through it even after thermal cycling [21, 22]. Use tight tolerances for all nozzle joints. When assembling the nozzle, smooth and clean all joint surfaces and employ non-cracking, non-porous mortar. Avoid joint movement by holding the nozzle in place with a strong steel support structure [23]. Check the argon gas line for leaks that might entrain air and monitor the oxygen content of the argon. Finally, argon gas injection should be optimized, as discussed later in this article.

**3. Chemical reaction between nozzle refractory and steel** – Some clogs appear as a uniform film, rather than a sintered network of particles. These clogs are attributed to reactions between aluminum in the steel and an oxygen source in the refractory. This oxygen may come from carbon monoxide when carbon in the refractory reacts with binders and impurities [2] or from silica refractory decomposition [21-25]. Controlling refractory composition (eg. avoid Na, K, and Si impurities) or coating the nozzle walls with various materials, such as pure alumina [24] or BN [15, 25, 26] may help to prevent this and other clogging mechanisms.

Controlling chemical reactions at the refractory / steel interface has also been suggested as a countermeasure to clogging. Incorporating calcia into the nozzle refractory may prevent clogging by liquifying alumina inclusions at the wall, so long as CaO diffusion to the interface is fast enough and nozzle erosion is not a problem [27-29].

**4. Steel solidified in the nozzle** - Although heat losses from the nozzle refractories are very small, steel may freeze within the nozzle either at the start of cast, if the nozzle preheat is inadequate [3, 30], or within a clog matrix, where the flow rate is very slow. These problems are more likely if the steel superheat is very low, or the alloy freezing range is very large.

Figure 4 shows the temporary buildup of solid steel calculated on the nozzle wall at the start of casting for several different steel superheats [3]. Freezing occurs initially because the preheated nozzle wall temperature is significantly below the steel solidus. The nozzle walls heat up within a few minutes to melt this layer away, however, but clogging may start if another mechanism is triggered.

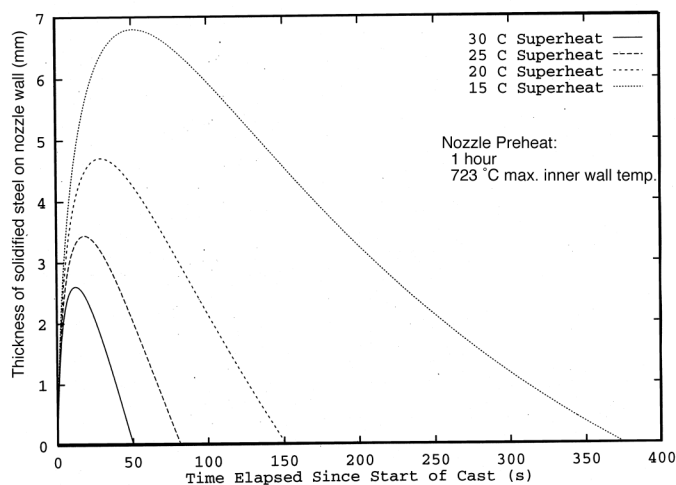


Fig. 4 Transient skull formation during startup due to insufficient nozzle preheat [3]

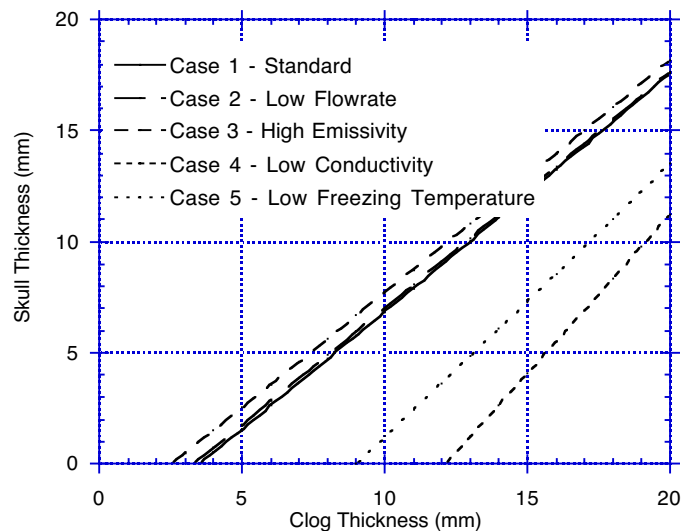


Fig. 5 Coupled inclusion and steel clog growth during steady casting [3]

Clog networks can grow more easily when they are supported by a matrix of solidified steel [1]. Some clogs consist solely of dense concentrations of oxides, as surface tension rejects steel from inner spaces. Other clogs consist of a network of small oxide particles which contain steel [5, 6, 27], especially for high carbon steels [10]. These clogs appear to form by first collecting and sintering together a network of oxides against the nozzle wall. [21, 23, 31]. After an initial clog layer of 3-12 mm thick has built up, the liquid steel trapped within it flows so slowly that it may start to solidify, as shown in Fig. 5 (depending on the flow and thermal conditions [3]). This strengthens the otherwise weak inclusion network and allows it grow further into the liquid, filtering inclusions from the steel flowing through it as it grows. Figure 5 shows the coupled buildup of the skull and clog layer

thicknesses during clogging. Only the innermost 3-12 mm of the inclusion network must be strong enough to withstand the drag of the turbulent steel flowing through it. As the roughness of the clog surface increases, the probability of intercepting and entraining particles increases and clogging may accelerate<sup>[4, 15, 32]</sup>.

## CLOG IDENTIFICATION

A score of different practices are helpful to minimize clogging<sup>[2]</sup>. The remedies may be classified as inclusion prevention, inclusion modification (Ca treatment), nozzle material / design improvement, and argon injection<sup>[1]</sup>.

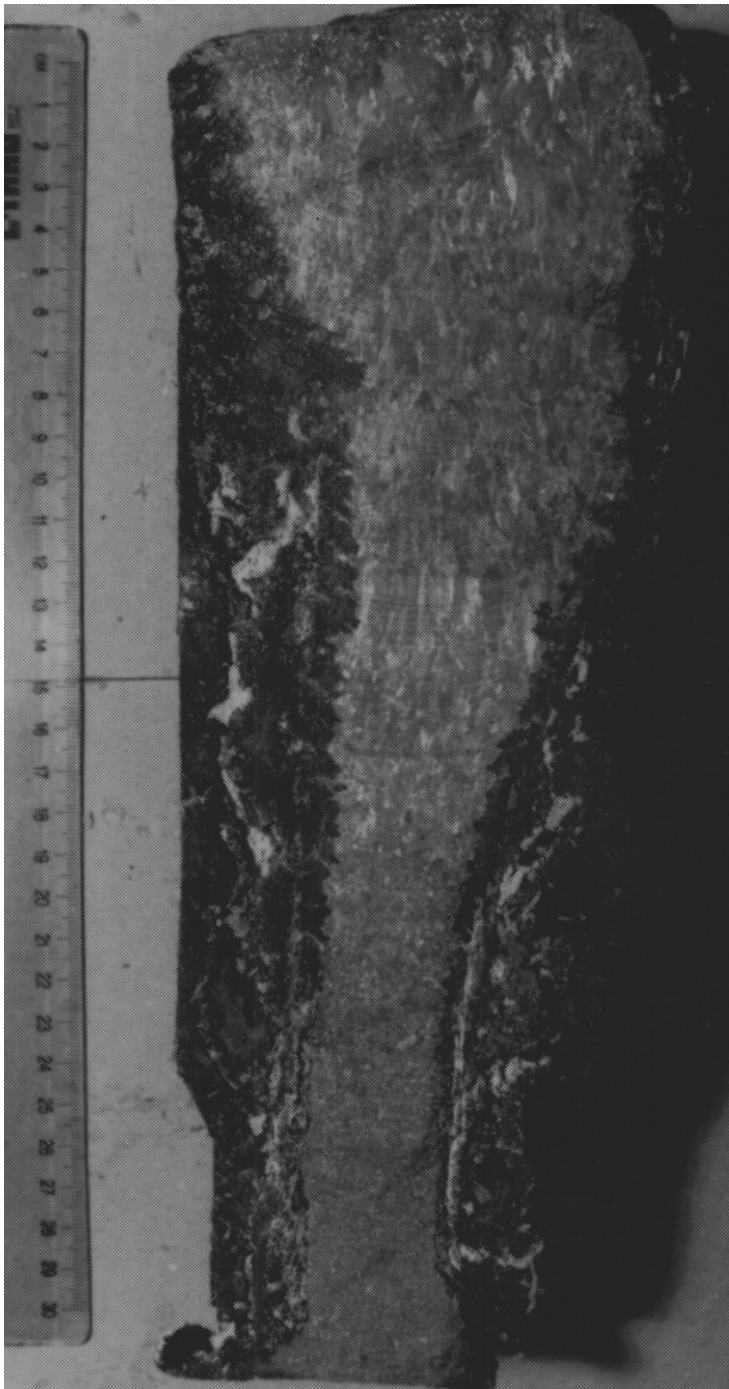


Fig. 6. Sample clog in upper tundish nozzle, (50% HCl macro-etch)<sup>[3]</sup>

The best remedial action depends on the steel grade and exact cause of the specific clogging problem being considered. Thus, the first step is to identify the clogging cause by monitoring important parameters during casting and by visual, microscopic, and chemical examination of clogged material.

A lot can be learned about the cause of clogging from careful visual inspection and analysis of the clog itself. An example clog in the upper tundish nozzle above the slide gate of a typical slab-casting operation is pictured in Fig. 6<sup>[3]</sup>. Clogs above the slide gate, such as this one, are particularly disruptive because they require a tundish change.

This particular clog was retrieved after casting five 250 ton heats of 0.0023%C steel containing 0.039% acid soluble Al<sup>[6]</sup>. Argon was injected at 6.5 l/min through a porous ring in a standard alumina-graphite nozzle with a measured back pressure of 14 kPa. This suggests that reoxidation from a leak in the refractory was not the problem in this example.

The light central area is steel that solidified after the slide gate was closed. The darker clogged regions on the sides generally contain alumina mixed within solidified steel. This indicates that the clog material had a sufficiently low volume fraction to be porous to molten steel (below about 17%)<sup>[3]</sup>.

An SEM analysis revealed that the alumina was coral-shaped and likely originated from deoxidation products that clustered and sintered together<sup>[6]</sup>. If the coral structure had resulted from the ripening of large dendritic clusters, this would indicate inclusion form-

ation in an oxygen-rich environment and would indicate a reoxidation problem, such as could occur from ladle opening problems, or from air aspiration into the nozzle. A few severely-clogged regions in Fig. 6 contain no steel and appear to result from ladle packing sand and tundish slag that was trapped during ladle transitions [6].

The shape of the clog appears to follow the contour of the steel flow through the nozzle. The shape at the top of the clog may have been altered during casting when a rod was inserted through the tundish in an unsuccessful and ill-advised attempt to dislodge it. The asymmetrical shape of the lower portion suggests that clog material tends to collect in the more stagnant regions just above the slide gate opening (bottom of Fig. 6). It also suggests that small heat losses from the stagnant steel within the clog matrix in these regions might allow it to solidify, thereby strengthening the clog and helping it to grow further [3].

Clogging was reduced in the operation of this example by making several practice changes and operating improvements [6]. In particular, the ladle opening practice was improved by redesigning the ladle to tundish shroud system and decreasing ladle slag carryover [6]. In addition, the tundish well preheating time was increased to avoid cracks in the ceramic due to thermal shock [6] and perhaps also to reduce initial skulling [3].

This type of analysis is vital to identify the cause of a clog so that proper corrective action can be taken in the plant. However, it is also important to identify clogging during casting so that potential quality problems in the cast product can be minimized or at least anticipated. In addition, realtime feedback can help in the assessment of clogging countermeasures.

## CLOGGING DETECTION

Clogging can best be detected during casting by simultaneous monitoring of several different parameters in real time: argon back pressure, nitrogen pickup, mold level fluctuations, and flow control position relative to casting speed.

**1) argon back pressure** - The argon back pressure is an excellent early indicator of potential air aspiration problems. Abnormally low or sudden drops in back pressure indicates that argon is short circuiting and there may be a crack or leak in the refractory allowing air aspiration somewhere. Increases in back pressure might indicate clogging over the nozzle pores, causing increased resistance to argon injection.

**2) nitrogen pickup** – As previously mentioned, increases in nitrogen content between steel in the tundish and the mold indicate the extent of reoxidation problems in the tundish nozzle.

**3) mold level fluctuations** - Increased clogging causes an increase in metal level fluctuations in the mold. This is documented in Fig. 7. These are caused by difficulties with the flow control trying to accommodate changes in the pressure drop required to maintain a constant flow rate into the mold. Subtle changes in the shape of the flow passage caused by clogging or nozzle erosion cause significant changes in the pressure drop. This is illustrated in the results given in Figs. 8 and 9.

Figure 8 shows flow vectors through four similar nozzles using the model described in Appendix I for the conditions in Table AI. The only differences involve the geometry near the slide gate. In each case, turbulent recirculation zones with high gas concentration are found just above and below the slide plate and in its cavity [33-35]. These recirculation zones and the sharp edges of the slide gate surfaces generate a large pressure drop, requiring a 52% gate opening, with no clogging (case a).

Slight erosion by the flowing steel may round off the ceramic corners (case b). This lowers the pressure drop (Fig. 9b) and requires the gate opening to close slightly (unless the tundish level drops as shown).

Alternatively, clogging tends to buildup initially in the recirculation regions<sup>[1]</sup> (case c). Initial clogging of this shape may streamline the flow path and decrease the total pressure drop across the nozzle. Again, the gate must close to accommodate this. Further clogging produces further streamlining and smaller pressure drops (case d). A comparison of these predictions with the plant measurement suggests that some rounding, initial clogging, or both occurred in practice. Because the changes in flow resistance vary greatly with small changes in the clog shape, the flow control does not always respond appropriately, and the resulting changes in flow rate cause level fluctuations.

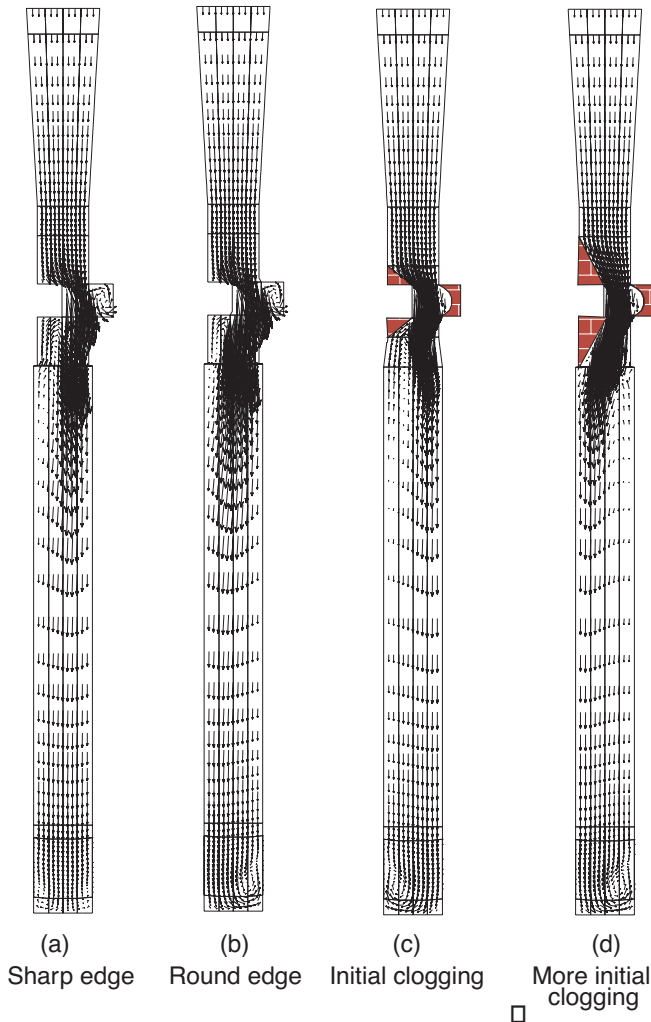


Fig. 8. Effects of initial clogging and rounded edges on nozzle flow pattern (center plane parallel to the narrow face) for Validation Nozzle B.

The clogging condition and edge roundness affects not only the pressure drop across the nozzle but also the jet condition exiting the ports. The jets in Fig. 8 vary from two small symmetric swirls to a single large swirl which can switch rotational directions. These changes will produce transient fluctuations in flow in the mold cavity which further contribute to level fluctuations.

To compensate for the pressure variations caused by initial clogging or erosion, the position of the flow control device (slide gate or stopper rod) must move. Because mass flow and jet angle from the nozzle ports changes with these movements (Fig. 10), this compensation will produce transient flow asymmetry in the mold.

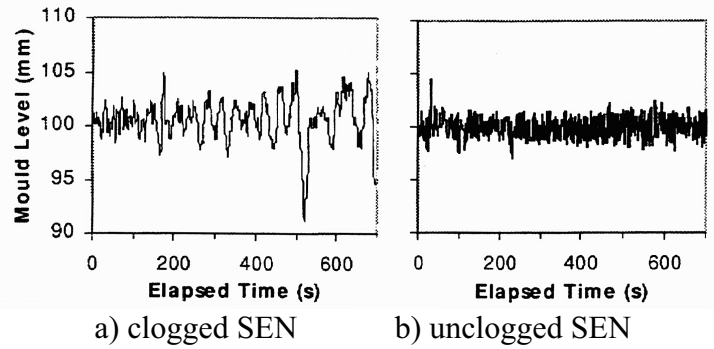


Fig. 7 Effect of clogging on severity of mold level fluctuations<sup>[36]</sup>

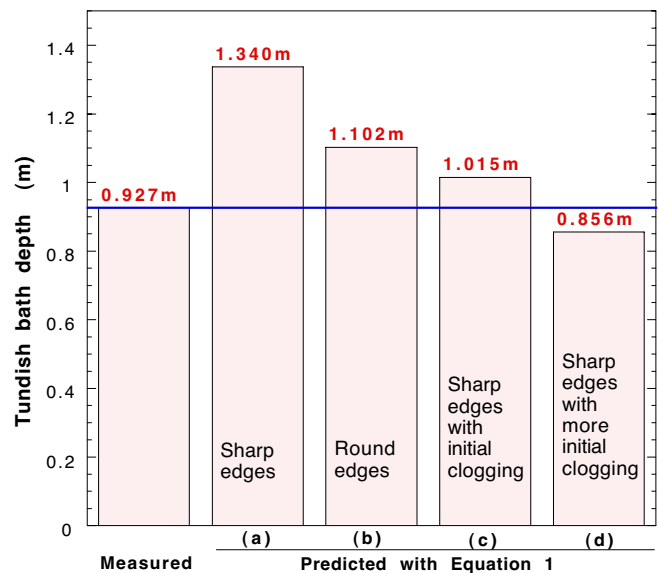


Fig. 9. Effects of initial clogging and rounded edges on tundish bath depth (Validation Nozzle B)



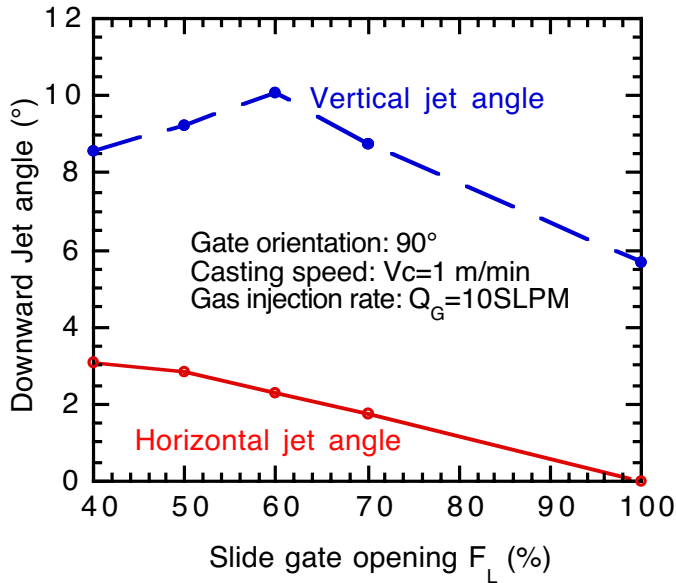


Fig. 10 Effect of gate opening fraction on jet angles exiting port into mold

Together with the changes in flow pattern exiting the ports, this will produce transient fluctuations in flow and level in the mold. Thus, initial nozzle clogging can be detected by monitoring these detrimental level fluctuations. Unfortunately, the severity of level fluctuations is affected by many other disturbances, so this is not a fully reliable measure of clogging severity.

#### 4) flow control position relative to casting speed –

With increasing alumina buildup, the clogging no longer streamlines the flow, but begins to restrict the flow channel and create more flow resistance. The gate opening then must increase to maintain constant liquid steel flow rate through the nozzle. This fact can be exploited to infer the severity of clogging in realtime by comparing the measured flow rate with the flow rate predicted for the given position of the slide gate or stopper rod in the absence of clogging. This flow fraction or “clogging factor” may be obtained empirically, or with the aid of computational models.

To develop an accurate clogging factor, it is important to accurately predict the relationship between casting speed, argon injection flow rate, gate opening position and tundish bath depth for the given geometry in the absence of clogging. Figure 11 shows the relationship between these variables, calculated for slab casting with

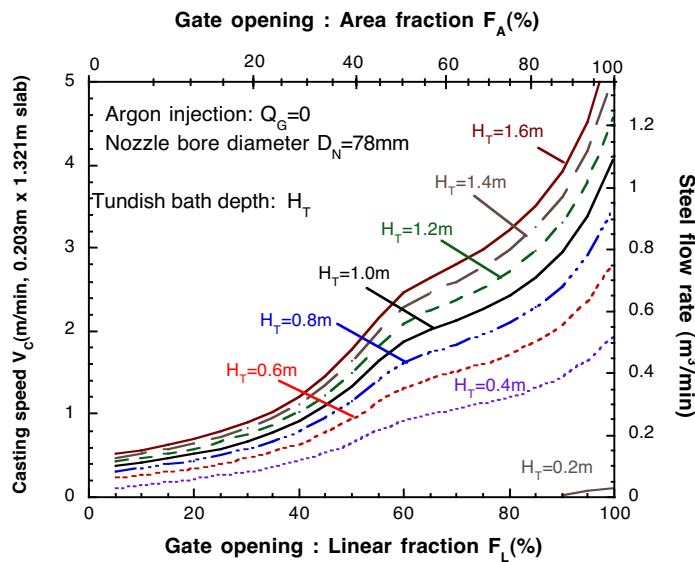


Fig. 11. Relationship between gate opening fraction, steel flow rate, and tundish depth (standard nozzle in Table AI with no gas injection [37])

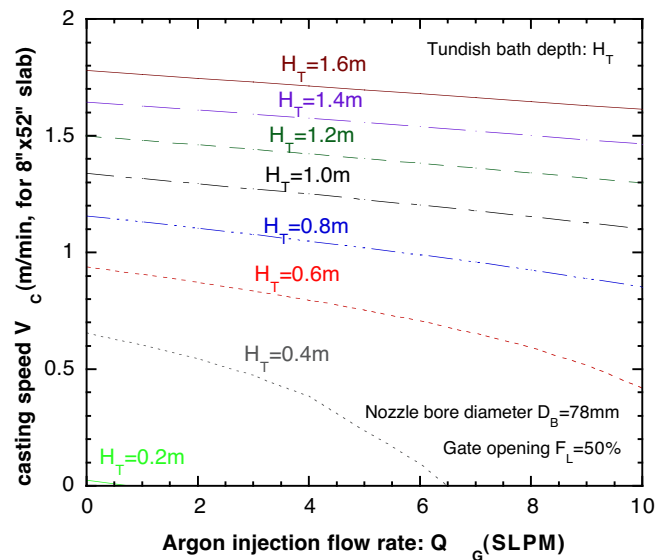


Fig. 12. Effect of argon gas injection (into the upper tundish nozzle) on decreasing steel flow rate (for a given tundish depth and gate opening) [37]

a typical slide gate nozzle (Appendix I and Table AI). During a stable casting process, tundish depth and argon injection rate should be kept constant. Gate opening is regulated to compensate for other effects such as clogging. For a given nozzle geometry and gas flow rate, higher casting speed is naturally produced from either a deeper tundish bath depth or a larger gate opening. Flow rate is particularly sensitive to changes in gate openings around either 50% or 100%. Injecting argon into the upper tundish nozzle (above the slide gate) tends to decrease casting speed (see Fig. 12) unless the gate opening increases to compensate.

Predictions from the model (Appendix I [18]) are compared with plant data in Fig. 13. Several thousand data points were recorded over several months [38]. Only first heats in a sequence were recorded in order to minimize the effect of clogging. The tundish bath depth was held constant ( $H_T=1.125\text{m}$ ) for these data, and the argon injection ranged from 7 to 10 SLPM. Gate opening  $F_P$  is related to linear gate opening,  $F_L$ , by  $F_P = (1-24\%)F_L + 24\%$  and the steel throughput (tonne/min) is 1.8788 times greater than casting speed (m/min.). The model matches the larger extreme of the range of measured gate opening percentage for a given steel throughput. This is likely because argon flow was slightly lower in the plant, the nozzle geometry was rounded, and, most importantly, there may have been some clogging.

The effect of clogging on the flow depends on both the size and shape of the clog. Many clogs in the nozzle bore are radially symmetrical [1]. These clogs likely have a similar effect to reducing the effective diameter of the nozzle bore. The effect of this type of clogging (or decreasing bore size) is quantified in Fig. 14. Gate opening must increase to accommodate clogging (or decreasing bore size) in order to maintain a constant flow rate for a fixed tundish level.

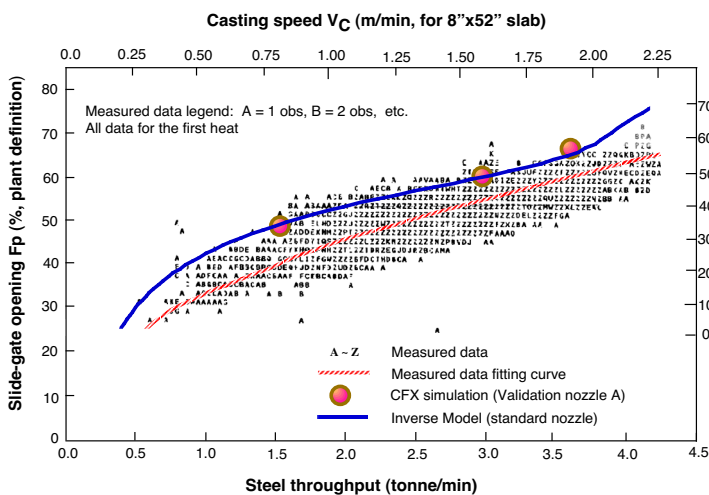


Fig. 13. Plant measurements of steel flow rate relationship with gate position, compared with model predictions (Validation Nozzle A)

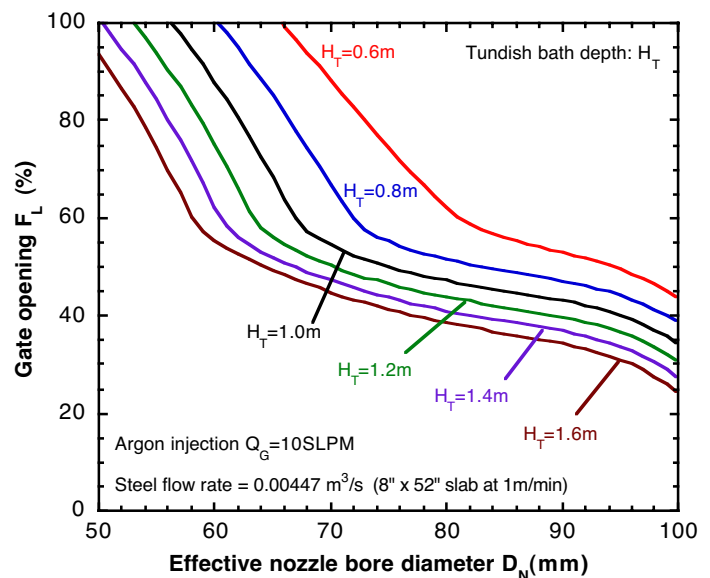


Fig. 14. Gate opening changes to accommodate clogging (decreased nozzle bore size) for fixed gas flow rate and casting speed

The gate opening is much less sensitive to clogging when the bore diameter is large and the gate opening is small (Fig. 14 lower right). This is because the flow resistance of the bore is much smaller than that of the flow control region, so long as the bore area is larger than the gate opening. Thus, initial bore clogging is difficult to detect from gate position changes. For the specific conditions in Fig. 14, clogging does not have a significant effect on steel flow until the linear gate opening exceeds 60%.

If clogging proceeds first in recirculation zones, then radially around the bore, while the gate opening itself remains free of buildup, then the effect on throughput is complicated, as shown in Fig. 15. The streamlining effect of the initial clogging first increases the throughput obtained for a given gate position. (In practice, maintaining throughput requires a smaller gate opening, explaining the variations in Fig. 13.) Figure 15 shows that throughput drops relatively little with increased clogging fraction until the effective bore area is reduced to nearly the gate opening area (depending on gas injection rate). During this time, a constant rate of clogging buildup might go undetected. Finally, further clogging causes a steep drop in throughput, as severe clogging restricts the flow. For the typical (standard) conditions in Fig. 15, throughput does not suffer from clogging until nearly 50% of the nozzle is full of clog material! Thus, clogging severity inferred from changes in flow rate for a given gate position must be used with great caution, based on careful modeling, validation, and interpretation with the help of other signals.

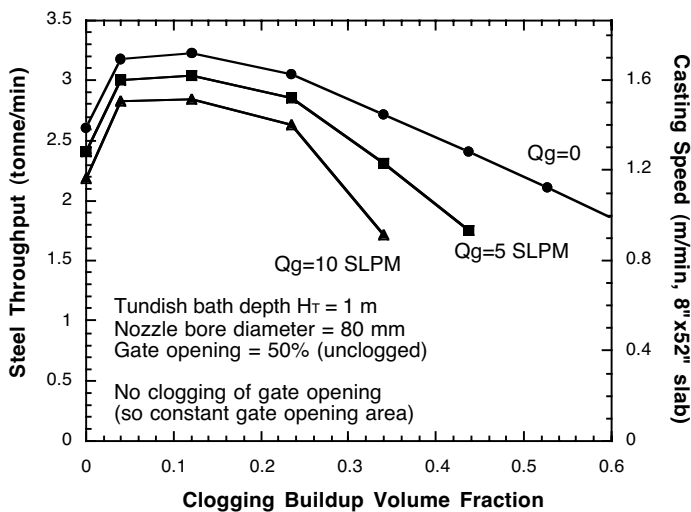


Fig. 15. Effect of clogging buildup on steel throughput (assuming constant gate opening area) [3]

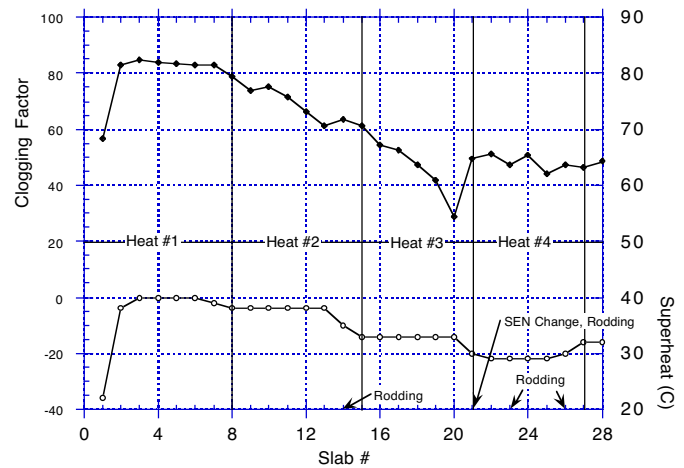


Fig. 16. Real time tracking of clogging factor and superheat for sample clog in Fig. 2 [3]

An example of real time tracking of an empirical clogging factor is shown in Fig. 16 over 4 heats [3]. The initial flow is significantly less than 100% (unclogged), suggesting that significant clogging occurred near the start of casting or perhaps there were model calibration errors. Clogging generally becomes more aggravated with time, as indicated by the decreasing clogging factor prior to the SEN change. Rodding did little to improve the flow and is discouraged.

Note that the superheat also decreases over this time interval, although this may be coincidence. The lack of a consistent trend with superheat is likely because other factors are much more important, such as the total number of inclusions carried with the steel. In addition, the greatest drops in superheat occur briefly in the nozzle during transitions and do not correlate well with average superheat in the tundish.

## ARGON INJECTION OPTIMIZATION

Argon injection into the nozzle is widely employed to reduce nozzle clogging. Argon is often injected into joints and through circumferential porous slits inside the nozzle bore and enters the steel using either the natural pores in the ceramic <sup>[23, 39-41]</sup> or tiny holes drilled in the refractory <sup>[21, 23, 42]</sup>. A typical injection rate is 5 liter/min (STP) <sup>[26]</sup>. Several different mechanisms have been suggested for the improved clogging resistance:

- A film of argon gas forms along on the nozzle wall to prevent inclusion contact with the wall <sup>[17, 39]</sup>. This mechanism is likely only at very high gas flow rates <sup>[37]</sup> and likely also causes flow disruptions in the mold <sup>[43]</sup>
- Argon bubbles attach to the inclusions and carry them away <sup>[21]</sup>.
- Argon gas increases the turbulence, which dislodges delicate inclusion formations from the nozzle walls and breaks up detrimental concentration and surface tension gradients near the nozzle wall <sup>[44]</sup>. It is noted that this mechanism may sometimes be detrimental by increasing particle contact with the walls and enhancing deposition.
- Argon gas reduces air aspiration and reoxidation by increasing pressure inside the nozzle <sup>[10, 17, 18, 41]</sup>. Argon supplied through porous slits or into joints also helps by replacing air aspiration with argon aspiration.
- Argon retards chemical reactions between the steel and the refractory <sup>[2, 21]</sup>.

Argon greatly changes the flow pattern in the mold <sup>[45, 46]</sup>. Too much argon can cause the liquid and gas phases to separate, resulting in unstable flow and transient level fluctuation problems in the mold. <sup>[43]</sup> Excessive argon also may cause quality problems from bubble entrapment. Thus, it is very important to optimize the argon flow rate.

Argon may be injected into many locations, including the upper nozzle, upper plate, lower plate, collector nozzle, and SEN. A small argon flow should always be maintained around joints, (especially those between the slide-gate, the lower plate, and the SEN holder) to ensure that aspirated gas is argon and not air. The injection location makes a big difference to the pressure profile and corresponding air aspiration tendency. Injecting gas above the flow control (ie. into the upper nozzle) allows the constriction to open in order to accommodate the desired liquid flow. This lowers the venturi effect, so increases the minimum pressure and should be beneficial in avoiding air aspiration <sup>[18]</sup>. The magnitude of this effect depends on the tundish depth and casting speed, as quantified in Figs. 17 and 18. Injecting gas just below the flow control (ie. into the SEN) increases the venturi effect, which causes even lower pressures, so may aggravate aspiration <sup>[19]</sup>.

Many different criteria should be considered when designing an argon injection system. One such criterion is the argon injection rate which maintains at least one atmosphere pressure throughout the nozzle, so that air aspiration is avoided. Simulations were performed to investigate the effect of argon injection rate and casting speed on this “vacuum problem” for different fixed tundish depths and nozzle bores, using the computational flow model described in Appendix I and the standard nozzle in Table AI.

Figures 17 and 18 quantify how increasing argon injection and decreasing tundish bath depth both always tend to decrease the pressure drop across the slide gate, thereby raising the minimum pressure in the nozzle and making air aspiration less likely. The corresponding gate openings, along with both “cold” and “hot” argon injection volume fractions, are also provided for reference.

The worst aspiration problems are found at intermediate casting speeds, for a given nozzle, tundish depth, and gas flow rate. This is because higher steel flow rate tends to increase the pressure drop and vacuum problems. At the same time, increasing the flow rate allows the gate to open wider, which tends to alleviate vacuum problems. The worst vacuum problems occur at a linear gate opening of about 60%, regardless of casting speed. Increasing the gate opening above this critical value decreases the throttling effect, so vacuum problems decrease with increasing casting speed. Below 60% gate opening, the effect of lowering the casting speed dominates, so that vacuum problems reduce with decreasing speed. A further effect that helps to increase pressure at lower casting speed is that the gas percentage increases (for a fixed gas flow rate).

The common practice of employing oversized nozzle bores to accommodate some clogging forces the slide gate opening to close. Although this makes the opening fraction smaller, the opening area actually may increase slightly. Thus, the tendency for air aspiration due to vacuum problems will also decrease, so long as the linear opening fraction stays below 50%. However, this practice generates increased turbulence and swirl at the nozzle port exits, so should be used with caution.

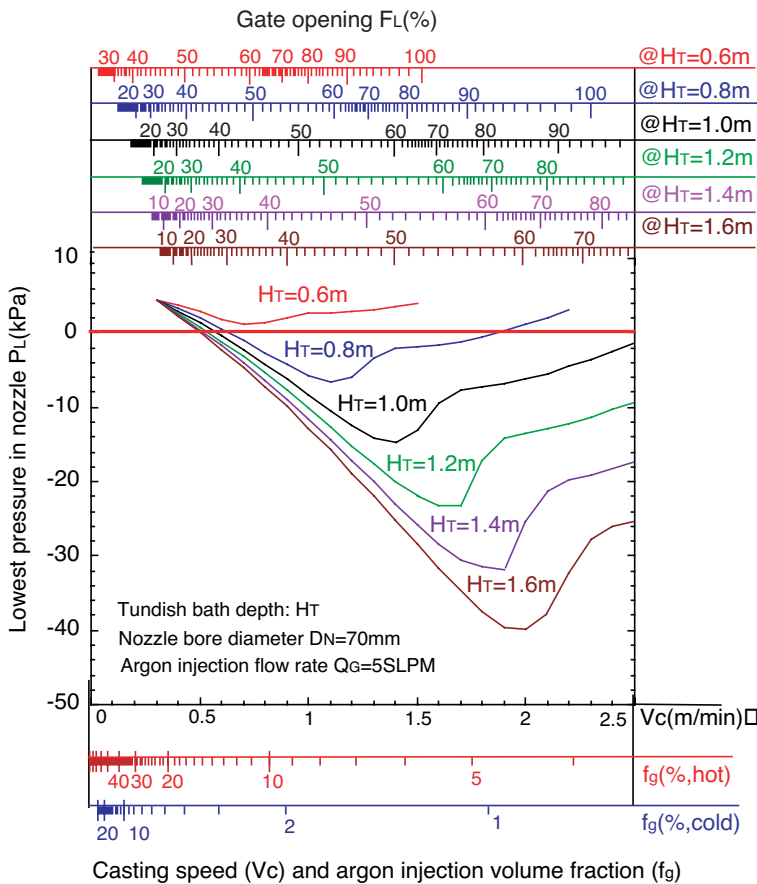


Fig. 17. Effect of casting speed on minimum pressure at various fixed tundish depths in a 70mm nozzle with 5 SLPM argon flow.

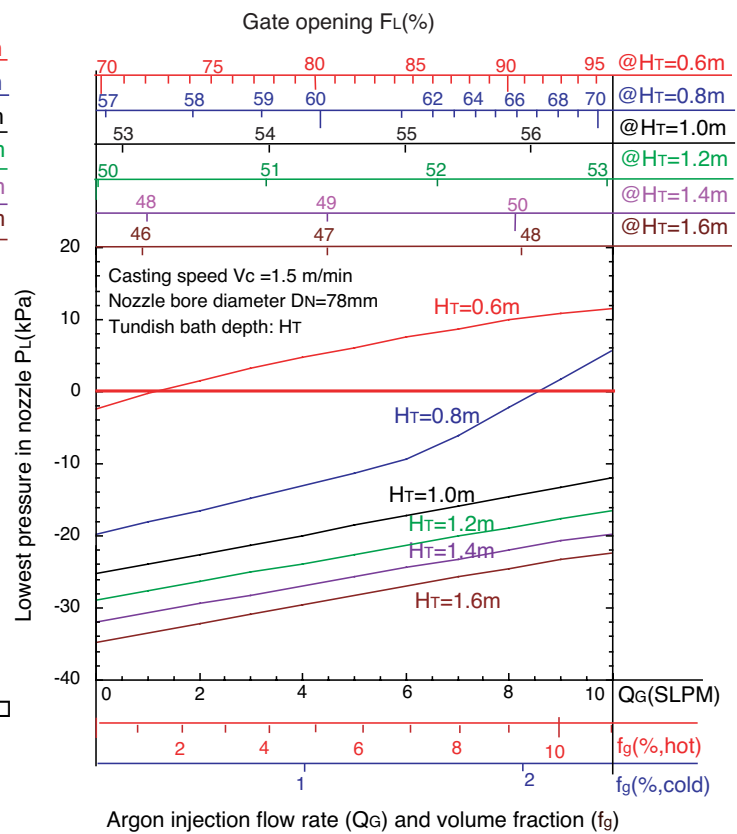


Fig. 18. Effect of argon injection rate on minimum pressure at various fixed tundish depths in a 78mm nozzle at 1.5 m/min. casting speed.

Injecting argon gas raises the minimum pressure and sometimes enables the transition from an air aspiration condition to positive pressure in the nozzle. The minimum argon flow rate required to avoid a vacuum condition can be read from Fig. 19. It increases greatly with tundish bath depth. For a given tundish depth, the minimum argon flow rate first rapidly increases with increasing casting speed, and then decreases with

increasing casting speed. The most argon is needed for linear gate openings of about 60% for the reasons discussed earlier.

The argon injection rate should be greatly reduced during ladle transitions, or at other times when casting speed is low (below 0.5 m/min) or tundish level is shallow (below 0.6m). This is because it is not needed to increase pressure, which is already positive (See Fig. 19). Besides saving argon, this avoids the quality problems associated with high gas fractions.

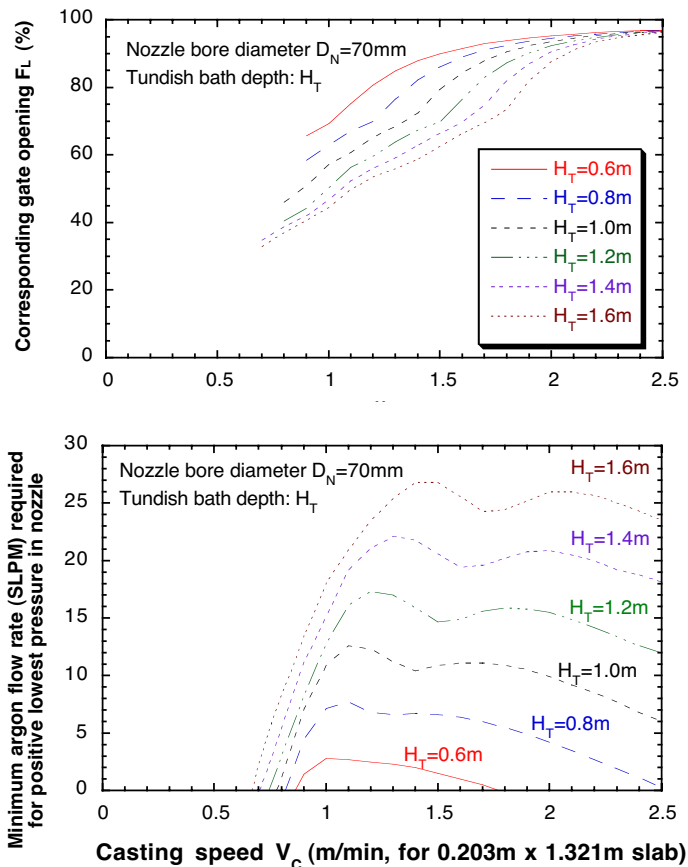


Fig. 19. Effect of casting speed and tundish depth on minimum argon flow rate required for positive pressure in nozzle (bottom) and the corresponding gate opening (top)

Fig. 19 shows that very large argon flow rates (over 15 SLPM for this nozzle geometry) are needed to maintain positive nozzle pressure for deep tundish level (deeper than 1.2m) and high casting speed (above 1.5m/min). At high casting speeds, a 0.2m increase in tundish bath depth typically requires an additional 5 SLPM of argon (roughly 5% increase in hot gas fraction) to compensate the vacuum effect. To avoid quality problems, the argon injection flow rate should not exceed about 15 SLPM (or 20% hot gas volume fraction, which corresponds to less than 5% gas at STP). Therefore, it is not feasible for argon injection to eliminate the vacuum in the nozzle when the tundish bath is deep and the casting speed is high.

Other steps should be taken to avoid air aspiration, such as choosing nozzle bore diameters according to the steel flow rate in order to avoid linear gate openings near 50-70% (about 50% area fraction). Less argon is needed if intermediate casting speeds are avoided so that the gate is either nearly fully open or is less than 50%. To increase gate openings above 70%, a smaller nozzle bore diameter could be used, but this allows little accommodation for clogging. To decrease gate openings to below 50%, a larger bore diameter is needed.

## CONCLUSIONS

Because the nature of steelmaking produces large volumes of liquid containing inclusions, which all channel through a restricted nozzle opening, tundish nozzle clogging is likely to remain a chronic problem of every continuous casting operation. This work has attempted to summarize current understanding of the major causes and cures of nozzle clogging, focussing on the contributions of mathematical modeling.

Clogging problems can be solved by first identifying the cause, through analysis of the clog material. Solutions philosophies are based on minimizing inclusions by improved steelmaking practices, optimizing fluid flow and transfer processes, controlling steel alloy additions, slag and refractory compositions, improving nozzle material and design, and avoiding air aspiration.

Air aspiration problems in the tundish nozzle can be detected by monitoring argon back pressure during casting and by checking for nitrogen pickup between the tundish and mold. Clogging and other quality problems are indicated by level fluctuations in the mold, which result from the changes in the nozzle pressure drop and jets exiting the ports. The extent of clogging can be inferred by comparing the measured steel flow rate with the theoretical value for the given geometry, tundish depth, gas flow rate and percent gate opening. This is not easy because clogging initially increases flow before restricting it. Finally, the argon injection rate should be optimized to prevent air aspiration while fostering good mold flow. The conditions needed to maintain positive pressure in the nozzle are quantified here.

## APPENDIX I – COMPUTATIONAL FLOW MODEL AND CONDITIONS

A three-dimensional finite-difference model has been developed to compute steady two-phase flow (liquid steel with argon bubbles) in tundish nozzles using the K- $\epsilon$  turbulence model. The casting speed and argon injection flow rate are fixed as inlet boundary conditions at the top of the nozzle and the gas injection region of the UTN respectively. For each 3-D simulation, the numerical model calculates the gas and liquid velocities, the gas fraction, and the pressure everywhere in the nozzle. The model equations are solved with CFX4.2 as described elsewhere [18].

Slide gate linear opening fraction  $F_L$  is incorporated into the nozzle geometry. It is defined as the ratio of the displacement of the throttling plate (relative to the just-fully closed position) to the bore diameter of the SEN. Argon is injected into the upper tundish nozzle (UTN) at the “cold” flow rate measured at standard conditions (STP of 25°C and 1 atmosphere pressure). To find the corresponding “hot” argon flow rate needed in the model, this flow rate is multiplied by about 5 [47] to account for the volume expansion of the sudden heating and pressure changes [33, 48]. The most relevant measure of gas flow rate is the hot percentage, which is the ratio of the hot argon to steel volumetric flow rates. Flow through the nozzle is driven by gravity so the pressure drop calculated across the nozzle can be converted into the corresponding tundish bath depth using Bernoulli’s equation, knowing the nozzle dimensions and submergence depth [49].

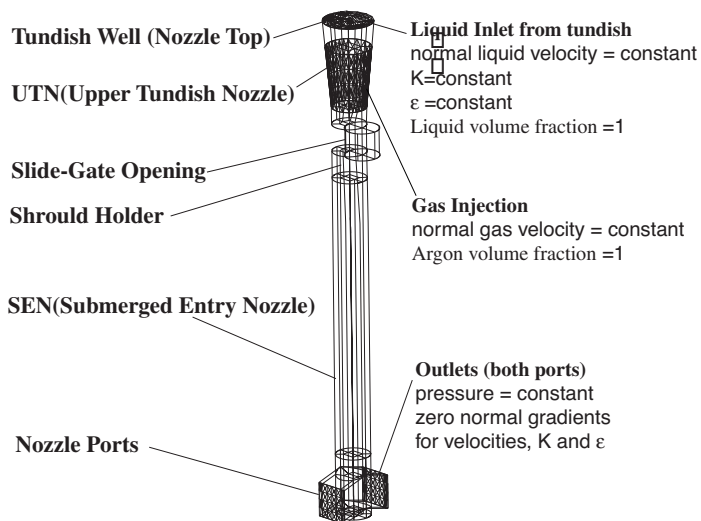


Fig. A1. Standard nozzle terminology and boundary conditions used in computational flow model

The accuracy of flow predictions near the port outlet has been verified both qualitatively by comparison with experimental observations and quantitatively by comparison with velocity measurements using Particle Image Velocimetry [50]. The model has been applied to study the effect of casting speed, argon injection rate, tundish level, and nozzle bore on the flow pattern and pressure drop within the nozzle [18]. The effect of nozzle port geometry and different orientations of the slide-gate has also been studied. [33]. Over 90 simulations were performed using the model, based mainly on the typical slide-gate tundish nozzle shown in Fig. A1, with the standard geometry and operating conditions given in Table AI. The results of this study were extended over a continuous range of operating conditions by curve fitting the 3-D model results and inverting the equation to express the results in arbitrary ways, using an “inverse model” described elsewhere [18].

TABLE AI Nozzle dimensions and conditions

Dimension & Condition	Standard Nozzle	Validation Nozzle A	Validation Nozzle B
Casting speed (m/min, 8"x52"slab)	1.0		1.21
Liquid volumetric flow rate (m <sup>3</sup> /s)	0.00447		0.0054
Liquid mass flow rate (ton/min.)	1.878		2.27
Tundish depth (mm)	904	1125	927
Argon injection flow rate (l/min at STP)	10	7~10	14
Argon bubble diam. (mm)	1.	1.	1.
UTN top diameter (mm)	114	115	100
UTN length (mm)	241.5	260	310
Gate thickness(mm)	63	45	45
Gate diameter(mm)	78	75	70
Gate orientation	90°	90°	90°
Gate opening(F <sub>L</sub> )	50%		52%
Shroud holder thickness (mm)	100	100	66
SEN length (mm)	748	703	776
SEN bore diameter (mm)	78	91~96	80
SEN submerged depth (mm)	200	120 ~ 220	165
Port width X height(mmXmm)	78X78	75X75	78X78
Port thickness(mm)	30	30	28.5
Port angle (down)	15°	35°	15°
Recessed bottom well depth (mm)	12	12	12

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