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CHAPTER 4.3 CONTINUOUS CASTING OPERATION: FLUID FLOW

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Many quality problems that originate during continuous casting can be directly attributed to poor control of fluid flow conditions. This chapter summarizes some of these problems and discusses the effect of continuous casting parameters on controlling the flow. The flow system and its terminology are illustrated in Fig. 4.3.1.

The task of the flow system is to transport molten steel at a desired flow rate from the ladle into the mold cavity and to deliver steel to the meniscus area that is neither too cold nor too turbulent. In addition, the flow conditions should minimize exposure to air, avoid the entrainment of slag or other foreign material, aid in the removal of inclusions into the slag layer and encourage uniform solidification. Achieving these somewhat contradictory tasks requires careful optimization.

4.3.1. Ladle and Tundish Flow

The importance of fluid flow starts in steelmaking and refining vessels including the ladle. The flow objective in these vessels is to encourage uniform mixing of the alloys, to agglomerate inclusions and to encourage their removal into the slag layer at the top surface. Flow is driven by the injection of gas bubbles, or by natural thermal convection. In the absence of gas injection, the differences in density of liquid at different temperatures creates significant flow. This tends to stratify the liquid into distinct layers, where convection cells circulate. The flow challenge then is to optimize the accompanying gas flow to achieve the flow objectives while minimizing problems such as disrupting the surface slag layer.

The tundish provides a continuous flow of metal from the batch ladle operation to the continuous casting machine. It also serves as an important metallurgical reaction vessel, where quality can be improved, maintained, or lost. The flow objective in the tundish is to encourage uniformity and inclusion removal, while avoiding flow-related problems. Tundish flow problems include surface turbulence, short circuiting, dead zones, and

vortexing. Excessive flow directed across the top surface can produce turbulence and lead to reoxidation and slag entrainment. Short circuiting allows incoming steel from the ladle to exit prematurely into the mold with insufficient time for inclusion flotation. Dead zones are stagnant, colder regions which inhibit inclusion removal and can slowly mix and contaminate the new steel flowing through the tundish. If the liquid level is too shallow, high-speed, asymmetric flow may produce vortexing, which can entrain surface slag down into the mold.

Flow behavior in the tundish is governed mainly by the size and shape of the vessel and the location of flow control devices: dams and weirs. The flow pattern is also affected by the steel flow rate and its temperature distribution. Thermal buoyancy tends to lift up the hotter, lower-density flowing steel, while colder steel tends to flow down the walls and along the bottom. A temperature difference of only a few degrees is enough to lift the jet flowing beneath the weir and completely reverse the flow direction in the second chamber of the tundish shown in Fig. 4.3.2.[1-3] Flow in the tundish is also greatly affected by the ladle-tundish nozzle geometry and gas in the ladle stream. Problems related to surface turbulence can be reduced by avoiding excessive argon levels in the ladle stream and by using fully-shrouded and immersed nozzles. A great body of literature on ladles and tundishes, including fluid flow exists elsewhere.

4.3.2. Transfer Systems

Steel flows from the ladle, through the tundish and into the mold where it solidifies, via the path shown in Fig. 4.3.1. Flow between vessels is driven by gravity. Between the tundish and mold, this driving force is proportional to the head of liquid metal between the top surface of the molten metal in the tundish and the metal level in the mold. Control of the flow rate into the mold is achieved by metering nozzles, stopper rods or slide gates.

4.3.2.1 Metering Nozzle Flow Control

The simplest means to control the flow rate is to choose the appropriate size of the opening in the bottom of the tundish that restricts the flow to the desired rate. This inexpensive method is used in conjunction with open stream pouring of lower quality steel, where some air entrainment can be tolerated. Air entrainment can be reduced, but not avoided, by surrounding the stream with argon gas via one of the shrouding methods shown in Fig. 4.3.3.[4] Of these choices, the bellows appears to be the most effective.

Metering nozzles have the disadvantage that variations of the liquid level in the tundish will produce variations in flow rate that must be compensated by changes in withdrawal rate of the strand in order to maintain a constant average liquid level in the mold. A second concern is that the condition of the stream is very sensitive to the flow pattern in the tundish and to any imperfections in the nozzle shape, such as oxide buildup or notches in the outside of the nozzle lip. The condition of the stream is important in open pouring because it directly affects the quality of the final steel product.

Different stream conditions are compared[5] in Fig. 4.3.4. A rough, turbulent stream must be avoided because 1) its irregular shape entrains much more air, leading to more and larger oxide inclusions in the product and 2) it creates fluctuations in the liquid level in the mold when it impacts the surface, leading to nonuniform solidification, surface defects and even breakouts. A tight, smooth stream entrains less air and creates less disturbance of the meniscus region while it penetrates deeper below the liquid surface. Tight streams are thus very desirable. The funnel in Fig. 4.3.3 helps to improve surface quality by substantially lowering meniscus turbulence, although it has little effect on air entrainment.

4.3.2.2 Stopper Rod Flow Control

To avoid reoxidation and produce higher quality steel, a protective ceramic nozzle can be used to shroud the flow of steel into the mold. The flow rate is controlled by restricting the opening with either a stopper rod, or a slide gate. The stopper rod system is illustrated schematically in Fig. 4.3.1 b).

Flow control with a stopper rod is slightly more difficult than with slide gates because the stopper must manipulated through the entire depth of the molten steel in the tundish and the area of the annular opening that controls the flow is more sensitive to displacement. In addition, a continuous nozzle does not allow fast exchange of SEN tubes and requires some other means for emergency flow stoppage. However, the stopper rod offers several significant advantages over slide gates:

1) natural prevention of molten steel from entering the upper tundish well and freezing prior to startup without the need for special flow control devices
2) natural prevention of vortex formation above the tundish well and possible slag entrainment into the nozzle when the liquid level is low
3) easier sealing to avoid air entrainment due to reduced number of moving surfaces
4) more uniform distribution of flow to both ports, so that flow entering the mold cavity is more symmetrical

4.3.2.3 Slide Gate Flow Control

Steel flows into the "upper tundish nozzle", through the slide gate opening, down the long "Submerged Entry Nozzle" (SEN) tube, and through the SEN ports into the mold cavity, as shown schematically in Fig. 4.3.1 a). In the 3-plate slide gate, pictured in this figure, the central plate is moved hydraulically to adjust the opening between the upper and lower stationary plates by misaligning the hole in the sliding plate relative to the nozzle bore. Alternatively, the 2-plate slide gate is missing the lowest plate, so the SEN is attached to the moving plate and travels as the opening is adjusted. This has the disadvantage of continuous variation in the alignment of the nozzle relative to the strand centerline. In both systems, the joints are all flooded with low pressure inert gas (argon) to protect against air entrainment in the case of leaks.

Flow through the slide gate is governed by the size of the overlapped openings of the plates, as illustrated in Fig. 4.3.5. This opening size may be quantified in several different ways. Two popular measures are "area opening fraction", f_A, defined by the ratios of the shaded area to the total bore area, and "linear opening fraction", f_L, defined as the ratio of the distances S to T. For equal sized openings, these different measures of opening fraction are related by:

$$f_A = \frac{2}{\pi}\cos^{-1}\left(1-\frac{L}{D}\right) - \frac{2}{\pi}\left(1-\frac{L}{D}\right)\sqrt{1-\left(1-\frac{L}{D}\right)^2} \qquad (4.3.2)$$

where $\frac{L}{D} = \left(1+\frac{R}{D}\right)f_L - \frac{R}{D}$

f_A = gate opening (area fraction)
f_L = gate opening (linear fraction)
L = length of opening (m)
D = nozzle diameter (m)
R = offset distance from nozzle bore to reference line used to measure S and T (m)

Note that f_A is always slightly less than L/D, while f_L is always more than L/D. The linear opening fraction, f_L in Eq. 4.3.2, simplifies to exactly L/D if R is zero.

The steel flow rate depends mainly on the height of molten steel in the tundish driving the flow and the pressure drop across the slide gate. Flow rate naturally increases with increasing slide gate opening position and with increasing tundish depth, as quantified in Fig. 4.3.6 for typical conditions.[6] The flow rate is also influenced by the nozzle bore size, the amount of gas injection, the constriction of the ports, and the extent of clogging and wear. The flow rate produced under ideal conditions, such as presented in Fig. 4.3.6, can be compared with the measured flow rate in order to identify the extent of nozzle clogging.

4.3.3 Typical Flow Patterns in the Mold

Typical flow patterns for different molds and operating conditions are shown in Fig. 4.3.7. Flow is governed primarily by the condition of the jet entering the mold cavity, but is then affected by the amount of gas injection, the section size, the casting speed, and electromagnetic forces.

In casting square sections with open-stream pouring, stream penetration is generally shallow. The surface is turbulent with high velocity flow towards the meniscus, so entrainment of mold slag is likely. With a straight-through nozzle, stream penetration is very deep and recirculating flow travels a long distance before flowing upwards to the meniscus corners. With a quiet surface, slag entrainment is unlikely with this condition, but the meniscus might become too cold and stagnant. Adding side ports to the straight-down nozzle produces an intermediate condition. With shallow submergence, high casting speed and excessively large side ports, surface turbulence and mold slag entrainment are a danger in small section billet casting with this nozzle. In general, the relative size of the side and bottom ports can be adjusted to optimize the flow condition to avoid defects.

In slab casting, the mold flow pattern varies between the two extremes shown in Fig. 4.3.7. With an upward directed jet exiting the nozzle or a large amount of argon gas injection, the flow will quickly reach the top surface and travel away from the nozzle towards the narrow faces before being turned downwards. This “single roll” flow pattern is more likely with multi-port nozzles, or bifurcated nozzle with small, upward-directed ports. It is also encouraged by shallow nozzle submergence, low casting speed, or large mold widths. Surface velocities and level fluctuations are high, so mold slag entrainment and surface defects are likely.

With the other typical mold flow pattern, the steel jet enters the mold cavity from a more deeply-submerged nozzle with larger or downward-angled entry ports of a bifurcated

nozzle. The submerged jet then travels across the width of the mold to impinge on the narrow faces. The jet then splits. Some of the flow travels upward towards the meniscus and back across the top surface towards the nozzle. The rest of the jet flows down the narrow faces deep into the liquid pool. Two large recirculating regions are formed in each symmetric half of the caster, so this flow pattern is termed "double roll". Often, the flow pattern alternates between the single and double roll archetypes or it may attain some intermediate condition.

4.3.4. Flow Pattern Prediction and Measurement

The flow pattern in a given continuous casting mold can be determined in several different ways. Traditionally, understanding has been deduced from physical models constructed to scale from transparent plastic using water to simulate the molten steel. Water models have proven to be accurate for single phase flows regardless of the model scale factor, so long as the flow is fully turbulent. Obtaining accurate flow patterns is very difficult when gas injection is significant, and some phenomena, such as slag layer behavior, cannot be modeled quantitatively, owing to the inherent differences in fluid properties, such as density and surface tension.

Mathematical models can yield added insight into flow. Computational models based on finite-difference or finite-element solution of the Navier Stokes equations can include phenomena such as heat transfer, multi-phase flow, and solidification in steel casting without the inaccuracies inherent in a water model. Accurate calculations still require significant effort because these models need accurate property data, appropriate boundary conditions, numerical validation, experimental calibration, and a lot of computer time.

Fig. 4.3.8 compares the time-averaged flow patterns predicted using physical and mathematical models for a typical double-roll flow pattern.[7] The water model results are visualized using velocity vectors from particle image velocimetry.[8, 9] The calculated velocities are from a transient simulation of 3-D turbulent flow.[7]

Flow can also be measured directly in the actual steel caster. Surface velocities can be measured by monitoring the vibrations of a rod inserted into the flow through the top surface.[10] Another method to measure the molten steel velocity average across the mold thickness is with electromagnetic (MFC) sensors in the mold walls,[7, 11] which monitor the electrical current generated when steel moves through a magnetic field. The velocity component is then calculated from the time taken for signal disturbances to move between a

pair of probes. This method is accurate only in regions of unidirectional flow between the probes, such as found near the surface. Both of these methods require significant effort and expense to calibrate and operate. Alternatively, a crude estimate of steel flow direction across the top surface can be obtained using the same measurement method used to monitor slag layer thickness (Section 4.3.3.5). The steel flow direction can be crudely estimated from the angle plowed up by the liquid steel as it flows around an inserted nail, as illustrated in Fig. 4.3.9. This angle can be captured as a frozen lump on the bottom of the nail, if care is taken.

4.3.5. Quality Problems related to Mold Flow

Flow in the mold is important for many reasons. Because it is the last liquid processing step, poor control of flow in the mold can cause many defects that cannot be corrected. Problem sources include: the entrapment of air argon bubbles and solid inclusion particles in the solidifying shell, entrainment of mold slag, surface defects and breakouts due to level fluctuations, inadequate liquid slag layer coverage, meniscus stagnation, and jet impingement. Each of these problems related to fluid flow is discussed in turn.

4.3.5.1 Air Entrainment

Air entrainment at any stage in steel processing leads to detrimental oxide inclusions in the steel product. This problem is worst at the final stage of flow in the mold, because there is little opportunity to prevent the reoxidation products from becoming entrapped in the final product as catastrophic large inclusions.

Open stream pouring produces the worst air entrainment problems, as previously discussed. This can be minimized by controlling both flow in the tundish and the metering nozzle design and operation in order to produce the smooth stream shown in Fig. 4.3.4. Specifically, high speed flow in the tundish across the exit nozzles should be avoided by proper choice of flow modifiers and shape of the tundish near the nozzle exit. Castellated metered nozzles, for example, have grooves which introduce controlled roughness into the stream in order to avoid inconsistent severe roughness.[5]

Submerged nozzle casting radically reduces air entrainment. Entrainment is still possible, however, if there are leaks, cracks, inadequate sealing between the nozzle joints or if the nozzle material becomes porous. If the internal pressure in the nozzle drops below

atmospheric pressure, air will aspirate through any of these pathways into the nozzle. This can be identified by nitrogen pickup, but the oxygen reacts to form dendritic inclusion particles. Pressure in the nozzle is lowest just below the flow control device, due to the venturi effect of the metal stream. For a given steel flow rate, the pressure drop (and corresponding tundish height) both increase as the opening area is restricted, as shown in Fig. 4.3.10 for a typical slide gate nozzle.[6]

Air entrainment into the nozzle can be discouraged by proper introduction of an inert gas flow, which is one of the ways in which argon gas acts to prevent nozzle clogging. Adding argon gas can raise the minimum pressure in the nozzle above ambient, as shown in Fig. 4.3.11.[12] Note that this occurs because the slide gate must open up to accommodate the gas (shown in the top of Fig. 4.3.11), in addition to the pressurizing effect of the gas.[6]

The minimum gas flow rate calculated to avoid a partial vacuum is shown in Fig. 4.3.12.[6] When the bore opening is either very small or very large, the pressure never drops below one atmosphere (zero gage pressure), so gas injection is not needed to prevent aspiration. Less gas is needed at low casting speed and at low tundish level, when the pressure drops are lower. Maintaining a high gas flow rate during these times may disrupt flow in the mold and be detrimental to steel quality, as discussed in Section 4.3.8.5.

Design of the nozzle and flow control geometry should promote smooth flow with minimal recirculation, in order to both minimize the pressure drops that allow reoxidation and to discourage clogging. A sufficiently thick slag layer over the surface of the steel in the mold is also important. Finally, flow in the mold should be controlled to avoid surface turbulence that could entrain air.

4.3.5.2 Entrapment of Bubbles and Inclusions

Surface Entrapment

Most surface defects in the steel product originate in the mold at the meniscus, where the solidifying steel shell is very thin. The most obvious source of surface defects is the capture of foreign particles into the solidifying shell at the meniscus. Particles come from many sources, including argon bubbles and oxide inclusions generated by prior processes that are carried in with the steel entering the mold cavity. While argon bubbles naturally float, they sometimes have difficulty penetrating through into the slag layer, especially if they are small. If the meniscus is unstable, stagnant, or has a solidified lip or "hook", bubbles may be captured, forming pinholes just beneath the surface of the slab, as shown in

Figure 4.3.13 a).[13] Inclusion particles have less buoyancy, so are even easier to capture, as shown in Figure 4.3.13 b).[13] If they are not removed by scale formation or during scarfing, these surface inclusions will lead to line defects or "slivers" in the final product.

Internal Entrapment

Most of the bubbles and many of the inclusions carried into the mold eventually circulate near the top surface and float out into the slag layer. This is illustrated in Fig. 4.3.14.[14] Some particles are carried deep into the liquid pool, however, where eventually they may become entrained in the solidifying strand. Even gas bubbles traveling with the incoming jet occasionally are carried into the lower recirculation zone. In a curved caster, large particles in the lower recirculation zone will spiral towards the inner radius, where they may become trapped in the solidifying shell. This is illustrated by one of the trajectories in Fig. 4.3.14.[14] Entrapment is more likely at high liquid flow rates, especially when casting at high speeds, with wide slabs, with asymmetric flow conditions such as accompany nozzle clogging, or with transient conditions such as raising the casting speed. Entrapped solid oxide particles eventually lead to surface slivers or internal defects, which act as stress concentration sites to reduce fatigue and toughness properties of the final product.

Most particles are captured 1-3 m below the meniscus, independent of casting speed.[14, 15] Gas bubbles captured in this way eventually may cause blister defects such as "pencil pipe" which appear as streaks in the final rolled product. When the slab is rolled, the subsurface bubbles elongate and the layer of metal separating them from the surface becomes thinner. Later during annealing, they can expand to raise the surface of the sheet locally, especially if the steel is weak such as ultra-low carbon grades, or if hydrogen is present.[16] Trapped alumina inclusions or mold slag particles have been associated with similar defects.[17] This problem can be greatly reduced by lowering the liquid mass flow rate[18] and / or by ensuring that at least the top 2.5m section of the caster is straight (vertical), in order to avoid the spiraling entrapment mechanism.

4.3.5.3 Entrainment of Mold Slag

Mold slag can be entrained into the solidifiying shell due to vortexing, high velocity flow that shears slag from the surface, and turbulence at the meniscus. The capture of large inclusions into the solidifying shell then leads to obvious line defects or "slivers" in the final product, as discussed in Section 4.3.3.2.

Vortexing most often occurs during conditions of asymmetrical flow, where steel flows rapidly through the narrow passage between the SEN and the mold. This creates swirling just beside the SEN, as shown in Fig. 4.3.15 a).[19] This swirl or vortex may draw mold slag downward, near the sides of the nozzle. If it is then entrained with the jets exiting the nozzle ports, this slag will be dispersed everywhere and create defects as discussed in Section 4.3.3.2. In addition to the vortex, slag may also be drawn downward by the recirculation pattern which accompanies flow from the nozzle ports. Thus, slag entrainment is most likely with shallow nozzle submergence and high casting speed.

The entrainment of mold slag also occurs when the velocity across the top surface becomes high enough to shear mold slag fingers down into the flow, where they can be entrained. Fig. 4.3.16 illustrates this mechanism.[20] Once it has broken up into particles and been dispersed into the flow, much of this slag may become internal inclusion defects. To avoid shearing slag in this manner, the surface velocity must be kept below a critical value. This critical velocity has been measured in water – oil models as a function of viscosity and other parameters.[21, 22] Entrainment is easier for deeper slag layers, lower slag viscosity, and lower slag surface tension. The critical velocity may also be exceeded when the standing wave becomes too severe and the interface emulsifies, as sketched in Fig. 4.3.15. b).[23, 24] The critical velocity also depends on the relative densities of the steel and flux phases and the mold geometry.[24, 25]

High velocity surface flows also may cause emulsification of the slag, where slag and steel intermix and even create a foam, if too much argon gas is present.[17] This allows easy capture of particles via vortexing or surface shearing flow. Another mechanism for slag entrainment, meniscus turbulence, is related to level variations, discussed in the next section.

4.3.5.4 Level Variations

Many surface defects form at the meniscus due to variations in the level of the liquid steel on the top surface of the mold cavity. These variations take two forms: steady variation across the mold width known as a “standing wave”, and “level fluctuations”, where the local level changes with time. While the standing wave can cause chronic problems with liquid slag feeding (see next section), the time varying level fluctuations cause the most serious surface defects. To avoid these problems, the top surface velocity should be kept below a critical maximum velocity, which has been estimated to be 0.3 m/s [19] or 0.4 m/s.[26]

Defects from level fluctuations

Steady, controlled oscillation of the mold generates ripples across the liquid level, but does not present an inherent quality problem, because the liquid adjacent to the mold wall tends to move with the wall. Sudden jumps or dips in liquid level are much more serious, however.

A sudden jump in local level can cause molten steel to overflow the meniscus. In the worst case, the steel can stick to the mold wall and start a sticker breakout. Alternatively, a jump in level can cause an irregular extended frozen meniscus shape, or "hook". This extended meniscus can capture mold powder or possibly bubbles or inclusions, such as shown in Fig. 4.3.13.[13, 27] Variations of more than the oscillation stroke over a time interval on the order of one second are the most detrimental. Even low frequency variations (period >60s) may cause defects, if the meniscus overflows and the solid slag rim is imprinted on the shell or captured.[28] The microstructure associated with overflow of the meniscus is shown in Fig. 4.3.17 for a billet with a lap defect.[29]

A sudden severe drop in liquid level exposes the inside of the solidifying shell to the mold slag, and also leads to surface depressions. Relaxing the temperature gradient causes cooling and bending of the top of the shell toward the liquid steel. When the liquid level rises back, the solidification of new hot solid against this cool solid surface layer leads to even more bending and stresses when the surface layer reheats.[30] This sequence of events is illustrated on a 20mm long section of shell in the calculation results in Fig. 4.3.18, for a 20-30mm level drop lasting 0.6s.[30] When liquid steel finally overflows the meniscus to continue with ordinary solidification, a surface depression is left behind, such as shown in Fig. 4.3.19.

The microstructural changes and surface depressions associated with level variations are serious because they initiate other quality problems in the final product. These problems include surface cracks and segregation. Surface cracks allow air to penetrate beneath the steel surface where it forms iron oxide, leading to line defects in the final product. These defects are difficult to distinguish from inclusion-related defects, other than by the simpler composition of their oxides.

Detection of level fluctuations

Level variations can be measured by examination of the level control sensor signals, thermocouple signals, and the final condition of the slab surface. Mold level can be measured directly in several different ways, which include the popular NKK eddy-current sensor,[31] radioactive source detection,[32] electromagnetic methods such as the EMLI detector,[33] and other methods.[34]

The measurement of level fluctuations should not be confused with the measurement of the moving-average liquid level in the mold, which is used to control movement of the flow control device (slide-gate or stopper-rod). Control of the total flow rate requires measurement of the average liquid level. This is best accomplished by measuring the level where the liquid steel surface level is the most stable, (typically midway between the SEN and the narrow face) and by filtering (time averaging) the signal. The objective of this sensor signal is to remove the influence of local fluctuations, which are not directly related to the average level needed by flow control device. However, these local transient fluctuations are very important to surface quality. Thus, quality detection systems should always monitor the unfiltered signal from the level sensor. Even better is to monitor the unfiltered signal from a second sensor, positioned where the level fluctuations are greatest, usually near the narrow face.[26]

Vertical rows of thermocouples embedded in the copper mold walls near the meniscus offer an indirect, but much less expensive, way to monitor level variations around the perimeter of the mold. The temperature profile down the row of thermocouples can be used to indicate where the meniscus is located. Fig. 4.3.20 shows how the signal variations from the mold level sensors correspond with temperature variations measured in the mold wall.[35] The measured temperature variations lose sensitivity with increasing distance away from the meniscus, either beneath the mold hot face surface, or down the mold.

The quality of liquid level control can also be gathered by observing the oscillation marks on the exterior surface of the slab, which should be straight and regular with a spacing or "pitch" defined by the casting speed and oscillation frequency. Overlapping or wiggly oscillation marks indicate a serious flow problem in the mold. The variable pitch of the deep, severely-distorted oscillation marks in Fig. 4.3.19, for example, shows evidence of time periods when the liquid level is generally rising (where the oscillation marks are spaced further apart) and falling (where they are closer together).[28] In addition, the height of the standing wave is easily measured by variations in straightness. For example, the curved oscillation marks in Fig. 4.3.19 show evidence of a generally higher liquid level on the edges of the bloom, which is due in this case to mold electromagnetic stirring raising the liquid level in the corners.

Causes of level variations

Level variations have many causes that are not fully understood. High frequency fluctuations due to the turbulent nature of the flow increase with increasing velocity across the top surface, which depends on the jet velocity and the mold flow pattern.[26] Sudden

transient events such as the loosening of nozzle clogs or sudden changes in casting speed also cause sudden local level fluctuations. Lubrication problems in both oil and powder casting lead to level variation defects. Electromagnetic stirring too close to the meniscus can generate severe standing waves.[36] Even problems with feedback in the level control system can generate fluctuations.

Lower frequency level fluctuations can be caused by synchronized bulging and squeezing of the strand below the mold, which acts like an accordian bellows to alternately raise and lower the level in the mold. This problem is most likely just after casting speed changes, due to bulging variations moving through the rolls. This was likely the root cause of periodic defects similar to those in Fig. 4.3.19.[28] This can be minimized by avoiding constant roll pitch that amplifies the effect and by minimizing temporary slow downs in casting speed. Complete strand stoppage is particularly detrimental, because roll bending will then contribute to the bulging and the associated level variations.

4.3.5.5 Inadequate Lubricant

To maintain consistent mold heat transfer and avoid surface cracks, the infiltration of liquid mold slag into the gap between the shell and the mold must be kept uniform. To do this requires an optimum delivery of lubricant to the meniscus perimeter. Indeed, problems with the oil lubrication system are believed to be responsible in part for the defects associated with the meniscus overflow in Fig. 4.3.17.[29] In powder casting, it is important to have an adequate coverage of molten slag combined with an optimized oscillation practice and controlled resolidified slag rim. The many severe consequences of inadequate lubricant include breakouts, cracks, and surface depressions and are discussed in detail elsewhere.[37, 38]

The depth of the liquid slag layer can be monitored by dipping steel nails together with aluminum and / or copper wires vertically down through the slag layer, as shown in Fig. 4.3.9. The 1-5 second dipping time is critical and should be optimized experimentally. The aluminum wire does not melt above the liquid slag / powder interface only because heat transfer through the low conductivity powder layer is too slow if the dipping time is short enough. The steel / liquid slag interface is identified by the lump of steel solidified to its end. The entire profile of the slag layer can be found by inserting a board containing many nails, or by using sheets of steel and aluminum instead of nails.

The liquid slag layer should be deep enough everywhere to withstand the largest level fluctuations without the steel touching the powder layer. It should also be kept constant with time, as transients of any nature can lead to defects. Figure 4.3.21 shows the consequences of intermittent powder additions on liquid slag layer variations.[39] A deeper, more uniform liquid slag layer is encouraged by a deeper powder layer and by a level, steady, liquid steel flow across its top surface.[39] In addition, the powder melting rate, liquid slag viscosity, and its solidification temperature should be optimized for the casting conditions and steel grade.[38] Crystalline slags with a high solidification temperature are recommended for depression-sensitive grades, such as peritectic and austenitic stainless steels.[37] Glassy slags, with a low viscosity at 1300 °C, are recommended for other sticker-sensitive grades. Further discussion of this important issue is found elsewhere.[37]

4.3.5.6 Meniscus Stagnation

If the steel jets entering the mold cavity move too close to the meniscus, slag entrainment and surface defects from level fluctuations may result, as previously discussed. On the other hand, if the steel jet is directed too deep or has too little superheat, then the liquid surface will have very little motion and will become too cold. This can lead to inadequate melting of the powder, which relies on fluid flow to generate convective heat transfer to help transport heat across the liquid slag layer to melt the powder.[39] In addition, this can lead to freezing of the steel meniscus, which will aggravate the formation of hooks and associated defects shown in Fig. 4.3.13.[13] For example, decreasing surface velocity below 0.4 m/s has been measured to increase surface pinhole defects.[40]

To avoid these problems, the flow pattern should be designed to exceed a critical minimum velocity across the top surface, estimated to be about 0.1-0.2 m/s.[26] This can be achieved by designing the nozzle geometry to deliver an upward jet, as discussed in the next section. Alternatively, the superheat can be increased, although this tends to worsen problems with centerline segregation. Finally, higher surface velocity can be achieved by increasing casting speed, increasing argon gas flow rate, applying electromagnetic forces, reducing submergence depth, as discussed in Section 4.3.5.

4.3.5.7 Jet Impingement

Impingement of the molten steel jets onto the solidifying shell in the mold sometimes cause problems if the jet is either too hot or too cold. Breakouts occur when the steel shell at

mold exit is not strong enough to contain the liquid steel. Breakouts have many causes, which are discussed elsewhere. Sticker breakouts may initiate from a severe level fluctuation or slag lubrication problem. Another cause is local thin and hot regions of the solidifying shell, which can result from high superheat dissipation at the region where an excessively hot jet impinges on the inside of the shell.[41-43] Problems arise only if this local superheat dissipation is combined with slow heat extraction from the corresponding shell exterior. This problem is most likely in the off-corner regions, where the jet may impinge and the shell shrinkage also creates a larger gap.

As the steel flows from the nozzle through the mold, it quickly dissipates its superheat and drops in temperature, as shown in Fig. 4.3.22.[42] The coldest liquid is naturally found deep in the caster, at the meniscus, and at the top surface beside the inlet nozzle. The fluid is coldest here because it is both far from the inlet and stagnant. When a cold nozzle is inserted during an SEN exchange, the cool steel in this region is prone to skull formation, meniscus freezing, and even "bridging", where steel or slag freezes across the shortest distance between the nozzle and meniscus of the wide face, often leading to a breakout. The narrow face meniscus is prone to deeper hooks, especially on wide slabs with low superheat.

Almost all of the superheat is dissipated to the shell in the mold or just below, as shown in Fig. 4.3.23.[42] In slab casting with bifurcated nozzles, the impingement region on the narrow face absorbs the most superheat. This region extends to the off-corner region of the wide face, as shown in Fig. 4.3.22. Fig. 4.3.24 shows how shell growth depends on the combined effects of superheat input from jet impingement and heat removal to the mold walls.[42] Jet impingement produces a thinner shell on the narrow face, compared with classic parabolic shell growth on the wide face, as shown in Fig. 4.3.25.[44] The importance of this effect increases with higher casting speeds, higher superheats, and lower gap heat transfer.[42, 43] Asymmetric flow, such as caused by nozzle clogging also aggravates this effect.

4.3.6. Flow System Design

The flow system should be designed to avoid the problems outlined in the previous section. To achieve this, several different objectives should be satisfied.

The first requirement is to minimize transients during the operation. Sudden changes are the main cause of the flow instabilities which generate surface turbulence. Because flow

parameters can be optimized only for steady operation, each of the parameters which affects fluid flow must be controlled simultaneously. It is especially important to keep nearly constant the liquid steel level in the mold, powder feeding rate (to keep a constant liquid slag layer thickness), casting speed, gas injection rate, slide gate opening, and nozzle position (alignment and submergence).

Next, the steady mold flow pattern must be designed and controlled. It is affected by both nozzle design and operating conditions, which are discussed in the following sections. Nozzle geometry influences the flow pattern in the mold, which is greatly responsible for controlling surface turbulence and the accompanying defects. The flow pattern also depends on parameters which generally cannot be adjusted to accommodate the flow pattern, such as the position of the flow control device (slide gate or stopper rod), nozzle clogging, casting speed, strand width, and strand thickness. Fortunately, other parameters besides nozzle geometry can be adjusted to maintain an optimal the flow pattern. These include the injection of argon gas, nozzle submergence depth, and the application of electromagnetic forces.

4.3.7. Submerged Entry Nozzle Design

One of the most important functions of the nozzle is to promote a good flow pattern in the mold cavity. The jet flowing from the nozzle should have a flow rate, direction and other properties that has been optimized to achieve this, according to considerations discussed in the next section. In addition, the nozzle should discourage any large transient fluctuations, flow asymmetry or high turbulence levels. The shape of the nozzle is one of the few casting design variables that has an important impact on quality and yet can be easily changed at low cost over a wide spectrum of design shapes. Flow through a typical slide-gate nozzle, including the internal distribution of argon gas, and the outlet jets, is illustrated in Fig. 4.3.26.[6] This section discusses the influence of the following design variables on the condition of the jet entering the mold cavity:

Bore size
Port angle
Port opening size
Nozzle wall thickness
Port shape (round, oval, square)
Number of ports (bifurcated or multiport)
Nozzle bottom design

The initial choice of nozzle design should be made with the aid of both physical and mathematical models, discussed elsewhere. It should naturally perform well over the entire range of operation expected. When the operating range is very wide, it is better to use two or more different designs.

4.3.7.1 Bore Size

The first design consideration is capacity. Since the flow is driven by gravity alone (and can only be throttled down), the nozzle cross section should be large enough to accommodate the maximum desired flow rate to meet productivity demands. Larger diameter nozzles are naturally needed for higher casting speed. To fit more easily into the mold cavity and minimize the danger of bridging, nozzles for thin-slab and high-speed casting need elongated bores, such as 80x130mm, with the smaller dimension spanning less of the mold thickness. Oversized nozzle bores are sometimes used to accommodate some alumina buildup. However, this forces the nozzle to operate very restricted, which aggravates flow variations and negative pressure problems.

4.3.7.2 Nozzle Port Angle and Opening Size

The nozzle ports should be designed to deliver steel jets into the mold cavity in the desired direction with the desired level of internal turbulence, velocity, mass flow, spread, and swirl. More importantly, they should deliver these jets evenly with as few variations in jet properties over time as possible. The angle and size of the ports is very influential in achieving this.

The total area of the nozzle port exits is often made much larger than that of the bore, in order to accommodate some alumina buildup. As a consequence, the flow generally exits through only the bottom of the nozzle port,[45] as shown in Fig. 4.3.26 b).[6] Flow recirculation occurs in the top half, where steel actually flows into the nozzle.[46] Stagnant regions such as these may aggravate clogging.[47, 48]

Because flow at the top of the nozzle exit ports is slow and directed into the nozzle, the angle of the upper edge of the exit port has less effect on the angle of the flow leaving the nozzle than the bottom edge.[46] However, the shape of this top edge is important, as a smooth curve promotes attachment of the jet to the nozzle walls. This produces less

recirculation and greater flow rate through the port with the curved top edge, such as caused by clogging.[49]

A second consequence of large exit ports is that the nominal angle of the edges of the outlet port has less effect on the jet direction. Fig. 4.3.27 shows that the momentum of the downward flow through the nozzle with oversized ports carries the steel jet into the mold at a downward angle, regardless of the angle of the port edges.[46] For the 90mm high ports shown, flow into the mold is angled downward even when the port is angled upward. When the port edges are angled downward, the downward angle of the steel flow is always steeper.

When the port size is reduced such that the total port area is less than the bore area, then the angle of the nozzle ports becomes more important, as the flow is forced to conform more closely to the angle of the port edges.[49] Fig. 4.3.28 shows that the jet leaving a 45mm high upward-angled nozzle heads upward, instead of downward for the equivalent 90mm high port. For this reason, flow from multiport nozzles tends to conform more closely to the direction of the nozzle port edges, since each of the exit ports is smaller and is thus more effective at influencing the flow. However, the speed and turbulence levels of the jets exiting the nozzle both increase with the smaller ports.

When the port edges are effective, then steepening the port angle directs the jet deeper into the liquid cavity, and the flow pattern shifts downward. Of greater importance, the velocity across the top surface decreases slightly.[50]

4.3.7.3 Nozzle Wall Thickness

Increasing the thickness of the nozzle wall makes the nozzle port edges more effective at controlling the jet direction.[49] As shown in Fig. 4.3.29, the 12-mm nozzle has a steeper downward jet, while the thick-walled nozzle has more desirable uniform flow in the same direction as the port angle. The wall thickness also has three other important effects. It affects the size of the space in the critical region between the nozzle and meniscus, the thermal shock resistance of the refractories, and the erosion resistance at the slag line.

4.3.7.4 Port Shape

For oversized nozzle ports with the same outlet area (and other geometric parameters constant), tall and thin ports induce a steeper downward jet angle than short, fat ports.[6, 45]

This is quantified in Fig. 4.3.30 for a 50% open slide gate, cast at 1 m/min through a bifurcated nozzle with 78-mm bore and 15° downward ports.[6] Circular ports generate more swirl and have a larger spread angle than rectangular ports having the same port area.[49] All ports tend to become smaller and rounder with time, however, due to clogging. Port shape is less important than port size and angle in controlling the flow.[51]

4.3.7.5 Number of Ports

Multiport nozzles tend to control the flow direction more closely than do bifurcated nozzles, as discussed previously. A central hole added to the bottom of a bifurcated nozzle will encourage symmetry and stability in the mold flow pattern. At high casting speed, in wide molds, or in thin slabs, the mold flow pattern tends to oscillate periodically from side to side.[23, 52] The extra central hole makes this oscillation more difficult, leading to less surface level fluctuations.

In addition, the bottom hole sends some of the jet momentum deeper and consequently reduces the intensity of the flow near the surface. In square-section billet casting, the relative sizes of the side and bottom ports can be adjusted to control the jet momentum in order to optimize surface flow intensity.

4.3.7.6 Nozzle Bottom Design

The shape of the bottom of the nozzle has little effect on the mass flow and direction of the jets leaving the nozzle.[46] However, it does affect the turbulence levels leaving the nozzle, and the deposition of clogs, which might influence flow transients in the mold and subsequent surface turbulence. For example, a recess or "sump" in the bottom of the nozzle might accommodate more clogging and increase the stability of the jets leaving the ports. Thus, the sump nozzle might produce less transient fluctuations in the flow in the mold cavity and thereby improve quality.[51, 53] The shape of the nozzle bottom likely has less effect when the ports are angled upward.

4.3.8. Control of Mold Flow Pattern

In addition to nozzle design parameters, fluid flow in the mold is greatly affected by:

position of flow control device (slide gate or stopper rod)
nozzle clogging
casting speed
section size
argon gas injection rate
submergence depth
electromagnetics

Each of these important control variables are discussed in turn in this section. It is important to understand that these parameters, including the nozzle geometry, all act together to determine the flow characteristics. An increase in casting speed, for example, might be compensated by a simultaneous increase in submergence depth, in order to achieve the same surface flow intensity. Thus, all of these parameters must be optimized together as a system.

4.3.8.1 Flow Control Position

The flow rate of steel entering the mold is governed by the pressure head generated by the difference in steel levels between the tundish and the mold. It is further controlled by a stopper rod or slide gate system. In addition to controlling the overall flow rate, these devices also influence the flow pattern in the mold, by affecting the symmetry of the flow.

With a slide gate operation which moves parallel to the wide face (0˚orientation), the flow from the opposing two symmetrical ports in the bifurcated nozzle is very nonsymmetrical, as shown in Fig. 4.3.31.[6] The increased flow down the side of the nozzle beneath the gate opening tends to increase the flow rate leaving from the port on the opposite side. The increase can exceed 150% of the flow through the other port. [6, 54] The increased flow rate is accompanied by a much shallower angle into the mold (as little as half the downward angle from 25˚ to 12.5˚ for the opposite ports). This asymmetric flow is illustrated in Fig. 4.3.33 for a 50%-open slide gate.

Opening the slide gate perpendicular to the direction of the ports (90˚ orientation) avoids this asymmetry problem.[7] Instead, it introduces a consistent rotational component or "swirl" into the jet. As shown in Fig. 4.3.32, restricting the flow to less than 100% with this configuration also tends to induce a consistent horizontal angle to the jet and to steepen the vertical jet angle.[6] A 45˚ slide gate orientation has both the left – right asymmetry and

the swirl-based asymmetries, so likely should be avoided.[6] Stopper rods avoid the steady-state asymmetry of slide gates, but are still prone to transient fluctuations, especially when the stopper is misaligned slightly or has any erosion or clogging on or near to its critical control surfaces.

4.3.8.2 Nozzle Clogging

Inclusion particles in the steel may stick to the walls of the nozzle and disrupt the flow. In addition to slowing production and lowering nozzle life, the clog buildup can change the flow behavior exiting the nozzle ports. Inclusions may arise from incomplete refining, slag carryover from the ladle or tundish, refractory spalls, and reoxidation, if air is allowed to contact the steel. Further details on these inclusion sources and their prevention is discussed in elsewhere.

Flow through the nozzle and its ports depends on the cross sectional area of the opening at the flow control and on the sharpness of the edges there. Clogging affects both of these. As shown in Fig. 4.3.34 b),[6] if clogging and erosion rounds off the edges near the slide gate, the consequent streamlining of the flow reduces the total pressure drop and encourages consistent swirl at the ports. Clogging of the stagnant regions around the slide gate, Fig. 4.3.34 c) and d), further affects the pressure drop and causes reversals in the direction of the swirl. Slight changes in the shape of clogging causes significant changes to the mass flow and direction of the jets exiting the ports. In order to compensate for the changing pressure drop, the flow control position must change. This produces further changes in the outlet jet properties. The consequence of these inlet flow transients is manifested in flow at the steel – slag interface in the mold. Increased level fluctuations have been correlated with clogging.[35] Thus, it is important to detect clogging early and to avoid casting while clogged.

4.3.8.3 Casting Speed

Increasing casting speed tends to increase all of the velocities proportionally and produces little qualitative change in the time-averaged flow pattern in the mold, so long as other conditions are constant and there is no gas injection.[6, 46] However, increasing casting speed tends to increase transient turbulent fluctuations, and worsens the extent of flow pattern asymmetries, which oscillate between the two flow patterns illustrated in Fig. 4.3.15 b).[23] This in turn worsens detrimental surface turbulence and level fluctuations. The period of the

flow pattern oscillations corresponds to the residence time of a fluid particle in the upper recirculation zone, which is typically 5-30s.[23]

In addition, increasing casting speed increases the height of the standing wave on the top surface, which is highest where the jet momentum impacts on the steel-slag interface. For the standard double roll flow pattern in Fig. 4.3.35, for example, higher casting speed increases the interface height next to the narrow face,[55] where flux feeding into the gap becomes a chronic problem. The wave height increases with increasing casting speed, as shown in Fig. 4.3.36.[23] At very high casting speed, surface level fluctuation problems may suddenly increase greatly when the surface flow velocity exceeds the critical value for wave instability.[25] These problems are naturally an even greater concern for inherently high-speed casting processes, such as thin slab casting[23] and strip casting.[56]

The surface quality problems associated with high casting speed can be addressed by adjusting the nozzle geometry, increasing the submergence depth, and perhaps even applying electromagnetic forces, in order to the lessen the intensity of surface-directed flows. Improving internal cleanliness requires lower casting speed.

4.3.8.4 Strand Width and Thickness

For the same liquid steel flow rate, increasing the strand width or decreasing the strand thickness increases the tendency for transient variations in the flow pattern. Thin slab casting machines are therefore more prone to level fluctuation problems than conventional casters, because a higher casting speed is needed for a given flow rate.

Increasing strand width tends to increase the single roll flow pattern. In addition, and more importantly, the time oscillations in jet position are particularly severe in wide strands, where velocities are higher for a given casting speed.[57] Especially in very wide strands, (eg. 2m) the jet position may become so unstable that it sometimes impinges on the narrow face wall (with a conventional double roll flow pattern), and at other times impinges first on the top surface.[9] These variations are caused by the phenomenon of “vortex shedding”, as the walls of the strand are too far away to constrain the jet in the vertical plane. Overcoming this problem may even require a second inlet nozzle.

4.3.8.5 Argon Gas Injection

Argon is injected into the nozzle both to help reduce clogging and to influence the flow pattern in the mold. Thus, argon flow should be adjusted with other casting parameters in order to optimize the flow pattern. The average volume fraction of argon gas in the nozzle, f_g, is related to the liquid steel flow rate via:

$$f_g = \frac{\beta Q_g}{\beta Q_g + Q_l} \qquad (4.3.3)$$

where Q_g = gas injection flow rate at 25˚C and 1 atm
Q_l = liquid steel flow rate
β = gas volume expansion factor

The liquid flow rate may be found by multiplying the casting speed by the cross sectional area of the strand. The factor of gas volume expansion due to the temperature increase and pressure change, β, is about 5.[6] Although it is not possible to exactly reproduce the phenomena in a steel argon system with a water model, reasonable results can be obtained if at least the value of f_g is matched by injecting the "hot" argon flow rate, $\beta\ Q_g$., into the water model.[6]

The range of argon flow rates that can be safely used to optimize the mold flow pattern is limited by gas behavior in the nozzle. Too little argon may allow nozzle clogging. Excessive argon injection is expensive, and can generate transient variation of the jets entering the mold. Because steel does not wet the inside of the nozzle, a gas sheet may form and separate from the steel at high gas flows.[58] The gas leaves the ports intermittently and introduces significant asymmetry in the mold cavity.[22]

Adding argon lowers the density of the steel jet, increasing its buoyancy and making the jet bend upward. If the jet reaches the top surface of the mold before it impinges on the narrow face, increased surface turbulence is likely to result. Fig. 4.3.37 shows how behavior of the top surface changes from changes in argon injection.[9] With low gas flow, the double-roll flow pattern has a steeper standing wave near the narrow face, with flow moving back across the top surface towards the SEN. Increasing argon flow to above a critical level tends to reverse the surface flow direction, as the single-roll flow pattern carries molten steel immediately to the surface, raising the liquid flux level near the SEN. It also makes the flow pattern more variable, as it alternates between single and double roll. The critical argon level

for the flow transition is shown in the water model results in Fig. 4.3.38, measured in absolute units (l/min).[9] This critical level is less for lower steel throughputs, because the influence of gas buoyancy increases with slower moving steel. The critical level is also less for wider molds, where the jet has more time to bend upward from the buoyancy before it reaches the narrow face.[59] The critical level likely also depends on submergence depth, nozzle geometry, and strand thickness.

It is therefore important to control argon to the optimum level for a given set of casting conditions. Adjusting argon flow during operation is a good way to accommodate other changes in the casting conditions in order to maintain the flow pattern. To maintain a stable double-roll flow pattern, which is often optimal, the argon should be kept safely below the critical level.

4.3.8.6 Submergence Depth

The depth of nozzle submergence, as measured from the slag / steel / ceramic interface to the nozzle port, is often changed during operation in order to accommodate nozzle erosion at that interface. However, submergence depth also has an important effect on steel quality, which should be taken into account.

Increasing submergence depth naturally shifts the flow pattern downward, which tends to encourage the double roll flow pattern, discourages jet impingement on the steel / slag interface, and lowers the intensity of surface flow velocities. This decreases the amplitude of surface waves, as shown in Fig. 4.3.39, which lessens fluctuation and instability of the steel / slag interface.[60] Thus, deeper submergence lessens slag entrainment and encourages uniform slag feeding into the mold / strand gap, which tends to improve surface quality, as shown in Fig. 4.3.40. [60]

Increasing submergence depth too much, however, can cause quality problems in other ways. Deeper submergence may send more particles deep into the lower recirculation zones, where a greater fraction may become entrapped. The mold is last chance to remove inclusions before they are trapped as permanent defects in the final product. Deeper submergence also risks surface defects due to the fluid flowing across the surface being too slow and too cold. As a consequence, very deep submergence produces insufficient mixing and lowers heat transfer across the slag layer. This may lead to inadequate liquid slag layer thickness, meniscus freezing, and problems feeding slag into the interfacial gap, especially near the SEN. This increases problems with longitudinal cracks and transverse depressions,

as shown in Fig. 4.3.40.[60]

For a given operation, an optimum submergence depth should exist.[19, 60] For the particular operation studied for Fig. 4.3.40, this optimum depth was about 12 cm.[60] The optimum submergence depth changes with casting parameters. Steeper jet angles from the nozzle, wider strands, electromagnetic braking across the surface, lower superheat, and higher viscosity slag all tend to require shallower submergence. Higher casting speed and increased argon gas fraction both tend to require deeper submergence.

4.3.8.7 Electromagnetics

Electromagnetic forces can be applied to the molten metal in a number of ways to substantially alter the flow pattern in the strand. Induction forces are applied to the molten steel by passing current through electromagnetic coils positioned adjacent to the mold or strand. The two different methods are 1) to apply direct current to create constant forces that tend to slow down or “brake” the flow and 2) to apply alternating current to “stir” the liquid.

In electromagnetic "braking", shown in Fig. 4.3.41, electromagnetic forces are generally applied across the entire mold width in zones both above and below the jet inlet.[61] The resulting flow patterns can be studied with coupled computational models and with physical models using mercury or low-melting temperature alloys.[61, 62] These electromagnetic forces increase in proportion to the steel velocity to decrease that flow component. Careful slowing of the flow across the top surface can compensate for high casting speed and lessen the extent of level fluctuations and variations. Slowing the jets entering the lower recirculation zone can slow down the penetration of inclusions and gas bubbles and improve internal cleanliness. In addition, these forces can help to stabilize the flow pattern below the mold, thereby reducing transient fluctuations.

In electromagnetic “stirring”, the forces can be applied at the meniscus, low in the mold and / or near the region of final solidification low in the strand. Applying low frequency electromagnetic pressure onto the meniscus is a novel method to stabilize initial solidification and reduce the size of oscillation marks.[63] Mold stirring in the bottom half of the mold may help to remove superheat, to encourage nucleation, to stabilize the flow pattern, and to help reduce inclusion entrapment.[64] Final stirring low in the strand mixes the liquid in the region just before the final solidification point. The latter two procedures can increase the size of the central equiaxed zone and help to reduce centerline segregation

in the final product. Caution must be used, however, as white bands are an undesirable biproduct of the stirring.

Electromagnetic forces must be designed with consideration of all of the other parameters which affect fluid flow, in order to achieve an optimal flow pattern for a given operation. Improper application of electromagnetics can easily create great quality problems. Another disadvantage of electromagnetics is their high cost.

4.3.9. Summary

It is very important to optimize flow in the mold in order to avoid defects. Submerged nozzle casting is superior to open pouring because it lowers surface turbulence and reoxidation inclusions. Design of the nozzle geometry and flow system is still a challenging task which this chapter has addressed. Further discussion of fluid flow control and other aspects of design and operation of the continuous casting mold are presented elsewhere. [65, 66]

The effects of the many flow parameters on surface directed flows and corresponding defects are summarized in Fig. 4.3.43.[19] Directing too much flow towards the top surface generates surface defects, due to transients, turbulence at the meniscus, and inclusion problems from slag entrainment. These problems can be reduced with nozzle ports which the direct the jet more downward, decreasing casting speed, lowering argon gas flow rate, deeper nozzle submergence, narrower strand width, avoiding nozzle clogging, avoiding asymmetric flow such as caused by a restricted 0° slide gate, or by careful application of electromagnetic forces. A stable, double-roll flow pattern from a bifurcated nozzle is likely the best way to avoid these problems in slab casting.

Decreasing surface flows too much can also generate problems, however. These include surface defects due to the meniscus region becoming too stagnant, and a greater fraction of incoming inclusion particles being sent deep before they can be removed into the slag. Thus, a balance must be found in order to optimize the flow parameters to avoid defects.

A good nozzle should promote a good flow pattern in the mold. The flow pattern should be symmetrical and stable, to avoid vortexing, sloshing, and instability of the metal – slag interface. The greatest need is to avoid surface turbulence. At the same time, the flow should minimize the depth of penetration of the incoming stream, to enhance inclusion

particle transport to the slag layer interface, and to deliver steel to the meniscus that is not too cold.

To achieve these somewhat contradictory objectives requires design and optimization of the flow system as a whole. A given nozzle geometry can only be optimal within a fixed range of process conditions. Water models, computational models, and plant experiments should be combined to design the nozzle geometry and casting parameters in order to control flow in a given continuous casting operation to produce high-quality, defect-free steel.

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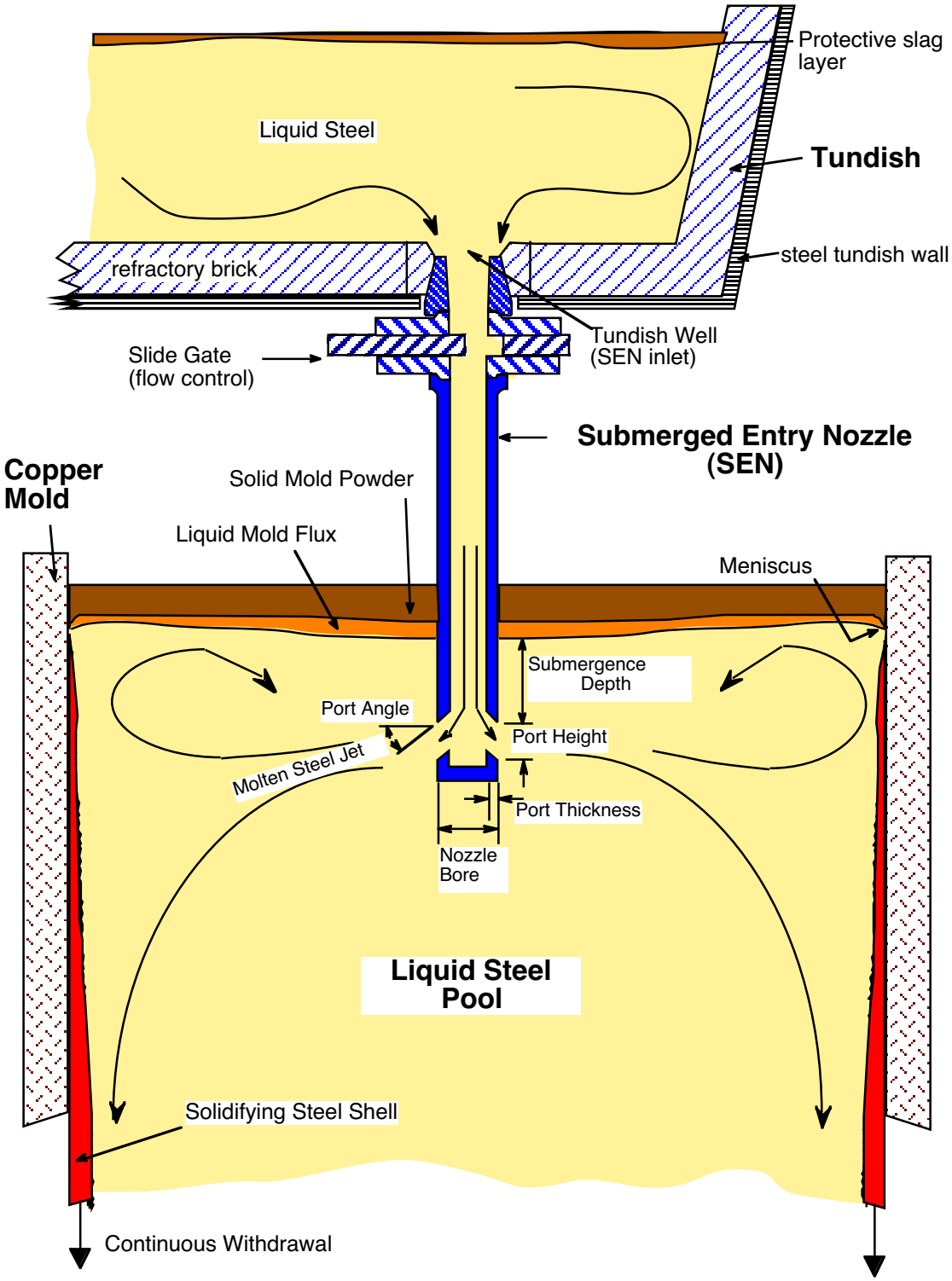
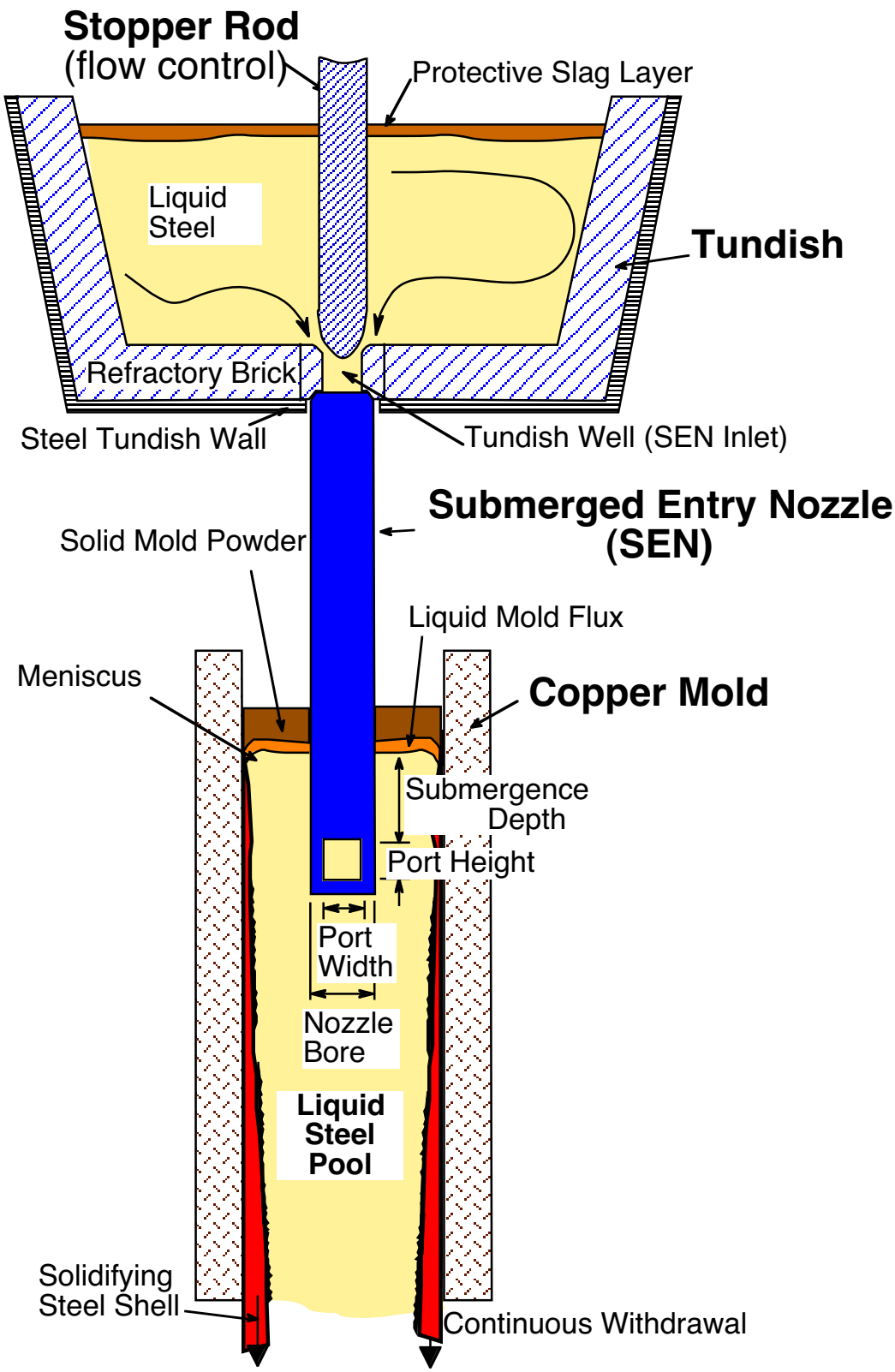


a)

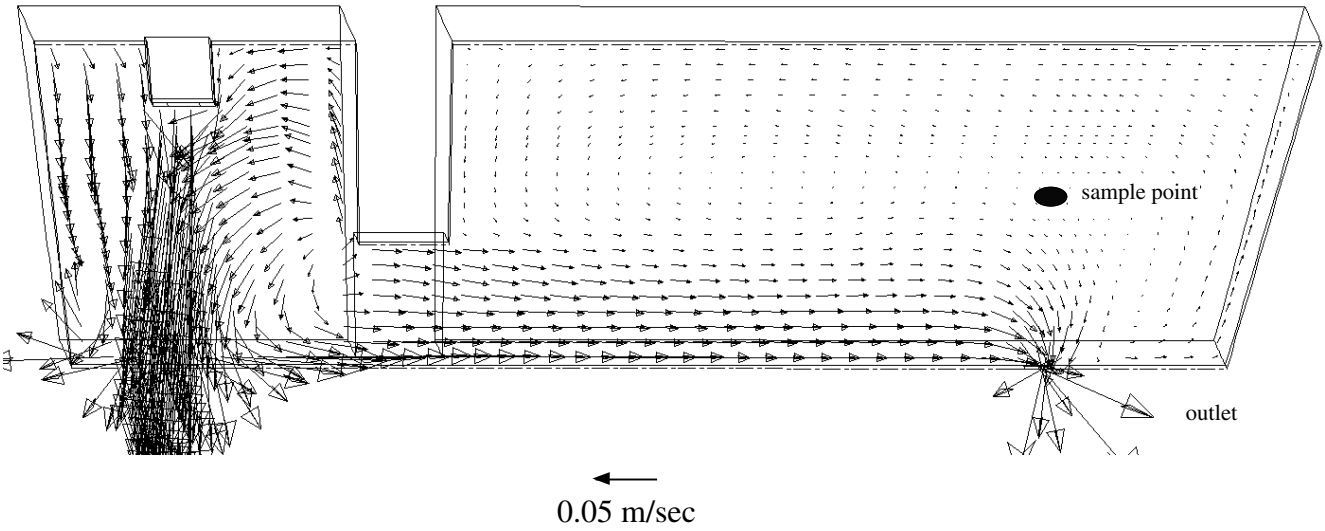
Fig. 4.3.1 Schematic of continuous casting process and terminology showing tundish, submerged entry nozzle, and mold

a) View towards wide face; slide gate operation

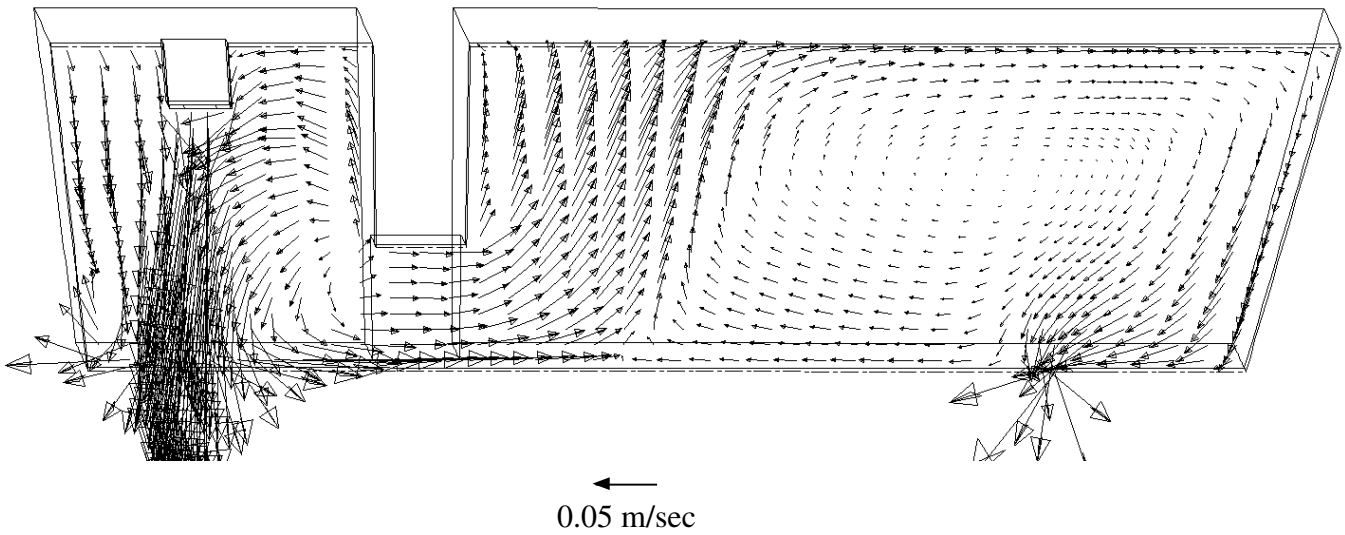


b)

Fig. 4.3.1 b) View towards narrow face; stopper rod operation



a)



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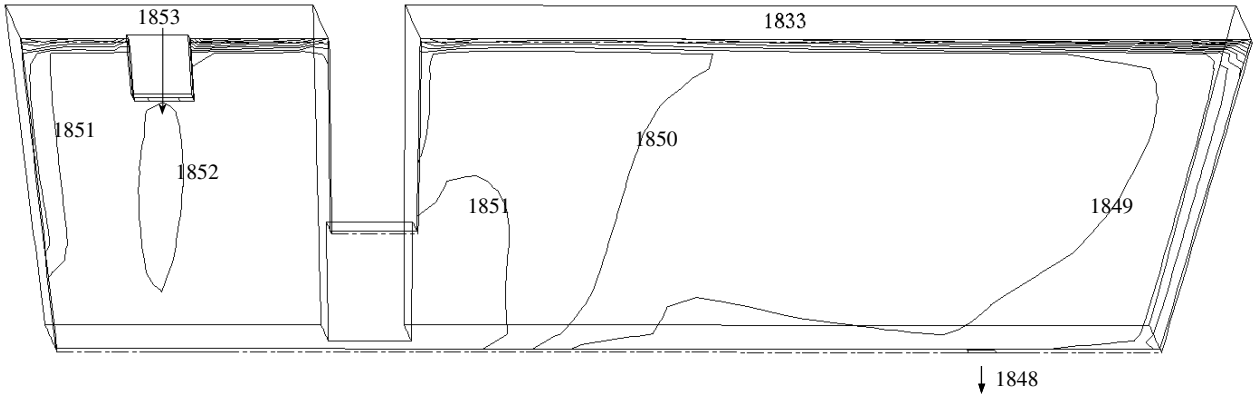


c)

Fig. 4.3.2 Steady flow distribution in the tundish [3] a) Isothermal model b) Coupled flow-temperature model c) Temperature contours corresponding to flow in b) (1853 K inlet into 1833 K initial temperature)

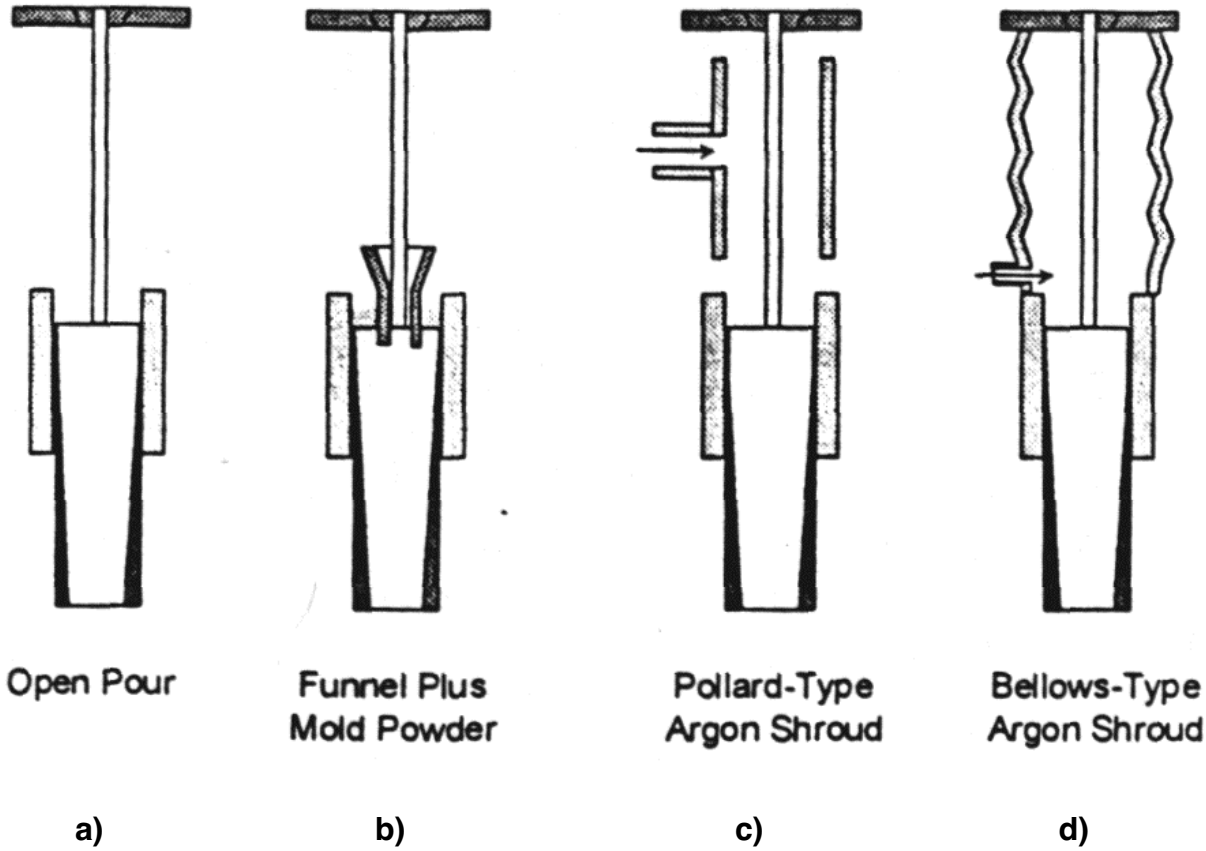


Fig. 4.3.3 Free stream pouring practices between tundish and mold [4]

a) Open pouring entrains the most air

b) Funnel to direct stream allows the application of mold powder, which reduces turbulence and oxidation at the steel surface

c) Pollard-type argon shroud flushes steel stream with gas

d) Bellows-type argon shroud better protects stream from air exposure

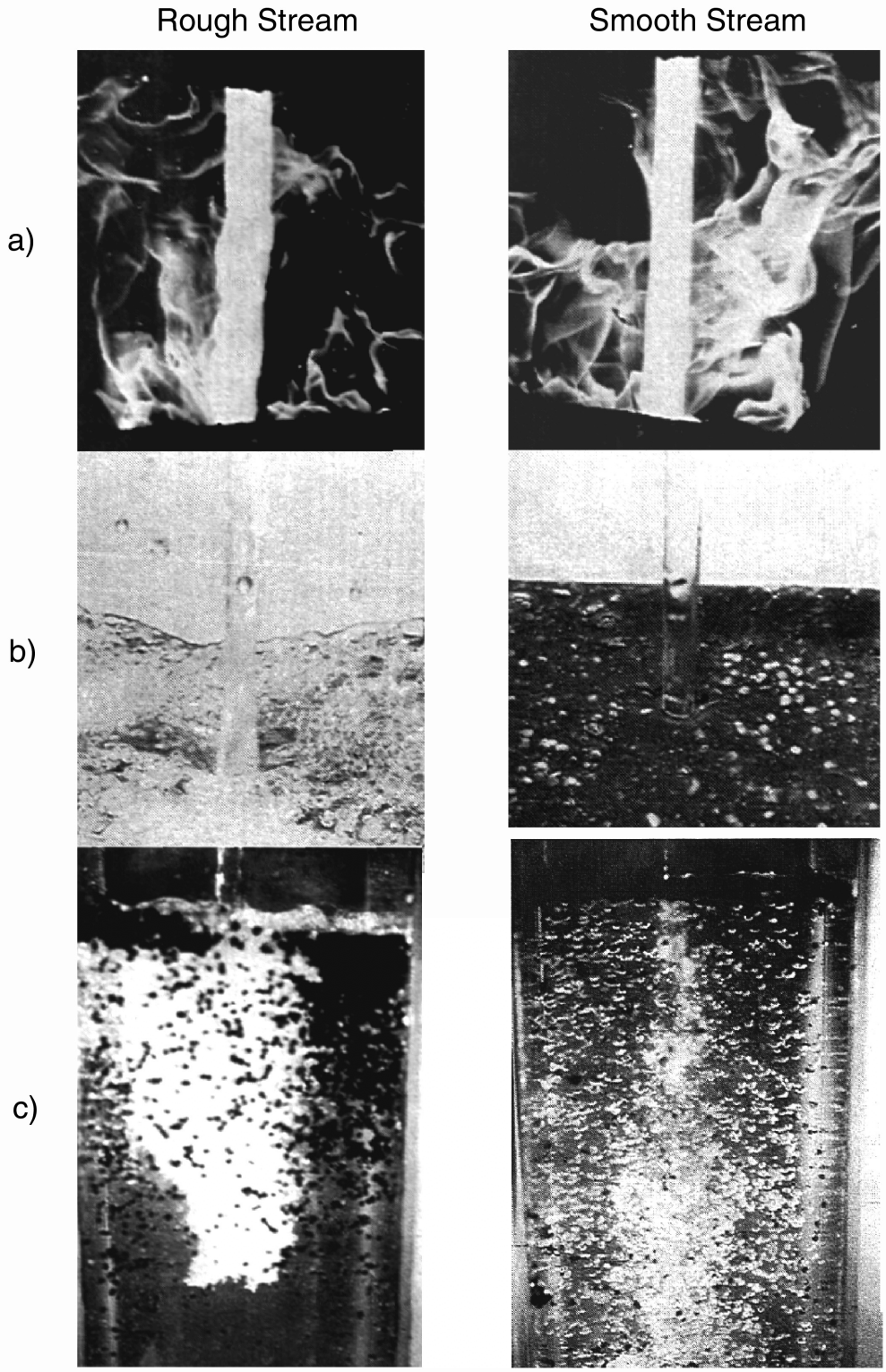


Fig. 4.3.4 Open-pour stream condition [5] a) Photograph of steel stream between tundish and mold showing irregular shape of rough stream which leads to increased air entrainment; b) Stream impacting liquid surface in mold water model showing greater turbulence and level fluctuations caused by rough stream; c) Stream penetrating beneath surface of water model showing deeper penetration of smooth stream

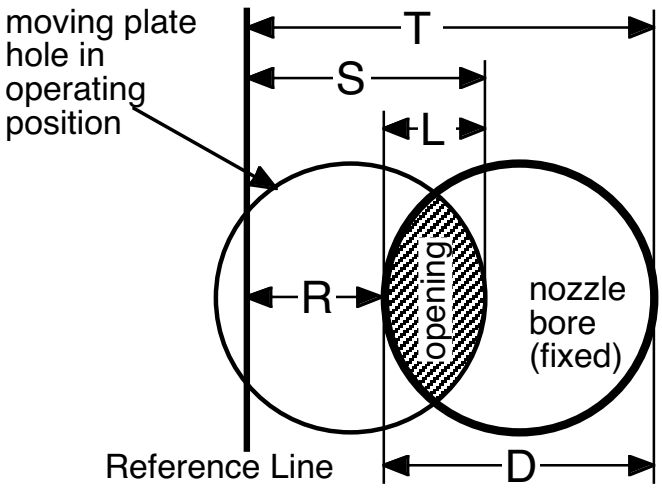


Fig. 4.3.5 Quantifying slide gate opening size

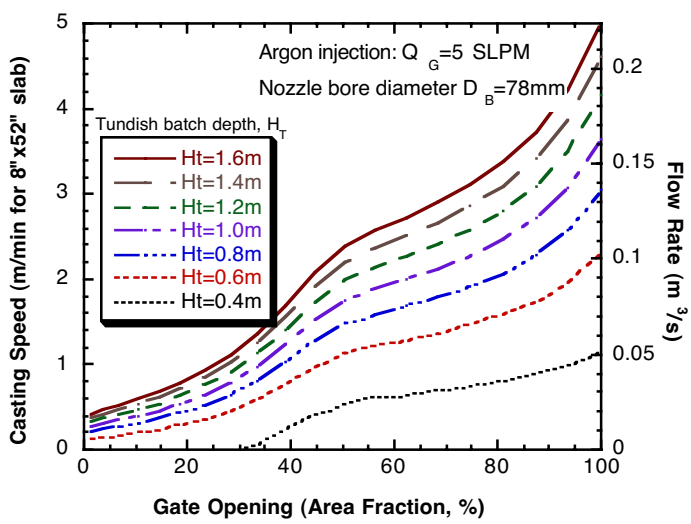


Fig. 4.3.6 Effect of slide gate opening size and tundish depth on steel flow rate [6]

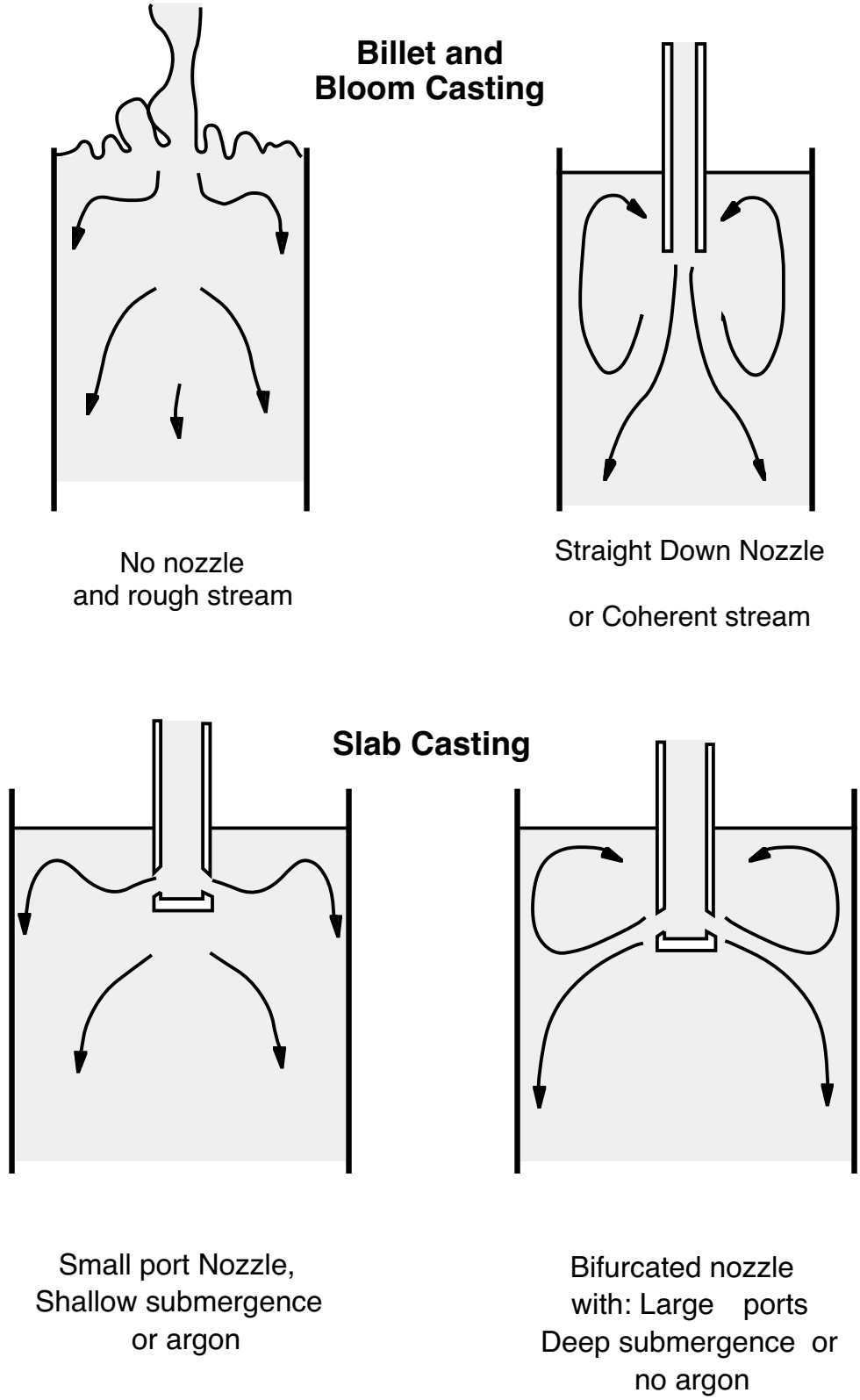


Fig. 4.3.7 Types of mold flow patterns and nozzles

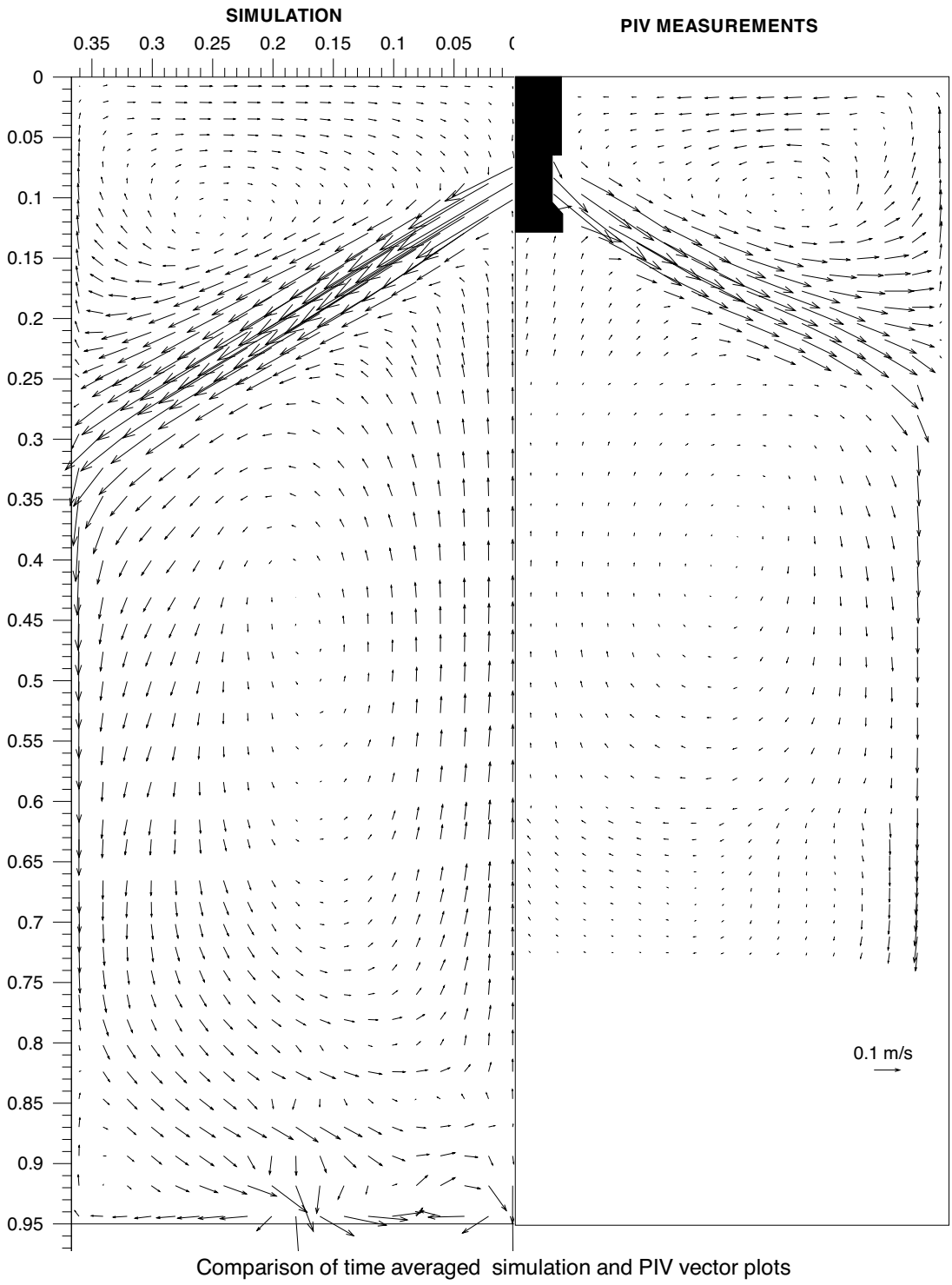


Fig. 4.3.8 Typical time-average velocities for a double-roll flow pattern [7] determined by a) Mathematical model (direct numerical simulation); b) Water model (particle image velocimetry)

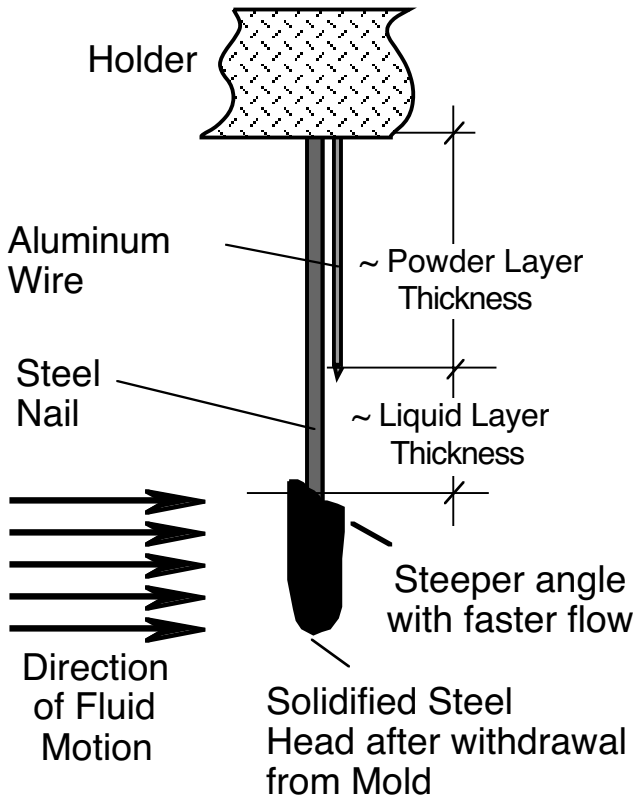


Fig. 4.3.9 Crude measurement of flux layer thickness and surface velocity

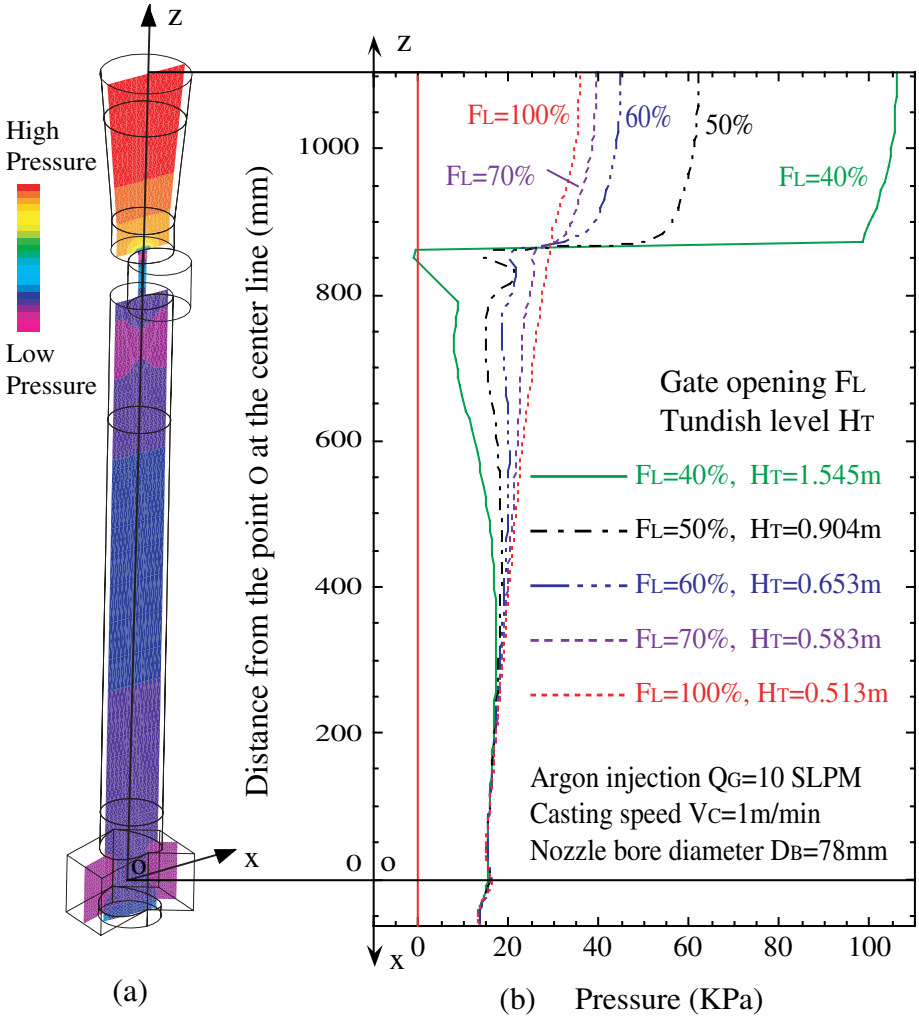


Fig. 4.3.10 Pressure drop calculated down nozzle [6]

a) Pressure contours in centerplane showing that major variations are in vertical direction

b) Effect of slide gate opening on vertical pressure distribution

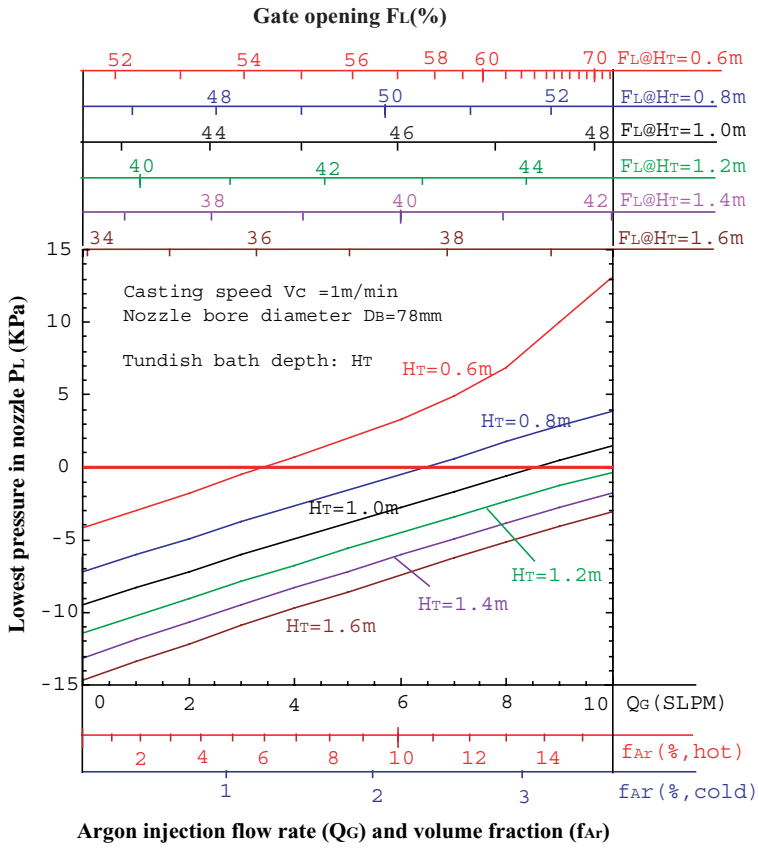


Fig. 4.3.11 Increase in nozzle pressure caused by argon gas injection and accompanying increase in gate opening [6]. Each line on the top of the figure indicates the slide gate position corresponding to a different tundish level.

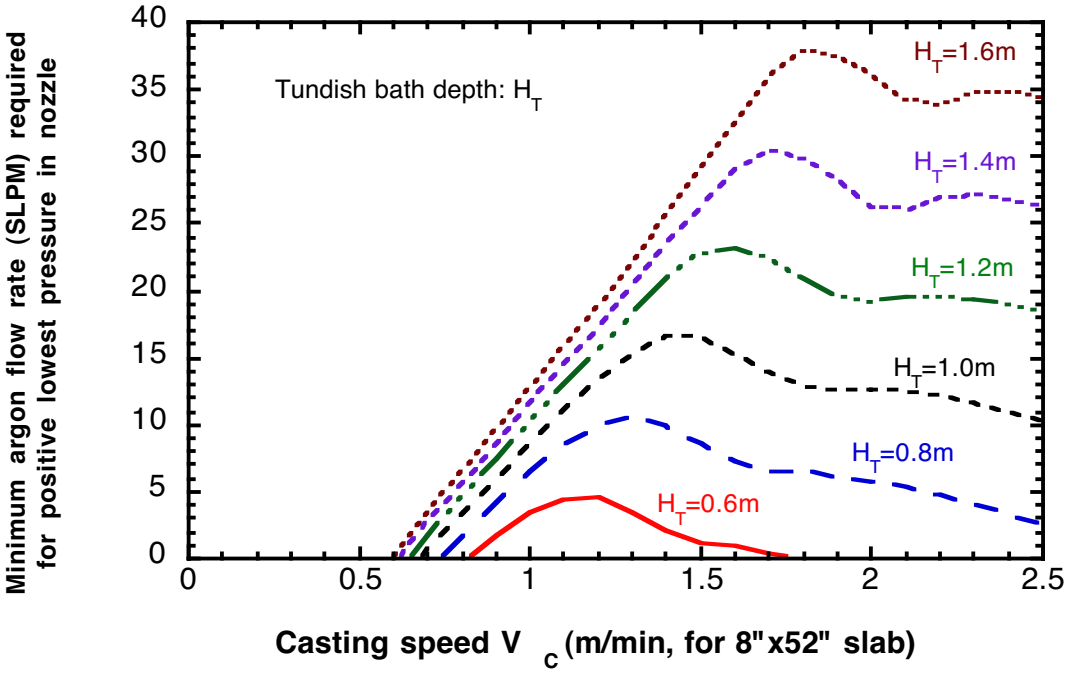


Fig. 4.3.12 Optimizing gas injection [6]

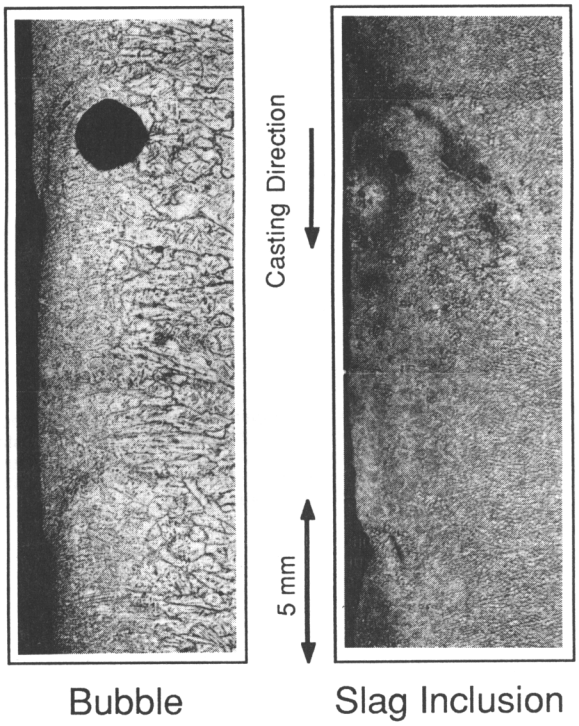


Fig. 4.3.13 Surface defects in steel slab caused by particles trapped beneath frozen meniscus [13]
a) Argon bubble trapped beneath oscillation mark hook
b) Slab surface inclusion

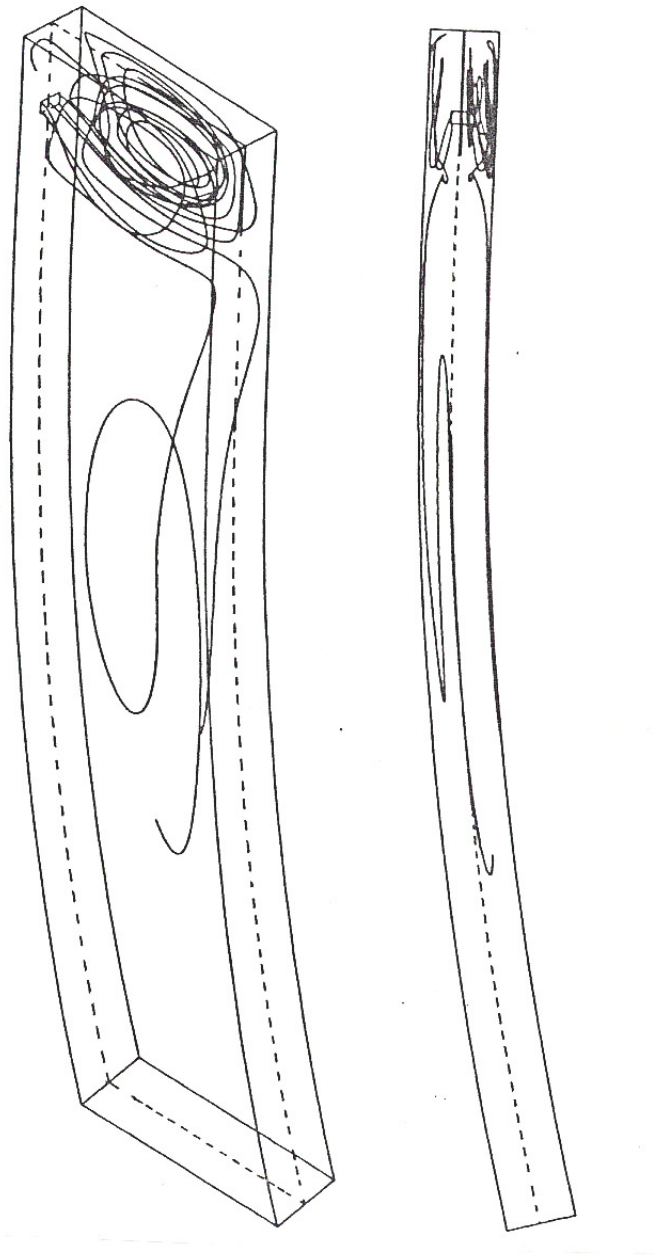
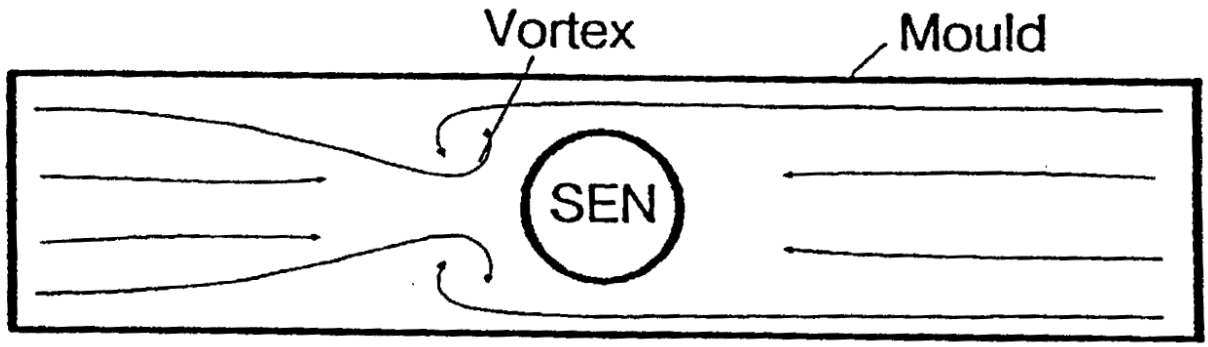
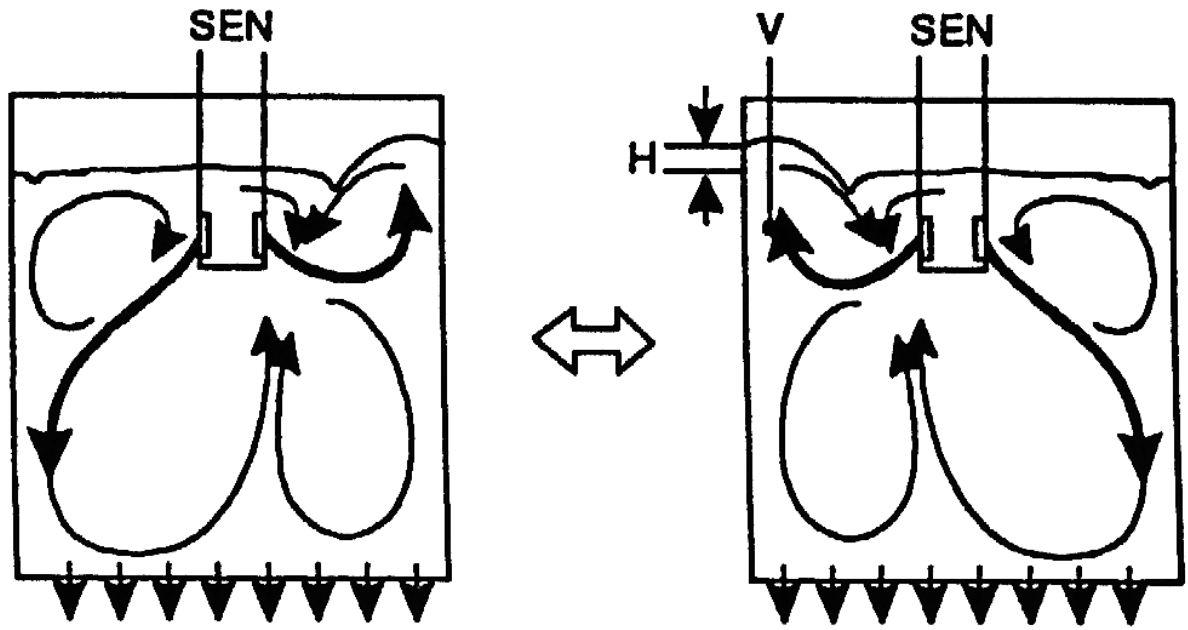


Fig. 4.3.14 Sample trajectories of five particles carried into the liquid pool, showing one large particle spiraling in lower recirculation zone towards solidifying shell on inside radius wideface [14]



(a)



(b)

Fig. 4.3.15 Mold slag entrainment due to detrimental high speed asymmetric flow pattern
a) vortexing at the top surface and [19]

b) asymmetric oscillatory flow in the liquid pool [23]

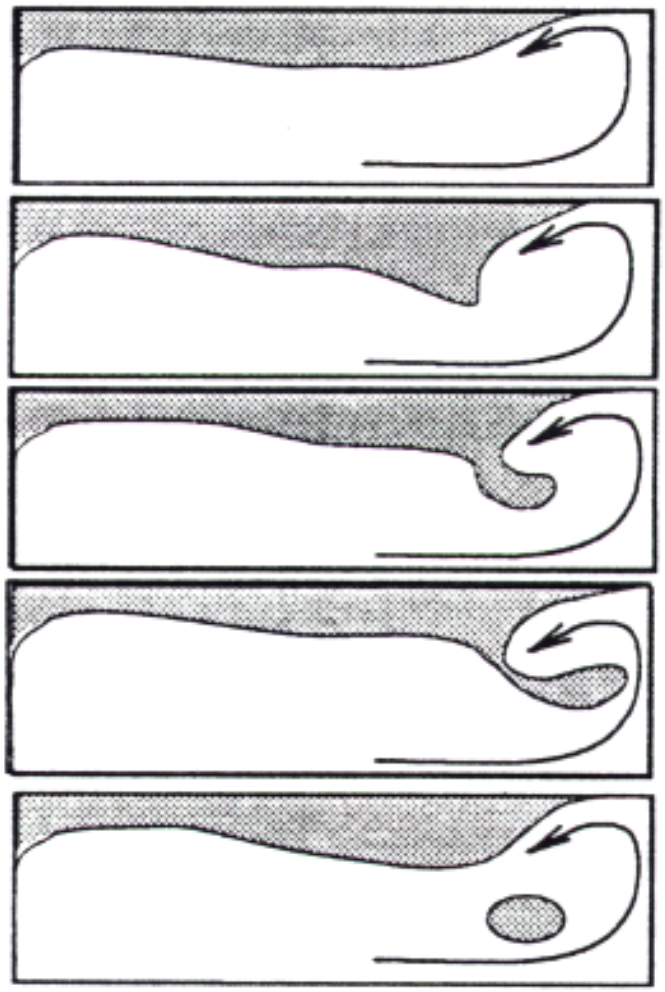


Fig. 4.3.16 Steps in slag entrainment due to excessive surface flow [20]

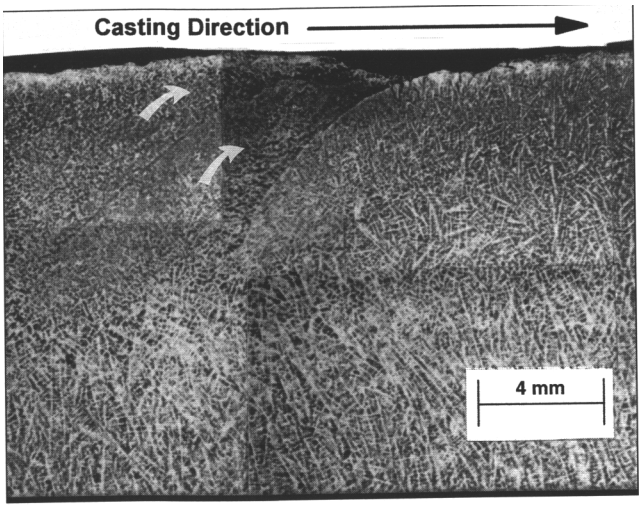


Fig. 4.3.17 Microstructure associated with overflow of the meniscus, shown for a lap depression defect in a billet. [29]

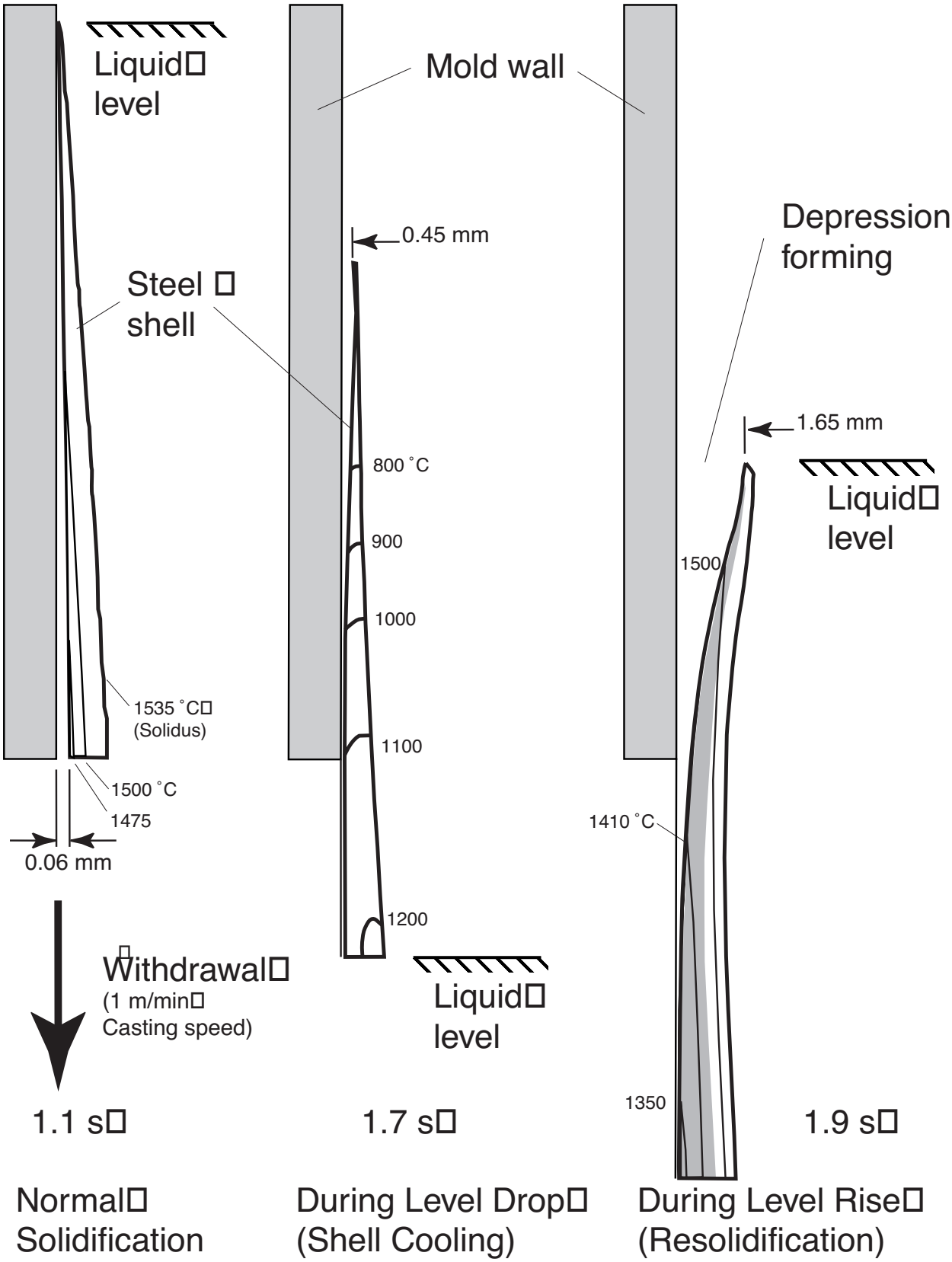


Fig. 4.3.18 Events calculated to occur during a severe, level drop (20 mm for 0.6 sec) which lead to a transverse surface depression [30]

Fig. 4.3.19 Severe transverse depression defect on a bloom surface

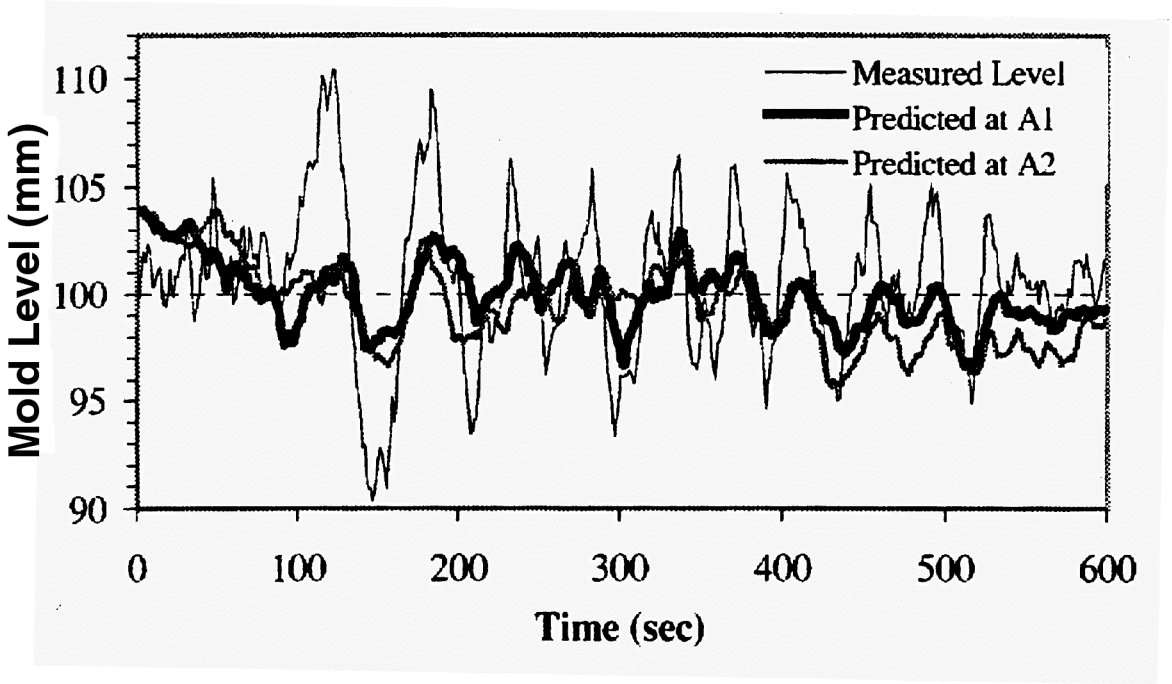


Fig. 4.3.20 Mold thermocouple signals correlated with level sensor measurement [35]

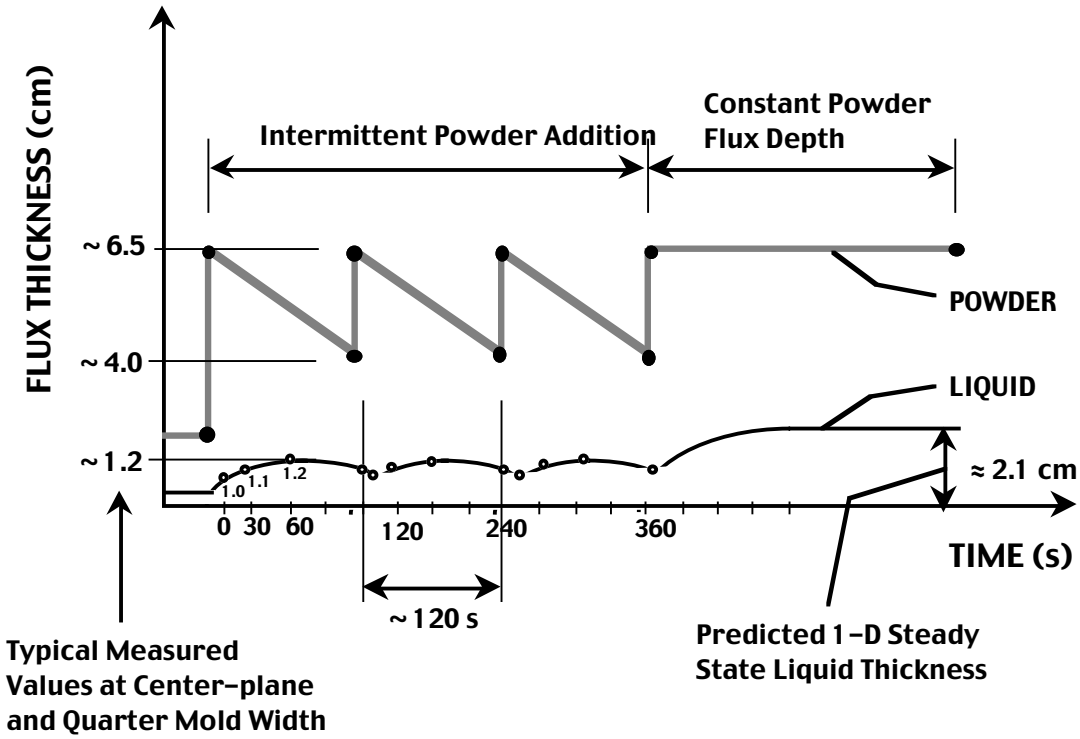


Fig. 4.3.21 Variation in flux layer thickness caused by intermittent powder addition, compared with steady-state maximum thickness [39]

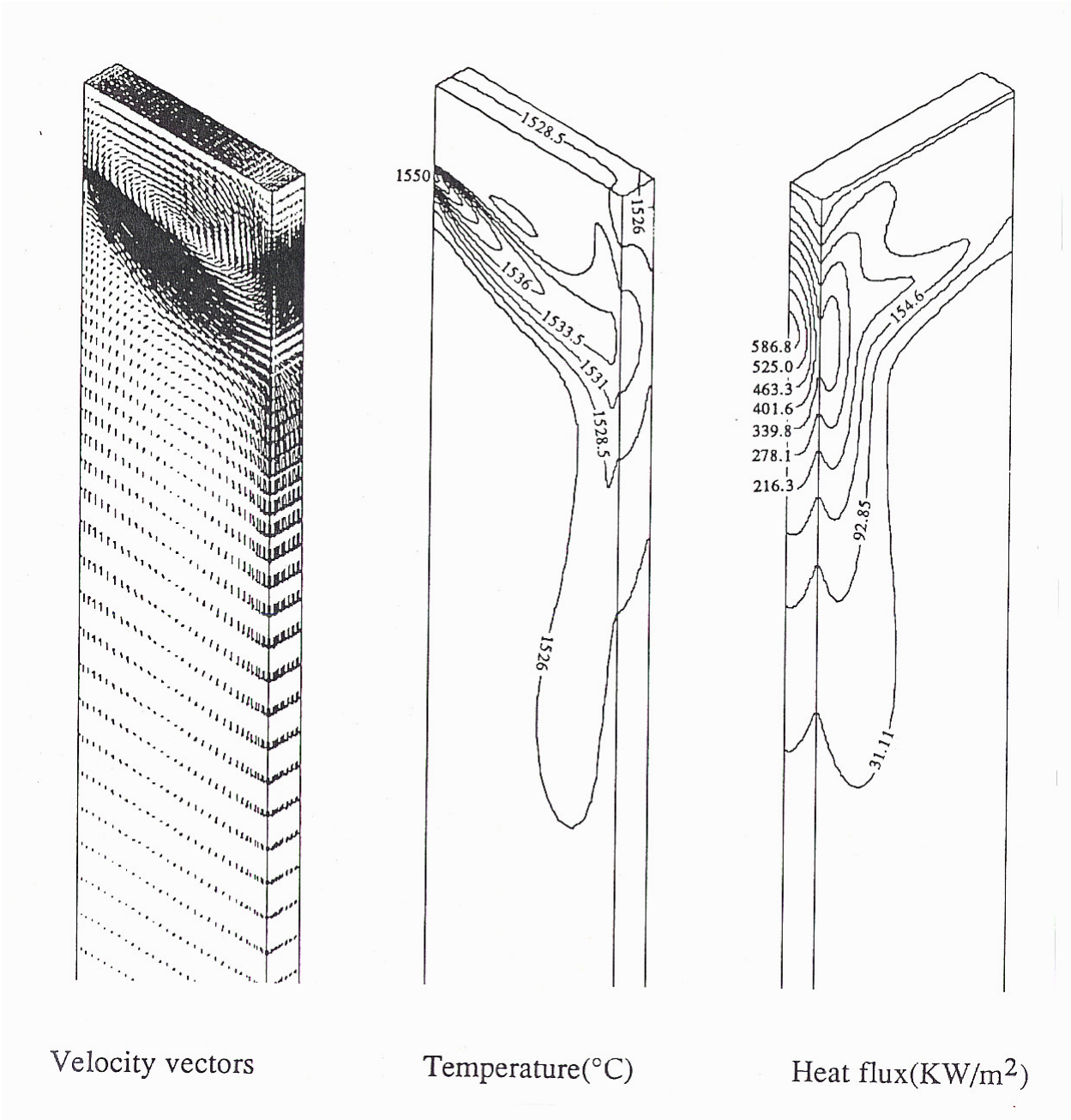


Fig. 4.3.22 Fluid flow velocities, temperatures, and superheat fluxes delivered to the inside of the solidifying shell calculated in the mold region of a continuous slab caster (220 x 1320 mm slab cast at 1.0 m/min) [42]

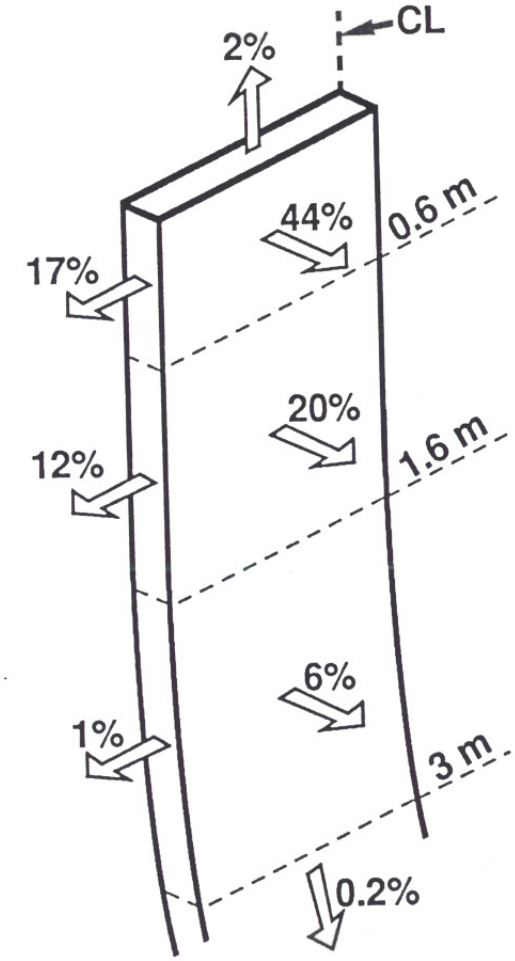


Fig. 4.3.23 Calculated distribution of superheat delivery to the shell [42]

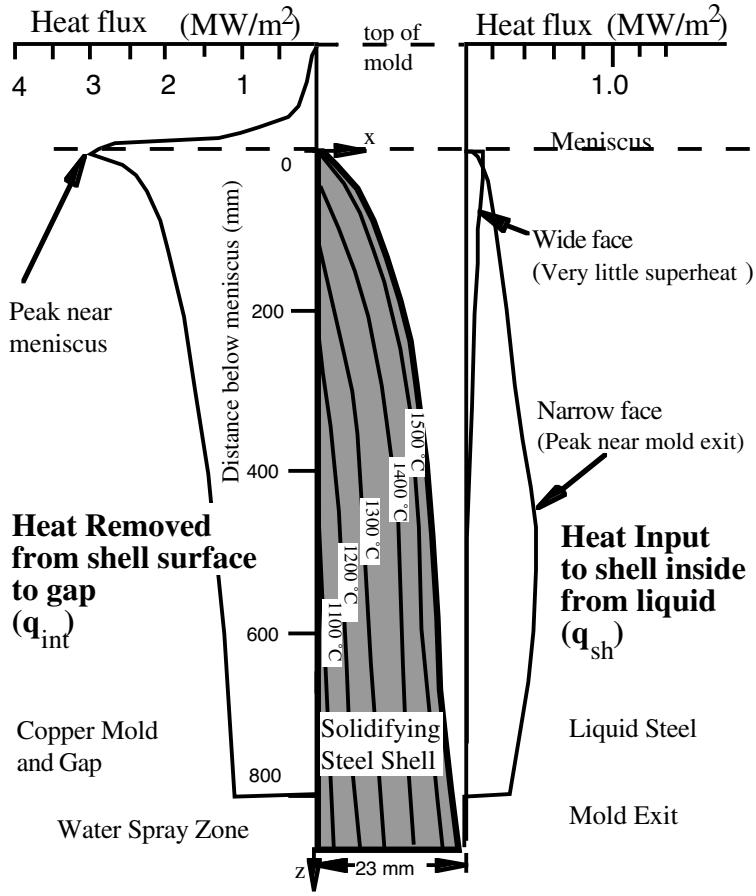


Fig. 4.3.24 Schematic of heat transfer through solidifying shell (narrow face) showing isotherms and heat flux profiles [42]

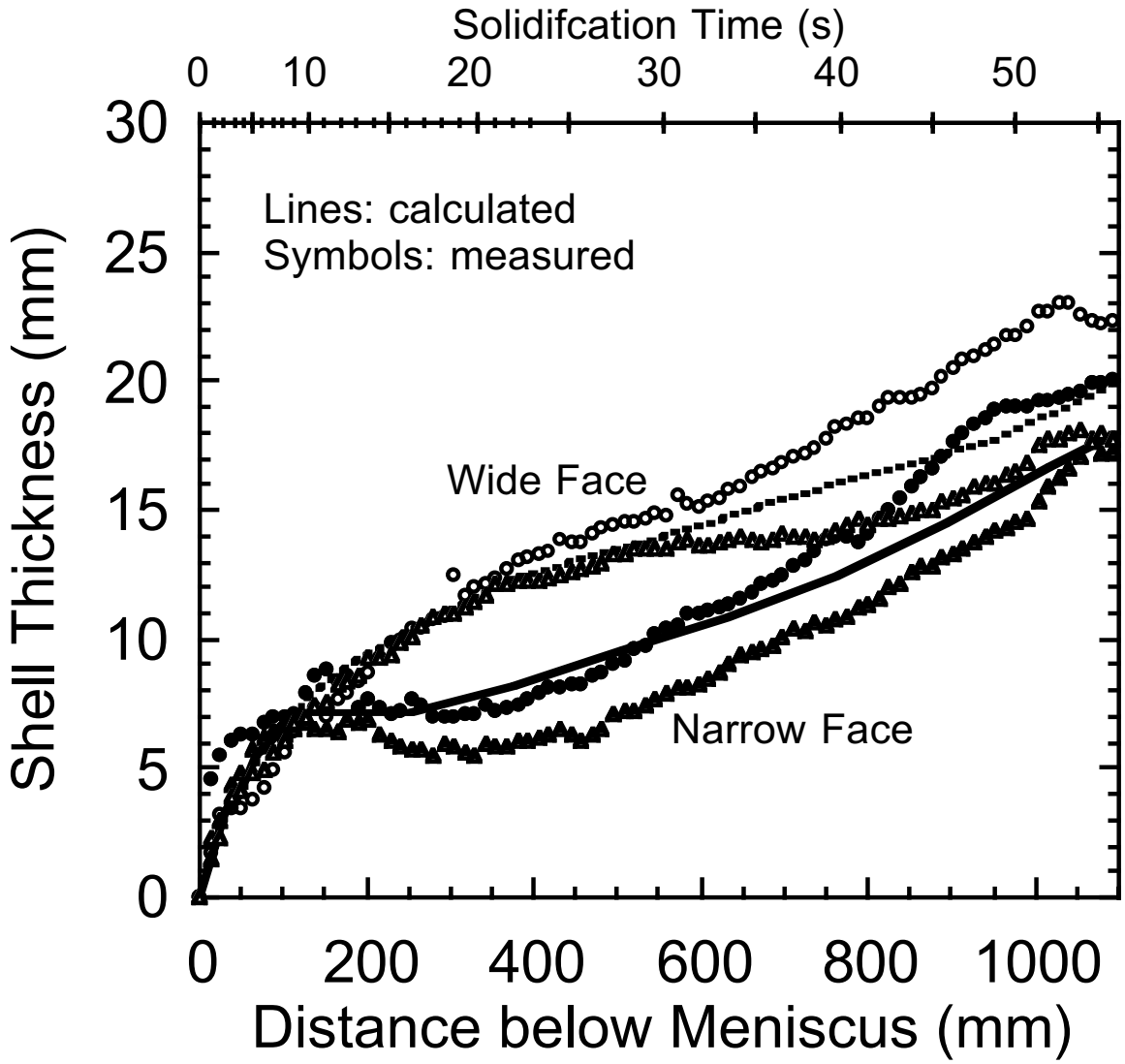


Fig. 4.3.25 Breakout shell thickness profiles showing thin region near location of jet impingement on narrow face, relative to steady shell growth down wide face. [44]

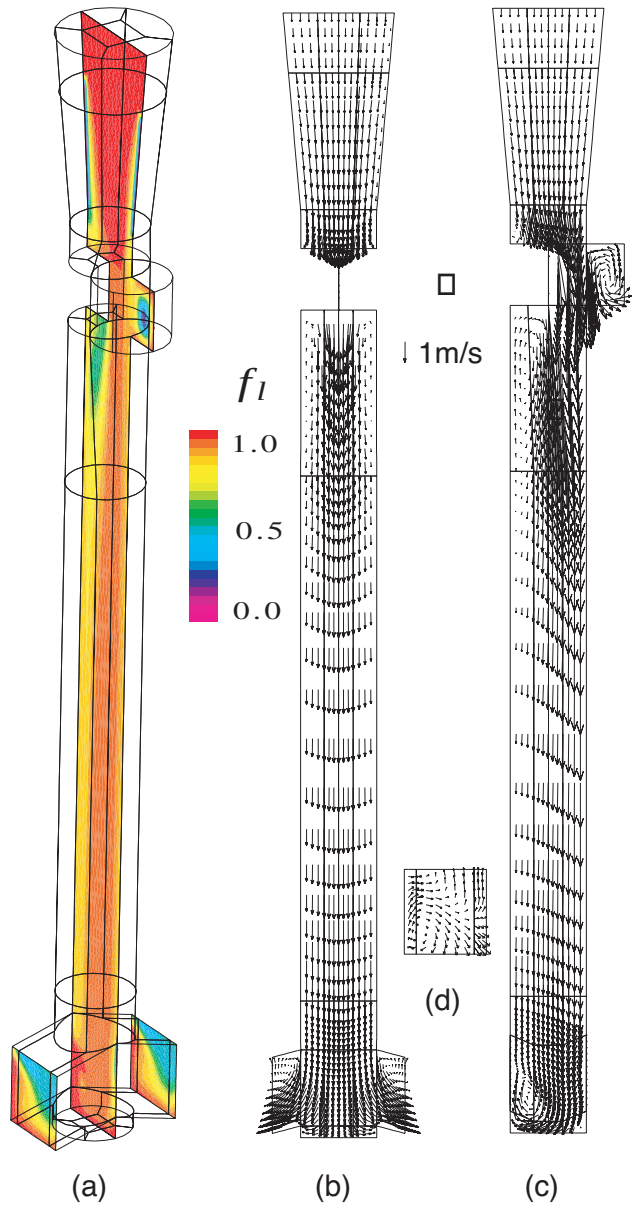


Fig. 4.3.26 Simulated flow field for a typical nozzle (16% gas; 50% open; 90˚ slide gate; 78-mm bore; 78-mm square ports) [6]

(a) Argon gas distribution (b) Velocities in center plane parallel to WF

(c) Velocities in center plane parallel to NF (d) Velocities at port outlet plane

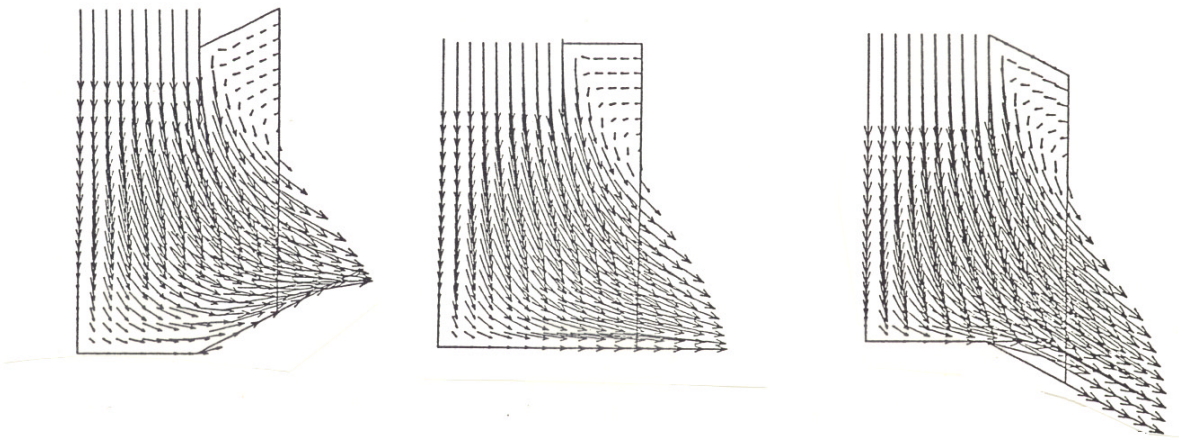
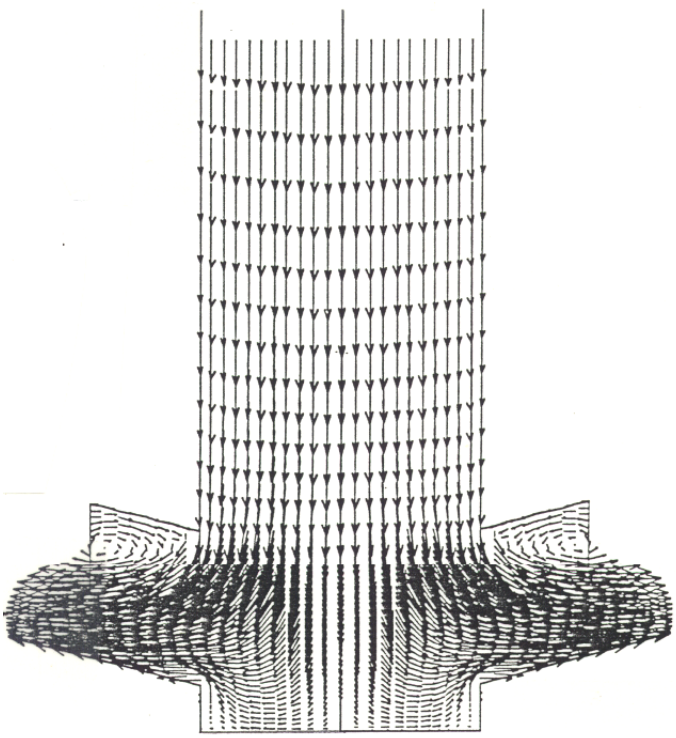


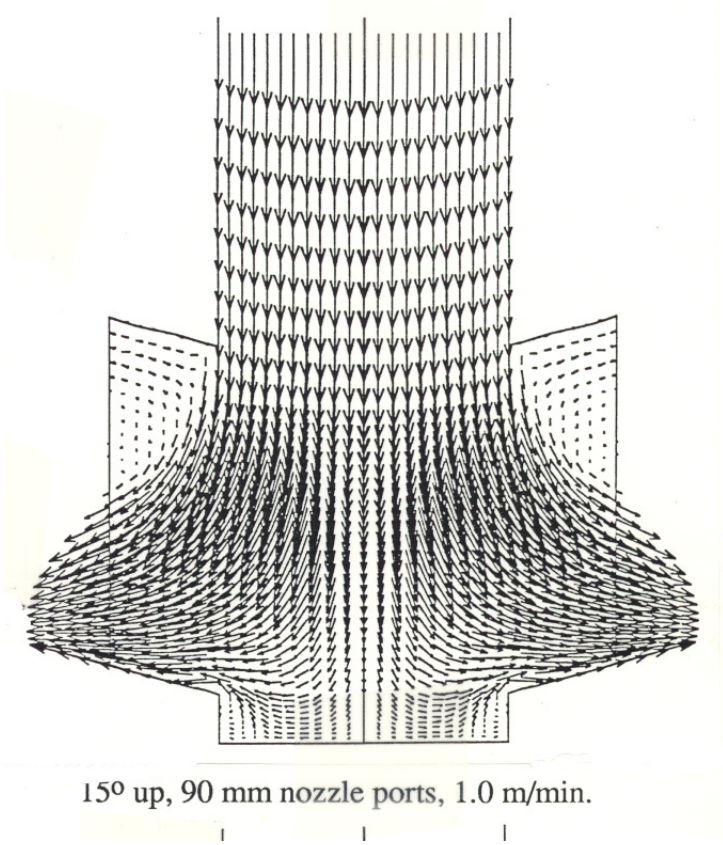
Fig. 4.3.27 Nozzle angle effect on flow exiting nozzle [46]



15° up, 45 mm nozzle ports, 1.0 m/min.

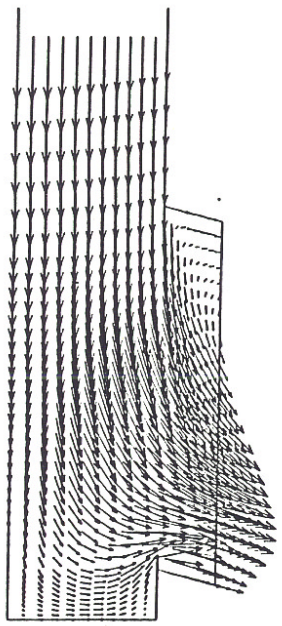
a)

Fig. 4.3.28 Port size effect on jets exiting nozzle (15˚ up, 1.0 m/min) [49]
a) short (45 mm) port height
b) tall (90 mm) port height

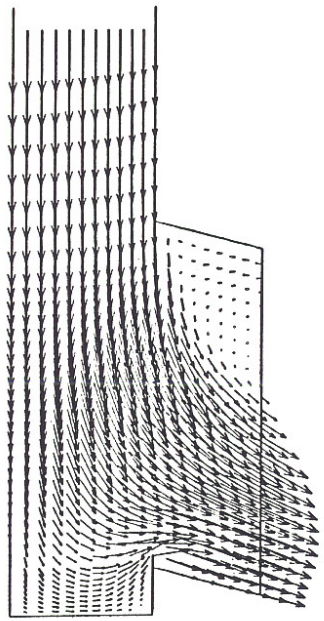


b)

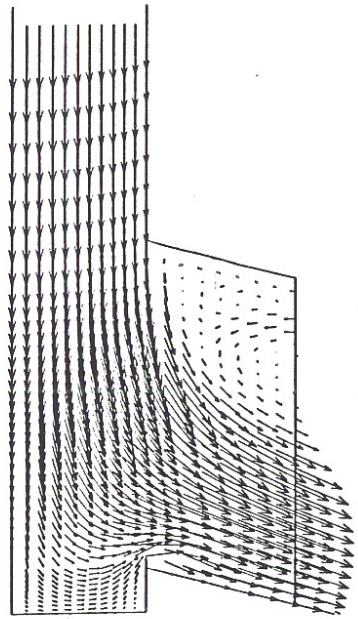
Fig. 4.3.28 Port size effect on jets exiting nozzle (15˚ up, 1.0 m/min) [49]
a) short (45 mm) port height
b) tall (90 mm) port height



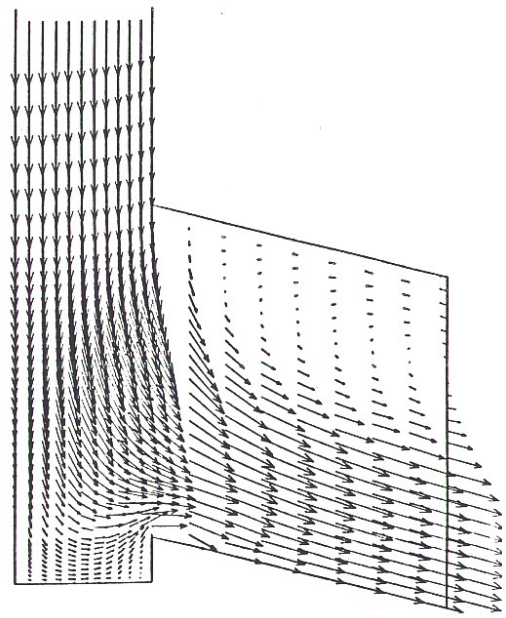
12 mm



25.5 mm



38 mm



76 mm

Fig. 4.3.29 Nozzle bore thickness effect on straightening flow exiting nozzle [49]

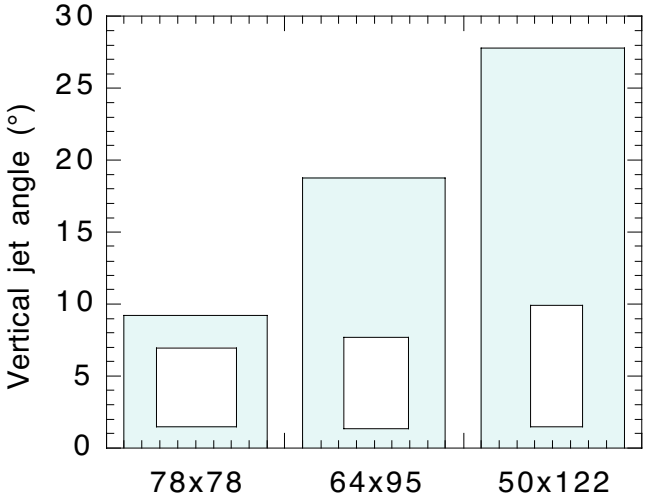


Fig. 4.3.30 Port shape effect on jet angle leaving nozzle [6]

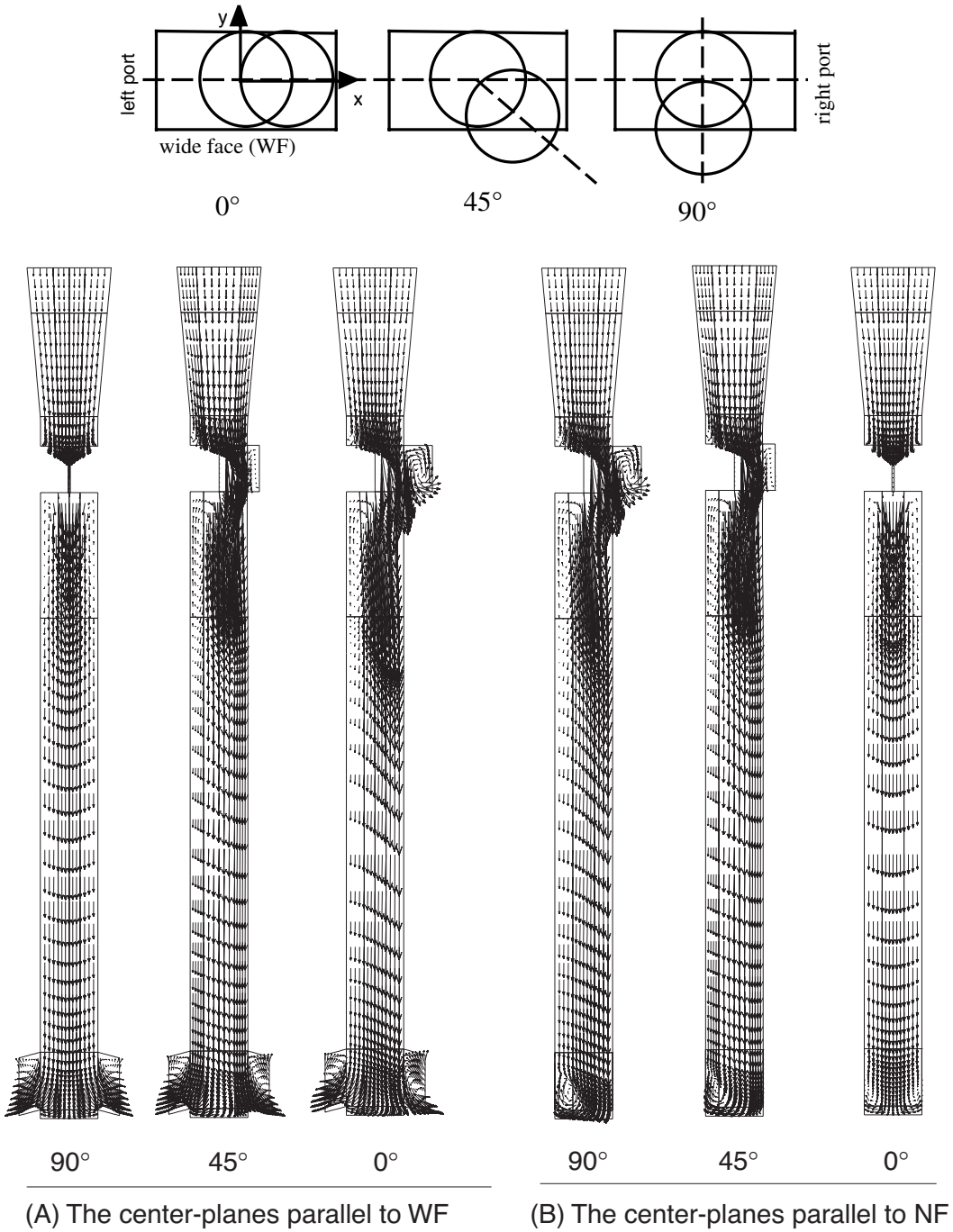


Fig. 4.3.31 Slide gate orientation effect on flow exiting ports [6]

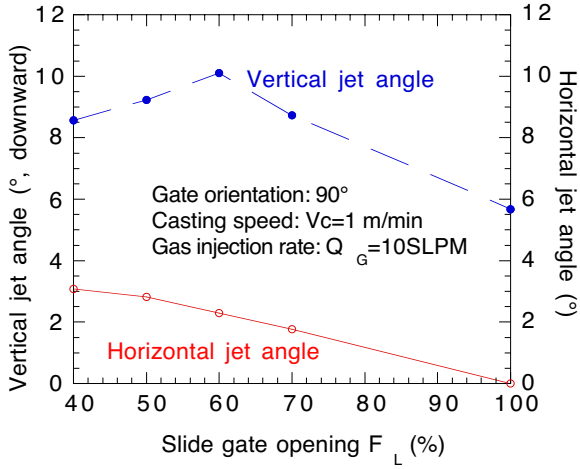


Fig. 4.3.32 Slide gate opening fraction effect on jet angles (90˚ gate orientation) [6]

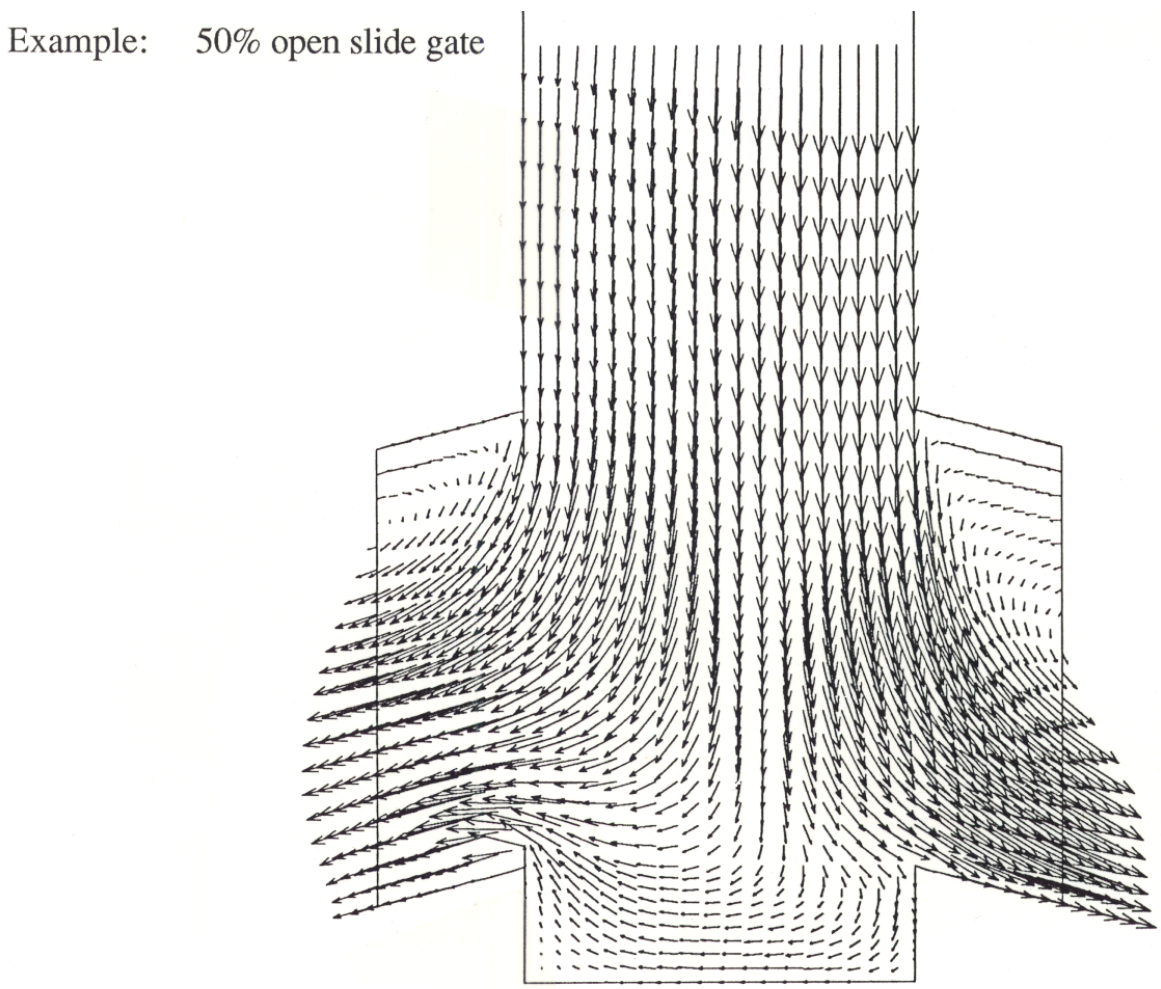
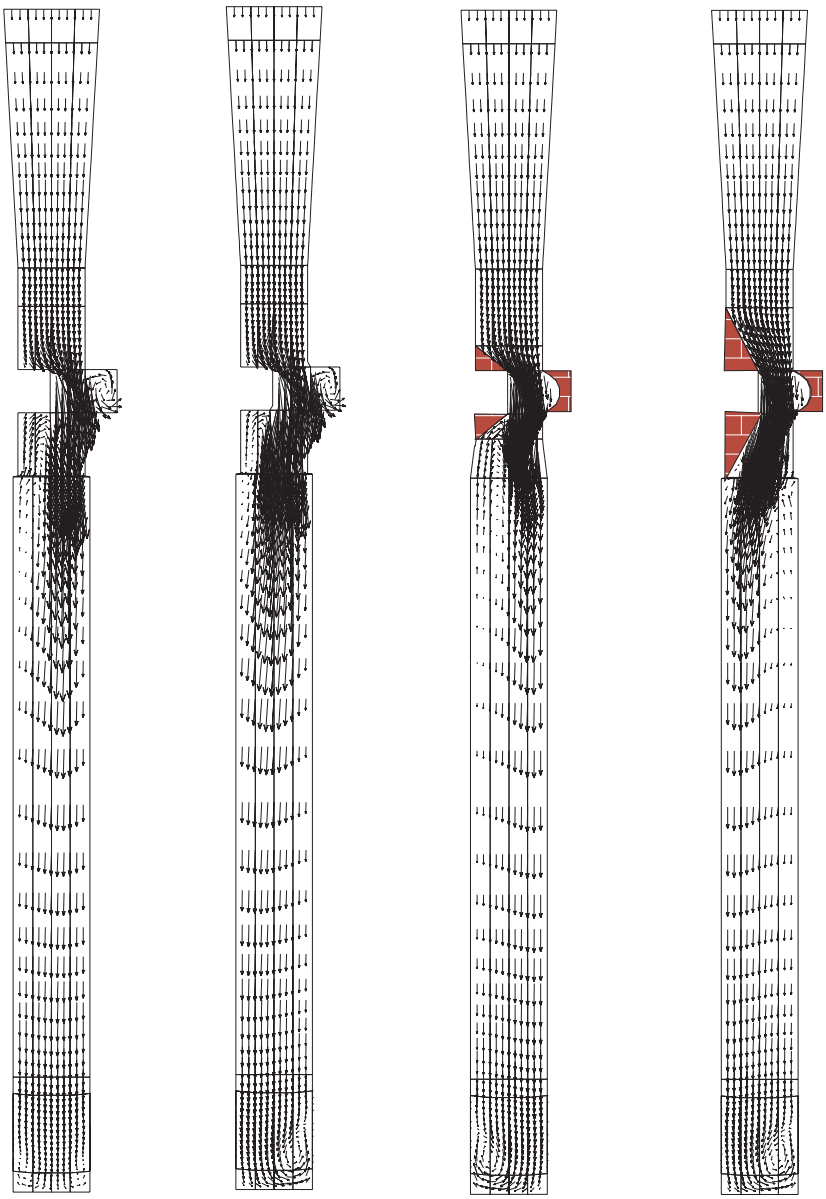


Fig. 4.3.33 Biassed flow caused by 50% open slidegate (0˚ gate orientation, no gas) [6, 54]
Left port has: 60% of mass flow and 17˚ down jet
Right port has: 40% of mass flow and 26˚ down jet



(a) Sharp edge (b) Round edge (c) Initial clogging (d) More initial clogging

Fig. 4.3.34 Effects of initial clogging and rounded edges on nozzle flow pattern [6] (view looking into port for 90˚ gate orientation)

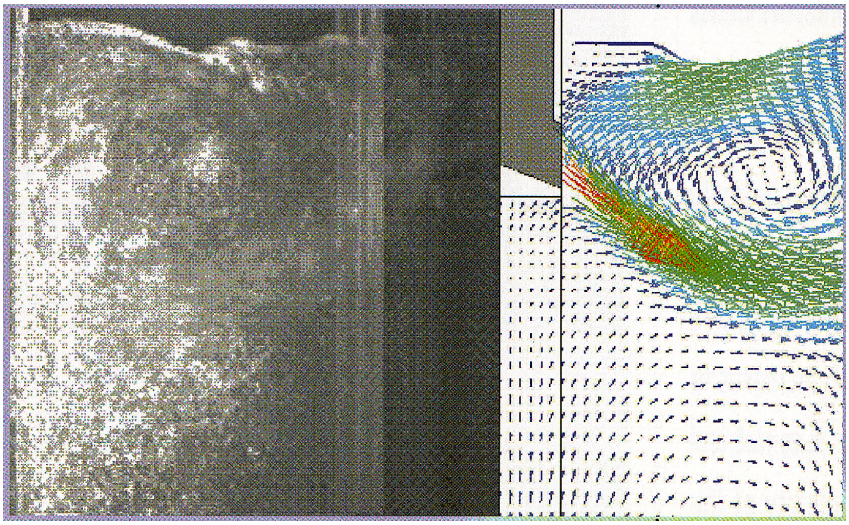


Fig. 4.3.35 High casting speed effect on surface turbulence [55]

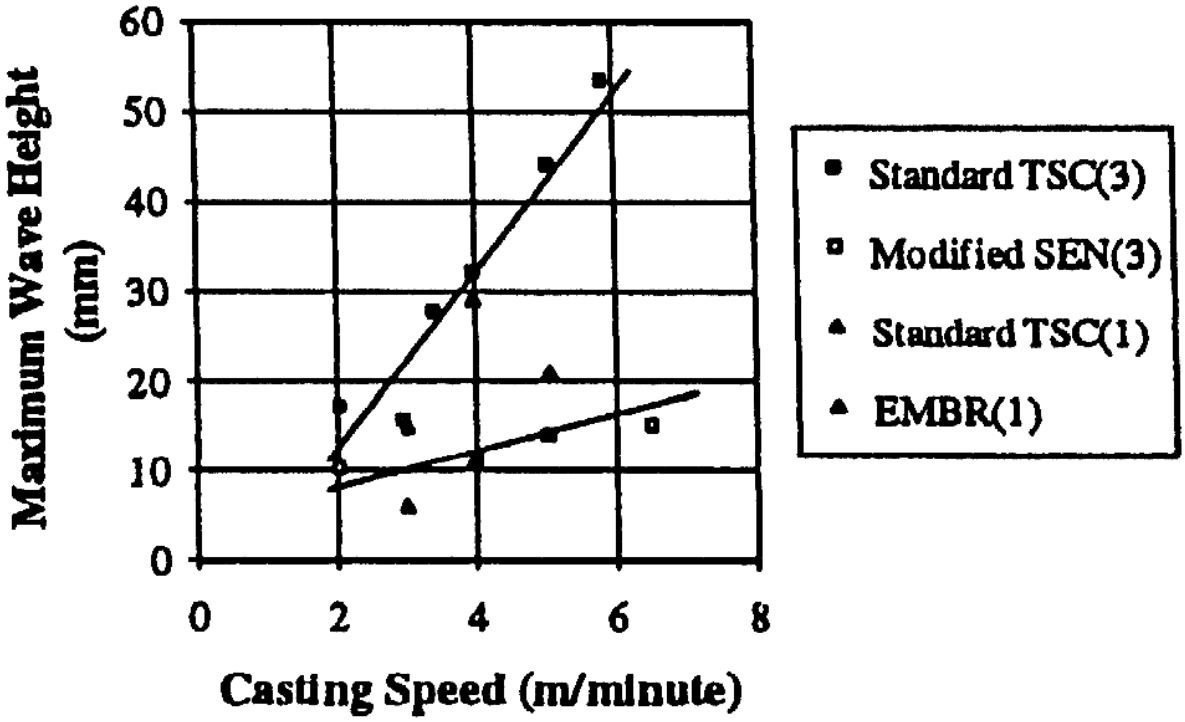


Fig. 4.3.36 Casting speed effect on surface wave height [23]

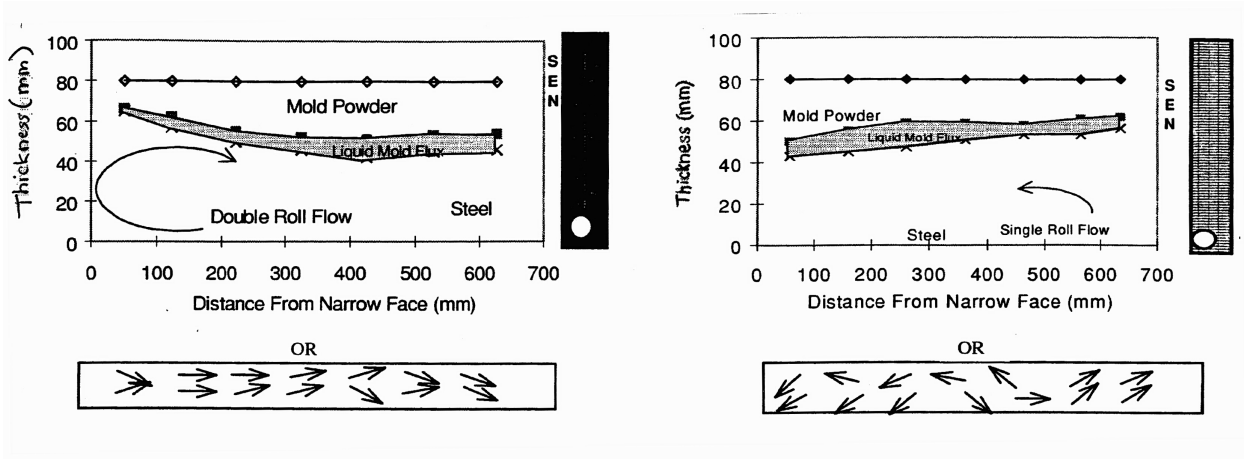


Fig. 4.3.37 Argon gas injection effect on flow pattern in mold and powder layer thickness a) 6.5 SLPM (11% gas) b) 13 SLPM (15 % gas) [9]

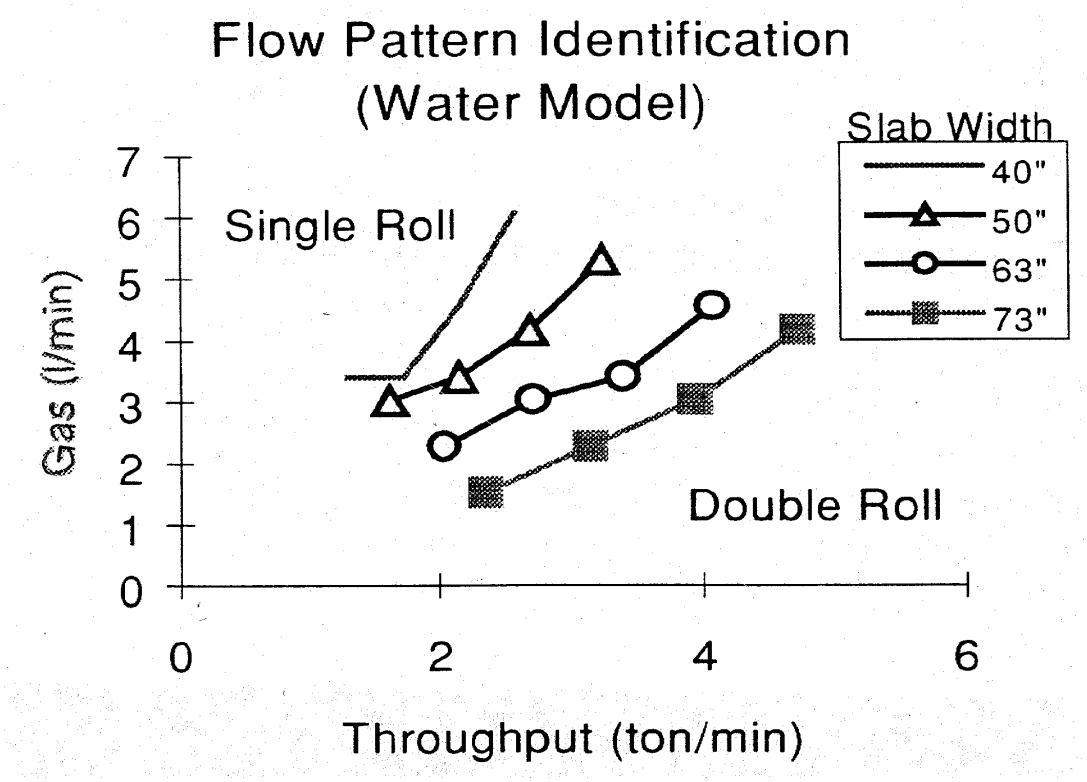


Fig. 4.3.38 Casting speed, gas injection, and strand width combined effects on type of mold flow pattern [9]

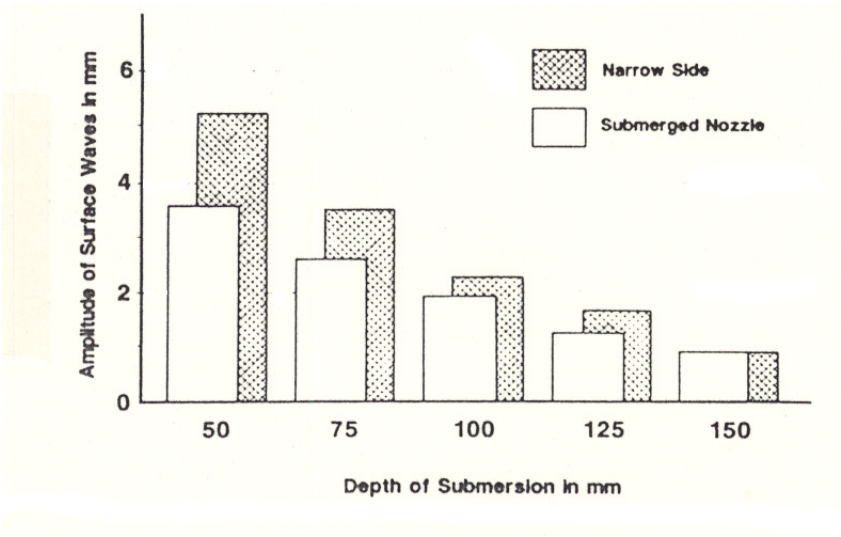


Fig. 4.3.39 Nozzle submergence depth effect on surface waves [60]

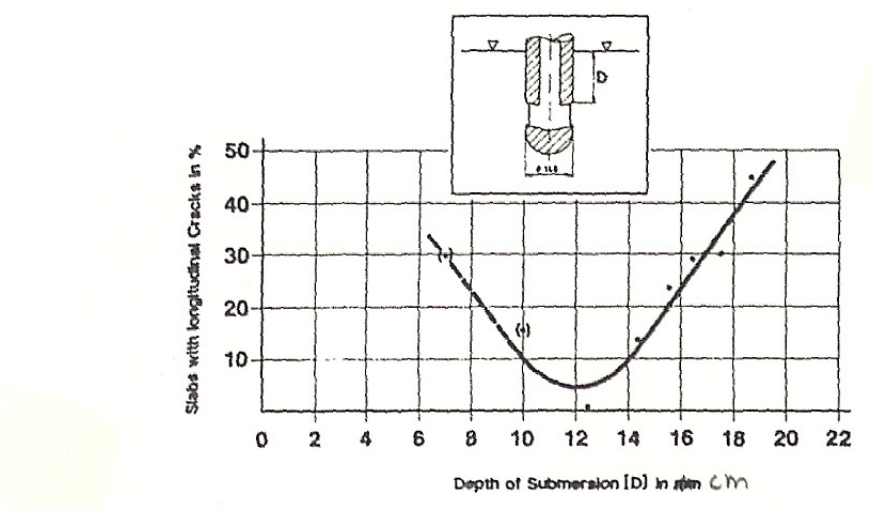


Fig. 4.3.40 Nozzle submergence depth effect on defects (longitudinal cracks) [60]

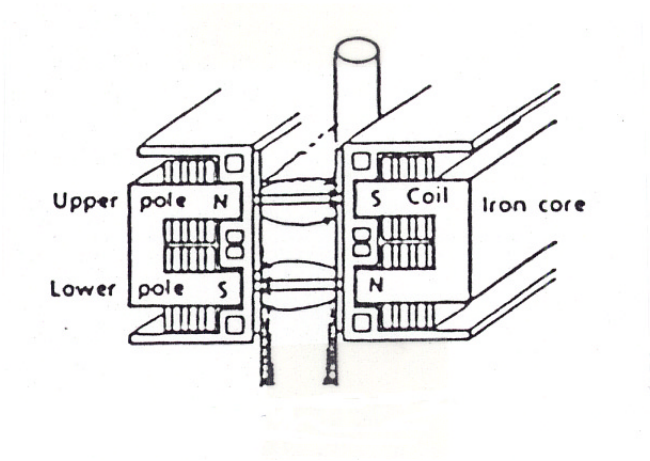


Fig. 4.3.41 Electromagnetic brake coils

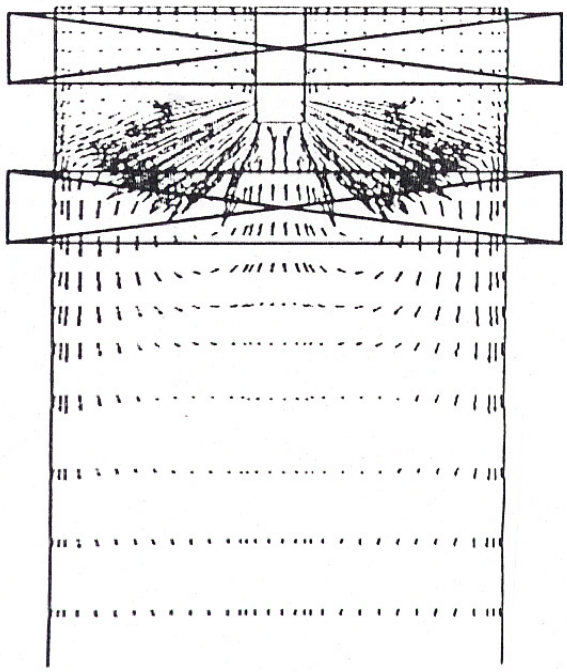


Fig. 4.3.42 Electromagnetic brake effect on mold flow pattern [61]

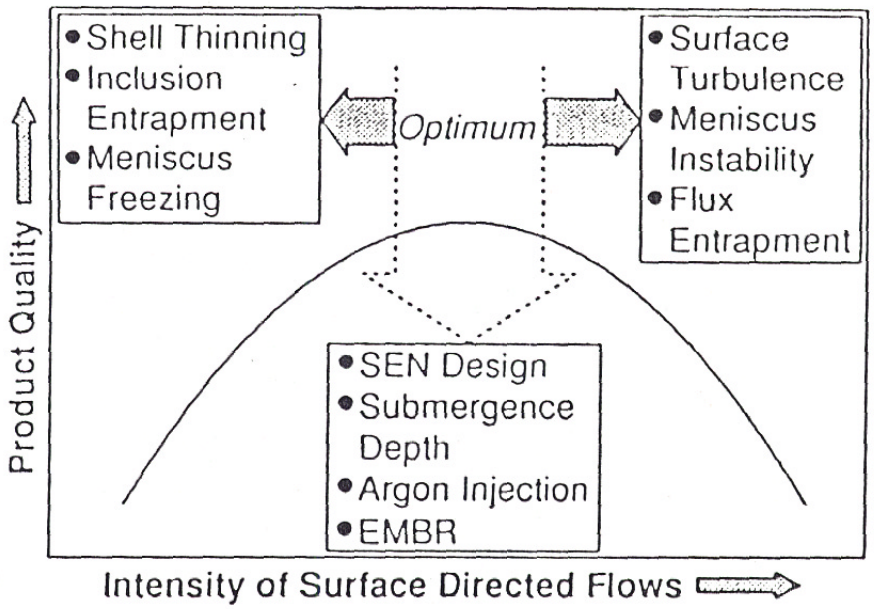


Fig. 4.3.43 Summary of fluid flow parameters effect on surface directed flow and corresponding effect on product quality [19]