The Importance of Computational Models for Further Improvements of the Continuous Casting Process

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INTRODUCTION

Continuous casting technology has advanced due to innovations resulting from knowledge gained from several different tools. These include expensive plant trials, laboaroray experiments, water models, and mathematical models. As the process becomes increasingly optimized and mature, simple trial and error is less likely to lead to success. At the same time, these trials become more costly, as more statistics must be gathered to quantify success. It is therefore important to have a correct understanding of the fundamental phenomena that occur in the process. Ideas which grow from deep understanding are more likely to lead to the successful trials and technology advances of the future.

Computational modeling is likely to play an increased role in generating this understanding in the future, as advances in both computer hardware and software are making the modeling tools more powerful.

Modeling has played a key role in many previous advances, which often involved relatively simple calculations. Examples include: unidirectional shell solidification models to design the containment length for a specified maximum casting speed; beam bending analysis to design support roll spacings to reduce bulging and internal cracks; thermal analysis to optimize water slot geometry to control mold hot face temperature, and shell shrinkage analysis to design parabolic tapers for billet molds. Modeling pioneers who contributed to continuous casting understanding include Brimacombe, Samarasekera, Schwerdtfeger, Wunnenberg, Fredriksson, Emi, Ohnaka and many others.

This paper will present a few examples of computational models and the practical insights obtained from them. Due to space limitations, these examples will be taken only from work at the University of Illinois, although it is recognized that multitudes of other examples can be found elsewhere.

IMPLEMENTATION OF PROCESS MODELS

Models can be implemented to bring about tangible process improvements in several different ways, which are illustrated schematically in **Fig. 1** [1]. Rooted in the fundamental laws of nature, numerical methods, and material property data, detailed simulations can improve basic understanding of the process. "Literature models" models are run only by the developer, so the understanding is communicated to process engineers through published results. New ideas may follow the increased understanding, which eventually may lead to process innovations. Alternatively, the engineer can run offline models to quantify and test hypotheses. In addition to generating confidence that an idea might work, these models can demonstrate the infeasibility of faulty ideas without expensive trials. Good ideas can be refined using offline models and optimized to select trial conditions. These models rely on careful lab experiments, physical models, and the results from plant trials in order to be accurate.

The process understanding at the center of this paradigm comes from many different sources, including modeling. The process engineer is sometimes temped to short circuit process understanding and rely solely on the results of plant trials to design trials to improve the process. This is the mode often used in "fire fighting" costly process problems. Although often successful in the short term, solutions achieved in this way can recur later. In addition, this trial and error approach requires many expensive trials.

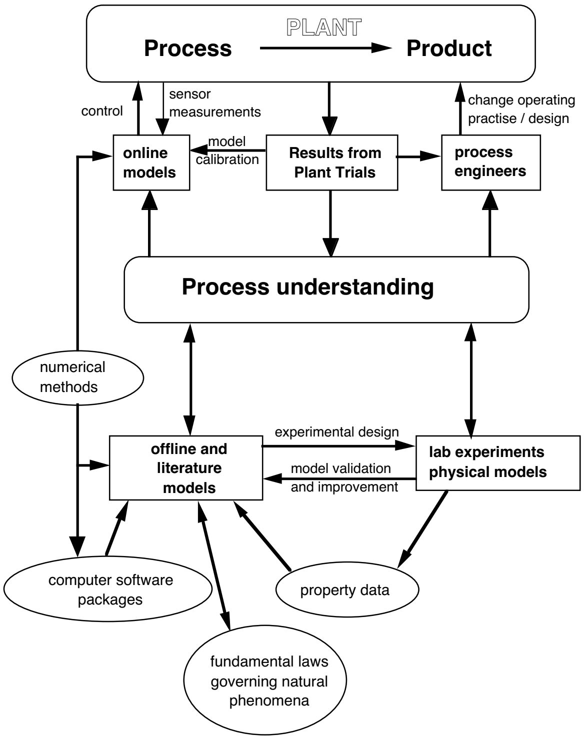


Fig. 1: Implementation of process models [1]

Ultimately, process understanding can be implemented into the process directly through online models. In the past, these models are often simple control algorithms, which rely heavily on feedback from sensors, such as mold level controllers. As computing power advances, online models are also advancing. Dynamic spray cooling models adjust water spray histories more accurately when based on true transient finite difference models of strand heat transfer. Knowledge regarding the mechanism of sticker breakout formation is quantified into sticker breakout detection systems to recognize the charactoristic temperature histories. Future online models will be used to process more thermocouple signals to detect other types of defects, perhaps using expert systems or other advanced algorithms. Before this is likely, the detailed understanding of how these defects form and relate to mold temperature histories must improve.

FLOW SIMULATION

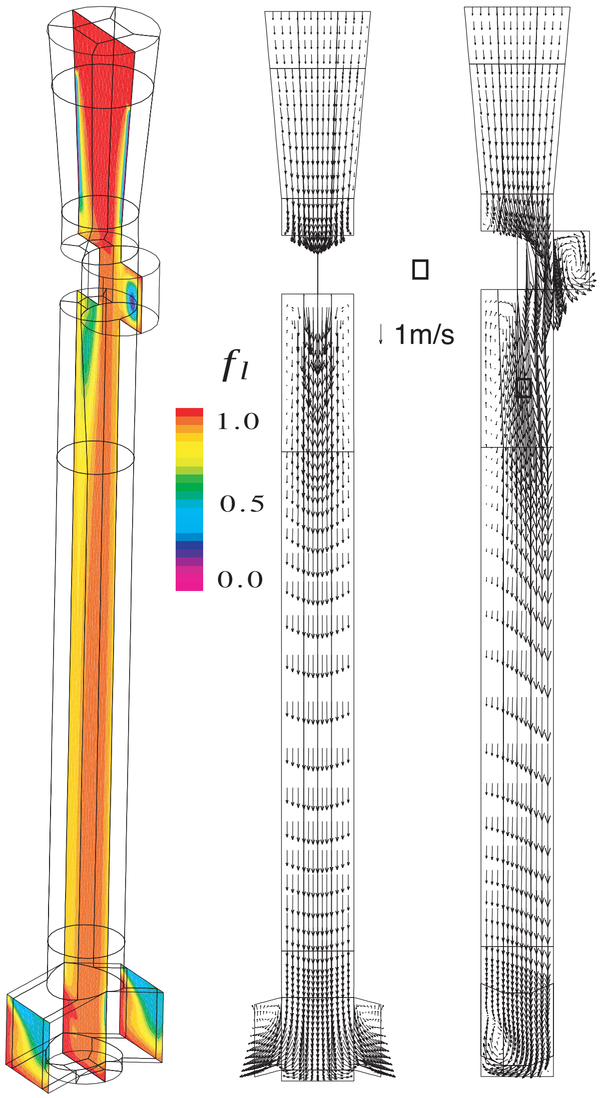
Many important advances have been made to continuous casting metal delivery systems through the use of water models. Tundish flow control devices and nozzle design improvements have come about through optimization based on the understanding obtained by visualizing the flow using these physical models. However, water models have difficulty in simulating multiphase flow (such as argon gas injection), due to the inherent differences between the physical properties of the steel / argon and water / air systems. Similar difficulties exist in the modeling of heat transfer in the liquid pool, solidification, and interactions between the liquid slag layer and the steel. These inaccuracies are one reason why extensive plant trials are still required to test new innovations in flow control devices.

Mathematical models have the potential to overcome these difficulties. Unfortunately, the simulations are still so difficult that to date, they have generally been no more accurate than water models. Important phenomena such as vortexing and slag entrainment are still slightly beyond the capability of numerical simulation. With improving computational power, this will change in the future.

The following subsections present examples of flow simulations applied to help optimize nozzle design, optimize argon injection, minimize transient flow, and optimize top surface powder layer behavior.

Nozzle design optimization

Past computational models of flow in nozzles have simulated steady state (time-averaged) velocity and pressure fields using turbulence models such as K-ε [2-6]. Sample simulation results are shown in **Fig. 2**, which illustrates three-dimensional multiphase flow through a typical slide gate nozzle, for a 203 x 1320 mm slab cast at 1.0 m/min with 10SLPM Ar injection, 50% gate opening, and 90° orientation of the slide gate. Note that the 90˚ orientation minimizes asymmetry between the two ports (B), but creates significant swirl flow in the jets (C). Previous simulations have shown that the 0˚ orientation generates significant asymmetry between the mass flow of the two jets entering the mold cavity, which causes detrimental bias flow in the mold and surface defects. Simulations predict that the 45˚-orientation gate exhibits both types of asymmetry at almost the same level. Use of the latter two orientations has declined because of this.



(A) (B) (C)

Fig. 2: Simulated flow field for a typical nozzle (A) Liquid steel / argon gas fraction (B) Velocities in center plane parallel to WF (C) Velocities in center plane parallel to NF [7]

Gas is observed to collect in the cavity of the slide gate, beneath the throttling plate, and at the top of the exit ports in **Fig. 2** (A). These gas pockets encourage bubble coalescence, leading to occasional surges of gas and corresponding flow disruptions in the mold.

The flow characteristics at nozzle outlet have been characterized for a wide range of nozzle geometries and casting conditions [7]. Proprietary design changes have been made to nozzle and port geometry at several different companies, based in part on the understanding gained from modeling results such as these.

Argon injection optimization

The model results have been applied further to investigate the minimum argon gas flow rates needed to raise the internal pressure inside the nozzle to avoid air aspiration. This is one of the ways in which argon acts to reduce nozzle clogging. The pressure drop calculated over the nozzle can be related to the tundish level needed to drive the flow using Bernouli's equation [6]. **Fig. 3** shows that the pressure just below the throttling plate may drop below atmospheric pressure for some conditions. This can lead to air aspiration through the joints or walls (if the ceramic is porous). Model simulations have been applied to optimize argon injection to avoid this problem [6].

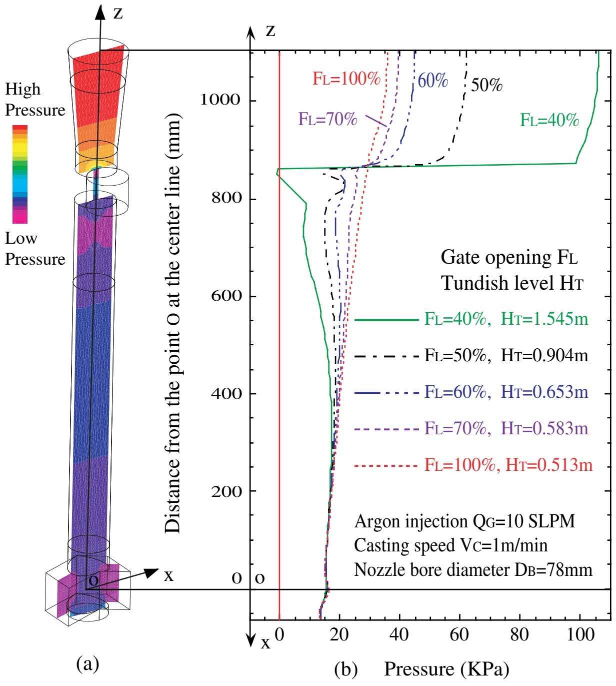


Fig. 3: Pressure distribution in an SEN (a) Shaded contour plot at the center-plane (b) Pressure profile along the centerline [6]

The particular nozzle investigated features argon injection into the lower portion of the upper tundish nozzle (UTN) just above the slide opening through a porous refractory wall chosen to produce uniform 1-mm bubbles. It had a 241 mm long upper tundish nozzle, 748 mm long SEN, with 78 mm bore diameter and 78 mm x 78 mm 15˚down ports.

Fig. 4 illustrates that increasing argon flow rate is indeed beneficial in being able to increase the minimum pressure in the nozzle. It is interesting to note, however, that part of this benefit arises simply due to the increase in slide gate opening required to accommodate the increased total volumetric flow. Increasing the gate opening also tends to reduce the pressure drop (for a given flow rate).

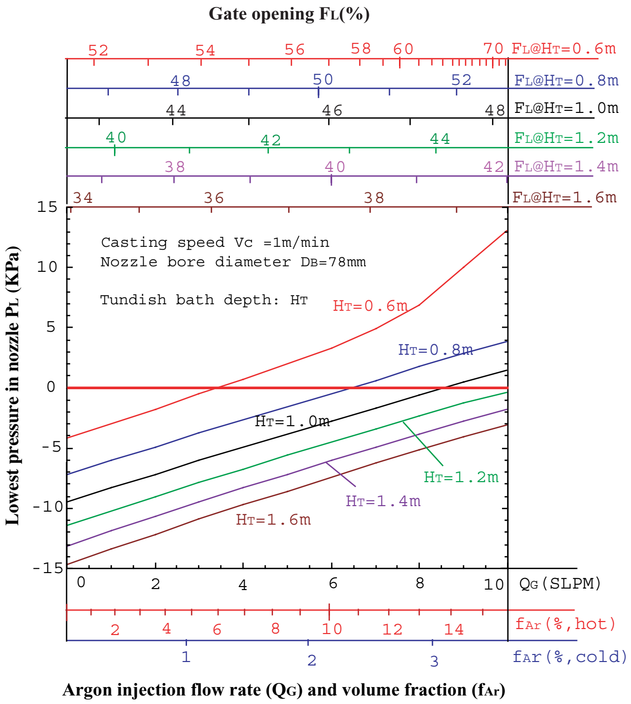


Fig. 4: Effect of argon injection flow on raising minimum pressure in the SEN for constant tundish depth and casting speed [6]

The results from many simulations of this nozzle using different slide gate openings, casting speeds, and argon gas levels were compiled together to determine the minimum argon flow rate required to just avoid negative pressure. **Fig. 5** shows the results.

Less argon is needed if the nozzle bore size is chosen to avoid intermediate casting speeds so that the gate is either nearly fully open or is less than 50%. With increasing tundish depth, more argon is needed. Specifically, for high casting speeds, a 0.2m increase in tundish bath depth typically will require an additional 5 SLPM of argon to compensate the vacuum effect. For deep tundishes, popular for avoiding inclusion entrainment and carryover, it is infeasible for argon to avoid the vacuum effect.

During slowdowns, the percent argon gas fraction increases while the tundish head and casting speed both decrease, which reduces the aspiration tendancy. Other modeling has shown the dangers of excessive argon gas in terms of radical changes to the fluid flow pattern in the mold cavity. Consequently, the argon gas flow rate used in several different plants has been decreased – both during steady casting, and particularly during slow-downs in operation. Some of the specific predictions for this particular nozzle have been validated with plant measurements [6]. and further implementation of these results is proceeding.

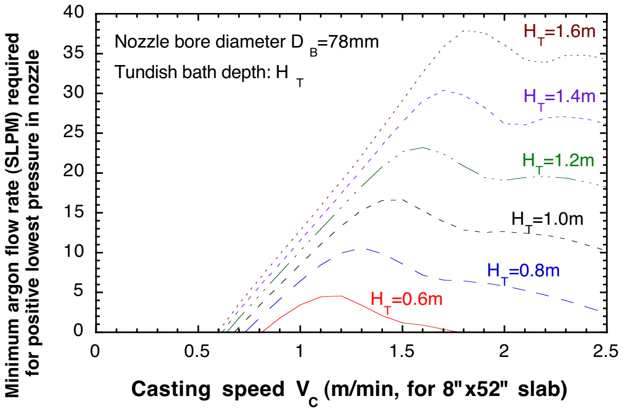


Fig. 5: Effect of casting speed and tundish depth on minimum argon flow rate required for positive pressure in nozzle [6]

Minimizing mold flow transients

Water models have traditionally been used to study complex flow phenomena in the mold. Computational models can help to understand the time-averaged flow patterns for steady casting conditions [8, 9], particularly when phenomena such as electromagnetic forces, heat, and mass transfer are of interest.

Recently, computational flow models have begun to be applied to shed light on transient phenomena, which are responsible for many of the important quality problems that arise during continuous casting [10, 11]. **Fig. 6** shows sample results of instantaneous velocity vectors calculated at the center plane of a slab caster using a 3-D direct numerical simulation (left) compared with measurements obtained using particle image velocimetry in a water model (right). Several hundred such frames were averaged to produce the time mean flow pattern, which consists of smooth flow loops both and below the jet. The differences between the time average and instantaneous flow patterns are quite striking, however. Intermittent flow structures often break away from the main flow. Such a structure is seen cutting across the lower recirculation zone in **Fig. 6**, greatly affecting particle transport in that region. Along the top surface, these transients create level fluctuations and temporary velocity increases that could entrain flux and cause other quality problems.

Although much of this complexity is due to the turbulent nature of the flow, the condition of the jet streaming from the nozzle is very influential also. Some nozzle designs lead to more surface turbulence than others do, for a given set of casting conditions.

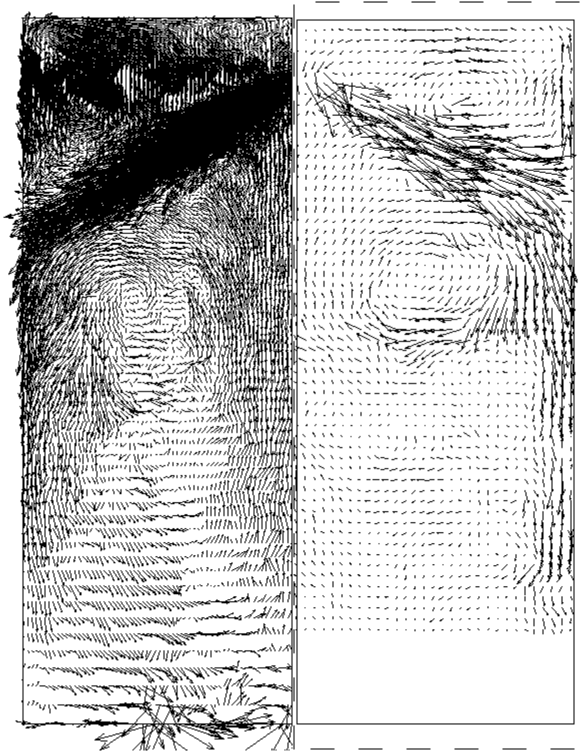


Fig. 6: Instantaneous velocity vector field in strand centerplane: simulated (left) and measured (right) [10]

It should be pointed out that computing power is still a major limitation of these transient calculations, as a month of supercomputer time was required for this two-minute simulation. Faster computers and algorithms will make this type of calculation increasingly popular in the future.

Top surface powder layer optimization

Understanding the behavior of the top surface flux layers is important to designing mold powders to ensure adequate flux feeding, and to avoid flux entrainment. Computational models are an important aid to plant experiments because the flow and thermal properties of flux and steel cannot be properly matched with water models.

An example 3-D computational simulation was performed for a typical double roll flow pattern for 1 m/min casting of a 230 x 1400 mm slab without gas through a 265 mm submerged bifurcated nozzle with 15°-down, 60 mm wide x 90 mm high rectangular ports [12]. The resulting interface profiles, shown in **Fig. 7**, reveal that the model is capable of matching plant measurements using nail board experiments [12]. The flux layer is dangerously thin near the narrow faces for these conditions, owing to both the raised contour of the steel and the shearing force from flow of steel towards the SEN.

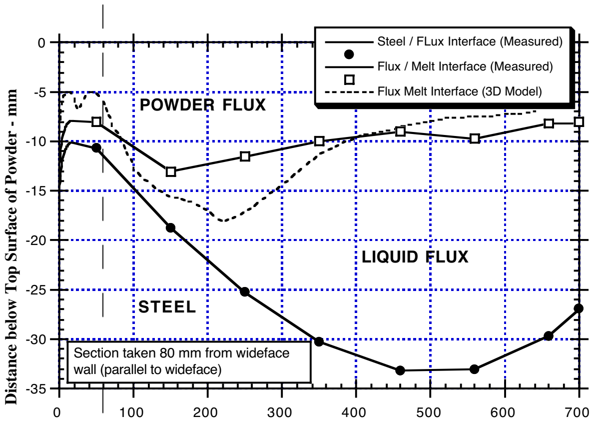


Fig. 7: Simulated and measured powder / liqiud flux interface showing thinner liquid flux layer near narrow face due to double-roll flow pattern [12]

The computational model can be further applied to investigate the effects of various practices on the behavior. For example, the results in **Fig. 8** show that intermittent powder addition leads to increased surface heat losses and thermal transients, which make the liquid flux layer thinner and variable over time. The increasing use of automated flux feeders may help to keep the powder depth constant, leading to steady and deeper liquid flux layers.

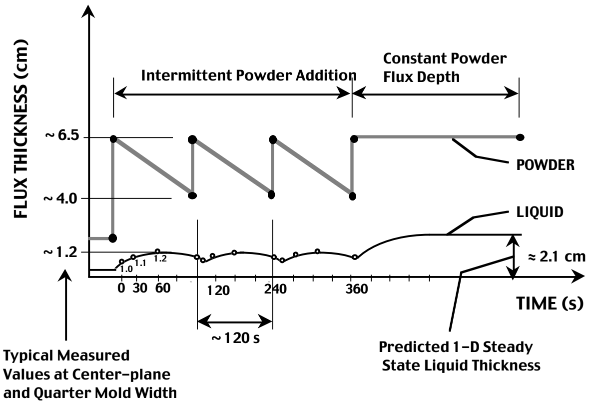


Fig. 8: Variation in liquid layer thickness caused by intermittent powder addition [12]

GRADE TRANSITION OPTIMIZATION

During sequence casting of different grades, composition variations arise in the product due to intermixing in the mold and in the strand. Models have been developed, validated, and calibrated to predict these composition differences, which exist both along the length and through the thickness of the slabs [13-15]. Many simulations under different conditions have revealed ways to change the casting conditions in order to minimize the intermediate region of the slab that must be downgraded [15]. The optimal solution depends on the cost of alternatives, such as flying tundish changes, grade separators and strand stoppages, the existance of a downgrade market, and the severity of the transition.

Example 3-D simulation results for composition evolution in a 220 x 1320 mm strand are shown in **Fig. 9** for a flying tundish change. New grade (composition = 1) is seen to penetrate into the old grade deep in the strand (composition = 0) faster than the casting speed, leading to centerline contamination of the old grade. This can be reduced with grade separators, thinner strands, lower casting speed (which reduces turbulence) and other changes. In addition, old grade persists in the mold and upper strand, leading to surface contamination of the new grade.

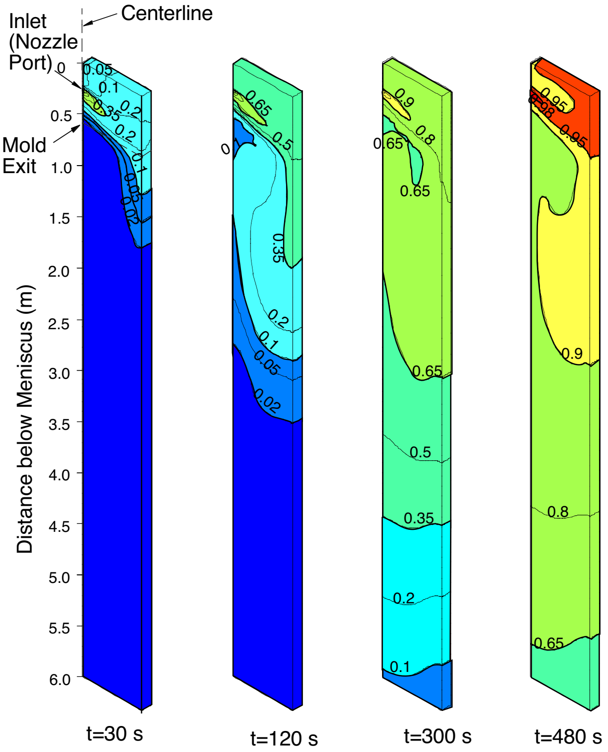


Fig. 9: Evolution of relative concentration in strand after a flying tundish change with no grade separator [13]

Sample predictions of the composition variations produced in the final slab are shown in **Fig. 10**. This simulation is for a 10.2 tonne tundish refilled from 4.1 tonnes in 90s feeding into a 200 x 1320 mm slab cast at 1.13 m/min. The results reveal the great differences between surface and center that can arise in a small tundish / thick slab operation. This has been confirmed by measurements of drilling samples, which match very closely with the predictions.

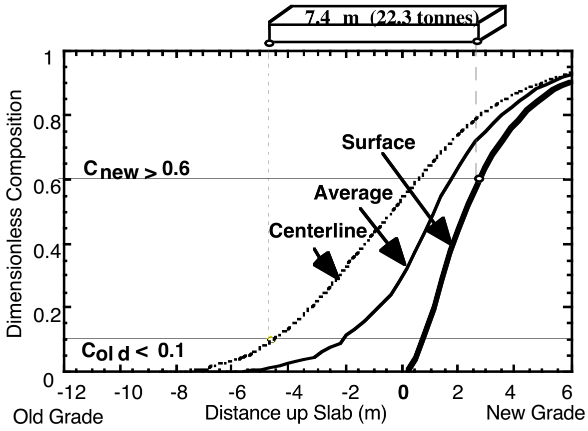


Fig. 10 a): 10 / 60 (stringent - lenient) grade transition [15]

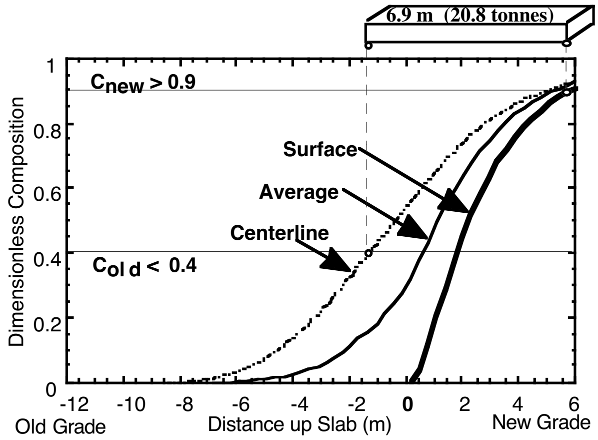


Fig. 10 b): 40 / 90 (lenient - stringent) grade transition [15]

Fig. 10. Relative composition variation within strand showing intermixed region for a small tundish operation

The length and position of the intermixed slab which must be downgraded changes with many conditions. A comparison of **Fig. 10 a)** and **b)** shows that even with the same casting conditions (leading to the same composition profile), the order in which two different grades are cast can make a difference. In this case, casting the grade with the more stringent composition restrictions before the lenient grade shifts the intermixed region more than 2m downstream. Although the downgraded length increases slightly for this small tundish operation, this procedure would greatly reduce the intermixed length if the tundish were large or the strand were thin.

Fast computational models that can accurately predict and quantify effects such as these have been developed [14]. These models are in use at several steel plants, where they are being applied to help with scheduling, optimizing casting conditions during the transition, identifying the slabs or slab portions that need to downgraded, and warning the customer about expected composition variations.

MOLD TAPER DESIGN

Compuational modeling is a natural tool for optimizing mold taper design. The governing phenomena are thermal contraction of the solidifying and cooling steel shell, which must be matched by the taper of mold walls, while taking into account the effects of mold distortion and variable thickness of the flux layer in the gap. The thermal contraction in turn is governed by the heat transfer from the shell, which depends on the steel grade and is complicated by phase transformations and strains due to elastic and viscoplastic creep deformation.

Modeling work has shown that the strand shrinks more near the top of the mold. Thus, a linear taper is inadequate for rigid mold-mold operations, such as round and square billet casting, where mold distortion is in the opposite direction. Parabolic or multiple taper profiles are needed and are now in common use.

For example, taper has been optimized at Ilva-Dalmine round bloom caster based on the predictions of computational models that were calibrated with temperature measurements from mold thermocouples. [16]. Sample predictions are shown in **Figs. 11 and 12**, for temperature and ideal taper of the mold respectively during simulated casting of a 280 mm diameter round billet with C162 flux.

In general, higher casting speed produces a hotter shell, so less taper is required, as shown in **Fig. 12**. However, the calculations also reveal that the flux layer thickness changes with casting speed and partly compensates for the change in the strand shrinkage. Thus, the change in taper with speed is much less than might be expected.

In slab casting, the narrow face mold wall bends towards the shell, partly compensating for the nonlinear shell shrinkage. Thus, a simple linear taper is not far from optimal for many conventional slab casting operations [17]. Along the wide face, the shell is held against the mold wall by ferrostatic pressure, so not much taper is needed.

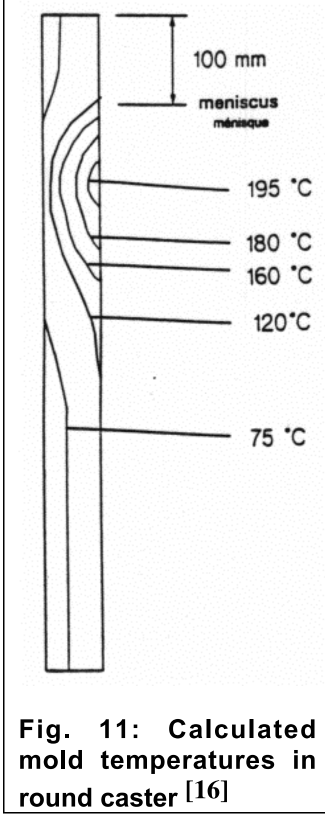


Fig. 11: Calculated mold temperatures in round caster [16]

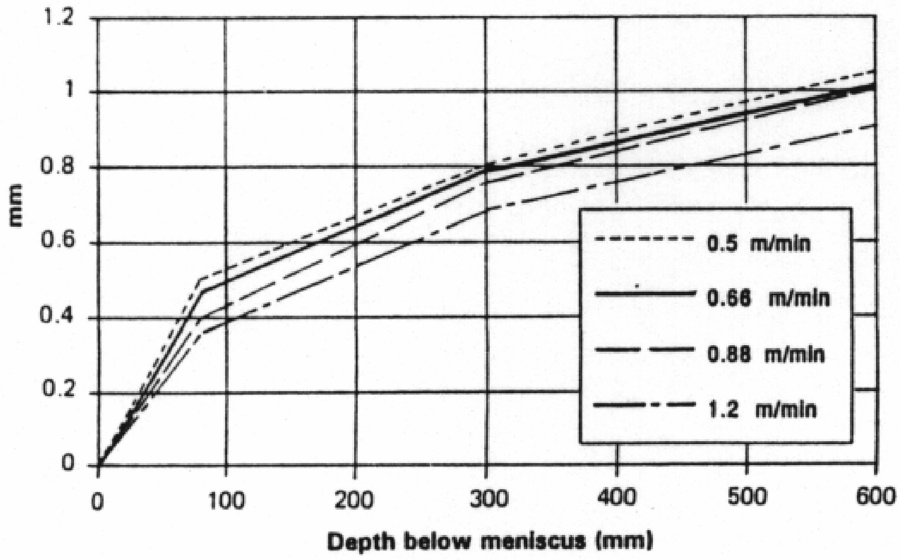


Fig. 12: Effect of casting speed on ideal triple-taper predicted for a round billet mold [16]

The future challenge of high speed casting of thin slabs and billets using mold flux will benefit from the application of models such as these to optimize mold taper for the new conditions.

THERMAL STRESS ANAYLSIS FOR UNDERSTANDING DEFECT FORMATION

Computational modeling has often been used to investigate possible mechanisms for the formation of defects such as cracks. Even simple 1-D solidification models have been used with great success for this purpose. For example, by comparing the shell thickness profile with the location of a hot tear, the distance down the caster where a misaligned roll inititiated a radial streak crack can be identified.

With other defects involving multi-dimensional effects and more complex stress development, more advanced thermal stress analysis is required. For example, longitudinal shell tears near mold exit involve thermal stresses, two-dimensional corner effects, gaps affected by mold taper, gap heat transfer phenomena, and superheat delivered to the solidifying shell from the impinging flowing liquid jet. Models to investigate these phenomena have been applied to several different problems [18].

One example problem is breakouts at the off-corner narrow face when mold taper is insufficient and superheat is too high. An example of the predicted temperature contours and distorted shape of a transverse region near the corner is compared in **Fig. 13** with measurements of a breakout shell from an operating steel caster. As expected, good agreement is obtained in the region of good contact along the wideface, where calibration was done. Near the corner along the narrow face, steel shrinkage is seen to exceed the mold taper. Thus, an air gap is predicted, which lowers heat extraction from the shell in the off-corner region of the narrow face. When combined with high superheat delivery from the bifurcated nozzle directed at this location, shell growth is greatly reduced locally. Just below the mold, this thin region along the off-corner narrow-face shell caused the breakout. Near the center of the narrow face, creep of the shell under ferrostatic pressure from the liquid is seen to maintain contact with the mold, so much less thinning is observed. This illustrates the tremendous effect that superheat has on slowing shell growth, if there is a problem which lowers heat flow.

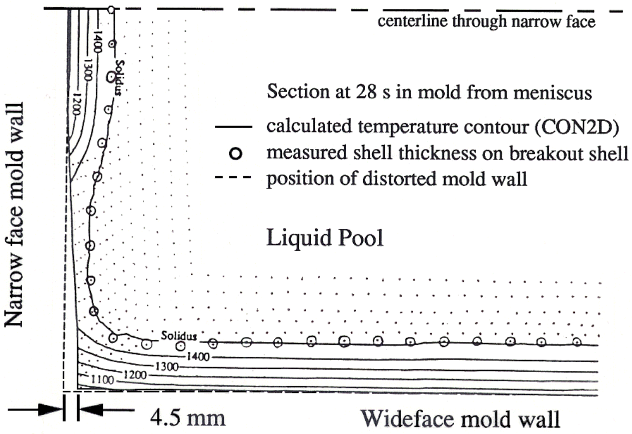


Fig. 13: Uneven shell solidification in corner of slab caster at mold exit caused by inadequate narrow face taper [19]

The modeling results, **Fig. 14**, show that lowering superheat helps to minimize the danger of this type of breakout. However, the results also show that improving the narrow face taper is a much better solution. Installing profilometers to continuously monitor and adjust taper during taper has been implemented in several casters. In addition, during widening width changes, taper should be increased according to [19]:

$$\Delta W = tapr_n \, W \, L + V_W \, L / V_C$$

where:

ΔW = difference in mold width at top and bottom of mold

$tapr_n$ = optimal taper at steady width (%/m),

V_W = speed of narrow face movement during width change

V_C = casting speed

W = mold width

L = mold length

Simulations such as these are needed to understand and help find solutions for new defects, such as those affecting thin slab and thin strip casting.

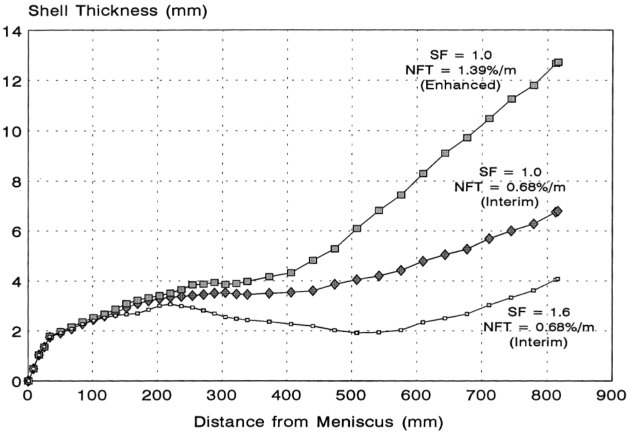


Fig. 14: Increase in shell growth along off-corner of narrow face with increased taper and decreased superheat [20]

CONCLUSIONS

As increasing computational power continues to advance the capabilities of numerical simulation tools, modeling should play an increasing role in future advances to high-technology processes such as the continuous casting of steel. Modeling can augment traditional research methods in generating and quantifying the understanding needed to improve the process. Selected examples of increased understanding that have accompanied modeling at the University of Illinois are presented in the fields of multiphase fluid flow in the nozzle, mold cavity, and powder layers, grade transitions, and thermal stress analysis applied to mold taper, and off-corner breakouts in slabs. This understanding has lead to practical improvements to the operation and product. Areas where advanced computational modeling should play a crucial role in future improvements include transient flow simulation, mold flux behavior, taper design, and online quality prediction, especially for new problems and processes such as high speed bilet casting, thin slab casting, and strip casting.

OUTLOOK

Future advances to the continuous casting process will not come from either models, experiments, or plant trials. They will come from ideas generated by people who understand the process and the problems. This understanding is rooted in knowledge, which can be confirmed, deepened, and quantified by tools which include computational models. As our computational tools continue to improve, they should grow in importance in fulfilling this important role, leading to future process advances.

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