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MODELING STUDY OF INTERMIXING IN TUNDISH AND STRAND DURING A CONTINUOUS-CASTING GRADE TRANSITION

Brian G. Thomas

Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign
1206, W. Green Street, 140 MEB
Urbana, IL 61801

ABSTRACT

A 1-D, transient mathematical model (MIX1D) has been developed to simulate the final composition distributions produced within continuous-cast slabs and blooms during an arbitrary grade transition. This work applies the model to investigate the effect of process variables on the extent of intermixing during a typical ladle change operation, where mixing occurs in both the tundish and the liquid core of the strand, prior to final solidification into slabs or blooms. The model was developed, calibrated, and verified with composition measurements on tundish outflow and at the surface and centerlines of slabs and blooms cast during grade transitions. Several different strategies were investigated to minimize intermixing. Results show that the amount of intermixed steel generally decreases with lower tundish weight at ladle open, increased holding time before refilling, increased plug flow through the tundish, decreased mold thickness, decreased mold width, casting the most stringent grade first, and using lower average casting speed during the grade change. However, the optimal philosophy depends greatly on the size of the tundish and the extent of the mix (which includes combinations ranging from lenient to stringent for either the old or new grades cast). Using the results of this work, grade changes can be customized for a given casting operation to minimize the amount of downgraded steel.

1. INTRODUCTION

The intermixing of dissimilar grades during the continuous casting of steel is a problem of growing concern, as the demand for longer casting sequences increases at the same time as the range of products widens. Steel producers need to optimize casting conditions and grade sequences to minimize the amount of steel downgraded or scrapped. In addition, the unintentional sale of intermixed product must be avoided. To do this requires knowledge of the location and extent of the intermixed region and how it is affected by grade specifications and casting conditions.

2. GRADE TRANSITION METHODS

Casting dissimilar grades can be handled in several different ways. The most extreme practice is simply to stop the caster when the first grade is finished and to restart it with the next grade as a new sequence. This method prevents mixing in either the tundish or the strand, so there is no intermixed steel to be downgraded. However, production time is lost to restart the caster. In addition, yield losses are incurred due to quality problems at the end and start of the cast strands. This method is best only if production capacity is not limited by the caster and many, very different grades must be cast.

To prevent mixing in the strand, grade-separator plates can be inserted into the mold.[1, 2] However, physical insertion of a “perfect grade separator” requires significant slow down or even stoppage of the strand. This incurs the risks of excessive bulging and cracks in the strand, breakouts, and damage to the casting machine. In addition, the separator plates add cost, and sometimes leak internally, producing up to a meter of intermixed length.

To maximize the benefit of a grade separator, it is best to use a “flying tundish change” at the same time. In this practice, the tundish is changed at the same time that the ladle containing the new grade is opened. Thus, mixing in the tundish is avoided. This practice is demanding on the plant operation and incurs a yield loss of the old steel remaining in the tundish, in addition to limiting the tundish life. Thus, its benefit depends on the amount of intermixed steel saved. Without the grade separator, this benefit is small.[3]

As an alternative to the perfect grade separator (plates), a less expensive “partial grade separator” may be inserted into the liquid steel in the mold. Its large thermal mass induces solidification across the strand at some depth below the meniscus, which greatly limits mixing in the strand. The partial separator is easier to insert with less slow-down and risk of damage to the caster than the perfect separator plates.[1] However, it is still necessary to scrap some product near the insertion region, and quality problems may accompany the slow-down needed to insert the separator. This practice is most beneficial when mixing in tundish is small and there is down-grade market available for the intermixed slabs or blooms.

Finally, the easiest practice is to continue casting the different grades as a single sequence. This method involves only a simple “ladle change”. In this method, “new” steel flowing from the next ladle will first mix with “old” steel left in the tundish from the previous heat. Steel then flows into the mold, where it undergoes further mixing in the long liquid pool in the strand while it solidifies. This method avoids losses in productivity, but produces the maximum length of intermixed steel.[3] Ideally, a market should be found for the intermixed steel. Casting conditions should be chosen to either minimize the amount of intermixed steel, or to optimize the mixing according to the market order. The remainder of this paper investigates how to do this, using a calibrated and validated mathematical model, MIX1D.[3]

3. EVENTS OF A TYPICAL GRADE TRANSITION

During a typical “ladle change” grade transition in sequence casting, the casting speed, V_c, total tundish weight, M, and flow rate into the tundish, Q, vary with time, as shown in Figure 1. Mixing begins when the new ladle is opened and the new grade of steel starts to flow into the tundish. This defines time zero. The curves at times less than zero represent events which occur prior to opening of the new ladle.

In preparation for replacement of the old ladle, the casting speed may be decreased. This lowers the flow rates so provides more time for the transition. The extra time also allows more solidification, shortening the length of the liquid pool in the strand, thereby decreasing the intermixed length. At the same time, the tundish volume decreases, particularly after the old ladle is empty of steel. Because the tundish volume at the time of opening the new ladle almost always corresponds to the minimum tundish level, the prior drainage procedure has no effect on mixing.

The amount of old grade remaining in the tundish at the time of ladle open is a critical process parameter, since lower minimum tundish volumes reduce subsequent mixing in the tundish. In the extreme case of a flying tundish change, this volume is zero.

Once the new ladle opens, the tundish refills to the desired operation level, according to the prescribed inlet flow rate and casting speed (outflow). Mixing in the tundish depends on the histories of the filling rate and casting speed, which eventually reach their steady values.

After leaving the tundish, mixing occurs in the strand (unless a grade separator plate is used). Diffusion is negligible in solid steel, so the initial profile of the solidified shell, including the entire surface of the strand below the meniscus, remains completely old grade. Turbulent flow may penetrate deeply into the liquid pool, however, bringing mixed steel far below the position of the meniscus at ladle open. Mixing increases towards the centerline, which solidifies last. Considering that the volume of liquid contained in the strand is similar to that in the drained tundish, mixing in the strand is very important.

It is clear that many events must be considered if the composition distribution in the final slab is to be predicted accurately. Specifically, the history of tundish volume after ladle open and the entire casting speed history must be taken into account in a fully transient model of mixing in both the tundish and the strand.

4. PREVIOUS STUDIES

Consistent with previous work on mixing,[3, 4] the liquid composition is specified as a dimensionless concentration, C:

$$C \equiv \frac{F(t) - Fold}{Fnew - Fold} \qquad [1]$$

where F(t) is the fraction of a given element at time t; F_{old} and F_{new} are the fractions of that element measured in the old and new grades respectively. In this definition, all concentrations range between the old grade concentration of 0 and the new grade concentration of 1. The dimensionless concept is useful because alloying elements intermix essentially equally.[4] This is because the turbulent mass diffusion coefficient, which does not depend on the element, is about 5 orders of magnitude larger than the laminar diffusion coefficient.[4]

Several researchers have measured the transient concentration exiting the tundish during a grade transition as a function of casting conditions, tundish geometry, and flow controls, using full-size water models.[5-7] It is relatively straight forward to match the results using simple, empirical equations.[7] Other researchers have investigated tundish mixing using finite-difference models.[8-10]

A previous mathematical model of mixing in the strand applied a 3-D finite-difference K-ε turbulence model to simulate a flying tundish change, using a supercomputer.[4] This model showed that composition was roughly constant across the width of slabs, which is consistent with the experimental findings of Fujii.[11] Subsequent work found that a simple 1-D model could reasonably approximate the 3-D results.[3] This 1-D model was used to examine the effect of grade transition method on intermixed length[3] and to investigate intermixing at Armco's Butler, PA works.[12]

5. MODEL DESCRIPTION

A one-dimensional finite-difference model, MIX1D,[3] has been developed to predict the composition distribution profile across a continuously-cast slab or bloom during a grade change. The model is fully transient and consists of three submodels, that account for mixing in the tundish, mixing in the liquid core of the strand, and solidification.

The first submodel calculates mixing in the tundish and consists of six mixing boxes, shown in Figure 2. The simple box model includes two "plug flow" zones, two "back-mixing" boxes, and two "dead" volumes, defined elsewhere.[3] The volume fractions of these boxes must total one, and empirically match measured concentration data exiting the tundish. The fractions can change with time, according to the filling history of the tundish.[3] Note that the dead-volume fractions assumed in this model would always total 50% if flow through each half of a two-strand tundish were completely independent and there were no totally stagnant regions. The plug flow volume fractions should equal the time of first appearance of new grade relative to the mean residence time.

The second submodel calculates concentration histories in the strand, based on the concentration history entering the mold from the tundish. This submodel includes two back-mixing boxes of the upper strand (typically 1.0 and 1.5 m in length). They are connected in series with a one-dimensional model of turbulent diffusion in the lower strand, as shown in Figure 3. Composition is solved as a function of time and distance through the thickness of the strand using a one-dimensional, transient, finite difference procedure. The turbulent diffusion coefficient was chosen as a function of casting speed, slab thickness, and slab width, to match results from a three-dimensional turbulent K-ε model calculation.[3, 4] Composition is assumed not vary across the width of the strand, which is roughly consistent with both three-dimensional calculations and measurements.[11]

The third submodel transforms the strand composition histories into composition distributions along the final slab or bloom product. This simple coordinate transformation assumes that mass transfer stops upon solidification. The shell thickness is input to the model as a function of time, given in Appendix I. Figure 4 illustrates the relationships assumed in the present work. Note that this method incorporates transient effects, such as changes in metallurgical length resulting from casting speed variations. Segregation is neglected, however.

The three submodels have been incorporated into a user-friendly FORTRAN program that runs on a 486 personal computer in less than one minute. Details of the formulation of this model are published elsewhere.[3]

6. MODEL VALIDATION

To ensure that the MIX1D model can accurately predict composition distribution during intermixing, extensive verification and calibration has been undertaken for each submodel. The strand submodel was first calibrated to match results from the 3-D finite-difference model.[3] The tundish and final composition models have since been validated with measurements from several different continuous casting machines, including small tundish (Armco, Allegheny Ludlum), large tundish (LTV, Weirton, Inland, and AK Steel), and bloom casting (BHP) operations.

Figure 5 shows model results of concentration exiting the tundish, for three different tundish configurations, representing typical small, large, and bloom casting tundishes. The specific casting conditions are given in Table I. The predictions are compared with chemical analysis of steel samples taken from the mold in the nozzle port exit streams by researchers at the respective steel plants. The bloom data were taken from one of the outer strands. The predictions match the measurements, due to calibration of the tundish volume fractions.

Figure 6 compares the MIX1D model predictions with composition measurements in the final slab or bloom, corresponding to the tundish conditions in Figure 5. The measurements were based on samples taken near the surface and centerline of the cast product, analyzed in a similar manner to the mold samples. The predictions are seen to match reasonably well for all cases. This is significant because there are no parameters remaining to adjust in the strand and slab / bloom submodels.

Table I Casting Conditions for Model Validation

Input condition	Slab - Small tundish	Slab - Large tundish	Bloom
Strand thickness, T	.203 m	.229 m	.400 m
Strand width, W	.978 m	.813 m	.630 m
Number of strands, #	2	2	4
Minimum tundish weight at ladle open, M_{min}	5.1 tonnes	46 tonnes	20 tonnes
Steady tundish weight, M	10.2 tonnes	52 tonnes	38 tonnes
Time holding tundish weight after ladle open before refilling, t_{wh}	0 s	0 s	60 s
Time for tundish weight to increase to steady state, t_{wu}	120 s	130 s	250 s
Volume fractions: dead, f_d	40%	48%	57%
Back-mixing box 1, f_{m1}	40%	25 to 8%*	10%
Back-mixing box 2, f_{m2}	15%	17 to 26%*	15%
Plug flow (total), f_p	5%	10 to 18%*	18%
Minimum casting speed at ladle open, V_{cmin}	0.64 m/min	0.508 m/min	0.20 m/min
Steady casting speed, V_c	1.0 m/min	1.016 m/min	0.52 m/min
Time to ramp down speed prior to ladle open, t_{vd}	5 s.	150 s	290 s
Time at low speed, t_{vmin}	0 s	105 s	150 s
Time to ramp speed back up to steady state, t_{vu}	300 s	45 s	230 s
Cooling conditions (Appendix I)	soft	hard	hard
element measured	Si	Mn	Cu
steel grade	Stainless	Plain low C	Plain low C

* box volume fractions were changed linearly with time during filling.

7. CALCULATION OF INTERMIX LENGTH

The model searches along the slab composition results to find the critical distances which define the position of the length of intermixed steel product which falls outside the composition specification of either the old or new grades. An example of this length of intermixed steel is illustrated in Figure 7, and naturally depends on the severity of the grade change.

The severity of the grade change refers to the tolerance for deviation from the specified composition for each of the old and new grades. The two tolerances are defined as dimensionless composition specifications for the old and new grades, C_{old}, and C_{new}, respectively. These specifications range between 0 and 1, according to:

$$C_{old} = \max\left(\frac{F_{old\ min} - F_{old}}{F_{new} - F_{old}};\ \frac{F_{old\ max} - F_{old}}{F_{new} - F_{old}}\right) \qquad [2]$$

$$C_{new} = \min\left(\frac{F_{new\ min} - F_{old}}{F_{new} - F_{old}};\ \frac{F_{new\ max} - F_{old}}{F_{new} - F_{old}}\right) \qquad [3]$$

where $F_{old\ min}$ and $F_{old\ max}$ are the minimum and maximum specifications of a given element in the old grade; and $F_{new\ min}$ and $F_{new\ max}$ are the corresponding values in the new grade. Searches are performed over all of the elements, to find the critical element(s), which has the maximum C_{old} (defining the boundary between the old grade, where C=0, and the intermixed steel) and the minimum C_{new} (defining the boundary between the intermixed steel and the new grade where C=1). Satisfying the maximum C_{old} in the old grade and the minimum C_{new} in the new grade ensures that the composition specifications are satisfied for the most stringent element, which may be a different element for the old and new grade boundaries.

The model then searches along the slab composition results to find the critical distances which correspond to the maximum C_{old} and the minimum C_{new} compositions. Different options are possible as criteria to calculate these two axial positions. The most stringent choice, assumed here, is to satisfy the grade specifications throughout the slab, including both centerline and surface. This is achieved by searching for the z locations which match the minimum C_{new} along the surface and the maximum C_{old} along the centerline.

When the final product is rolled into thin sheets, the average composition across the thickness might be the best criterion to characterize the properties. For this option, the composition data are first averaged over the 16 simulation points across the half-thickness of the slab. Both searches are conducted along this new average axial composition profile.

8. ANALYSIS METHODOLOGY

The MIX1D model was applied to investigate the effect of changing casting parameters on intermixing for several different casting operations involving mixing in both the tundish and the strand. These parameters include the severity of the grade change, tundish weight history, relative volume fractions of three different zones of the tundish (plug, mix, and dead), casting speed history, slab width, and slab thickness.

Due to the overwhelming importance of the first two parameters, (severity of the grade change and tundish weight at ladle open), results are interpreted in the context of 10 different cases. These consist of two different tundish weights, typical of small and large tundish operations, for each of five different grade change severities.

The two tundish sizes are similar to those of the plant measurements used in model validation. Severity of the grade change is expressed as the percentage difference in composition between the two grades cast: old and new, as explained in the previous section on intermix length calculation. The five grade specifications are:

10 : 90 (stringent - stringent) This is a radical grade change involving two very different compositions, and / or two grades with very stringent specifications. Contamination of either grade with only 10 percent of the other grade is enough to move the steel composition outside of the specification range and cause regrading. Examples might include a transition from a resulfurized steel to a desulfurized grade, or a high carbon to an ultra-low carbon steel.

10 : 60 (stringent - lenient) This means that a 40 percent deviation in composition of the lenient new grade (relative to the old grade) will still meet its specifications, while only a 10 percent deviation from the stringent old grade is allowed. A specific example arises when casting a 0.01% S heat with a 0.03% maximum S specification followed by 0.21% S resulfurized steel with a minimum requirement of 0.13% S.

<u>40 : 90 (lenient - stringent)</u> This means casting the same two grades (10 : 60) in reverse order, with the lenient grade (old) cast before the stringent grade (new).

<u>40 : 60 (lenient - lenient)</u> This typifies a small change in grade, where the two adjacent heats in the sequence have similar composition requirements. Alternatively, steel for a downgrade market must have a large tolerance for composition variation, so might also be defined by this specification.

<u>60 : 40 (overlapping)</u> This represents an even more lenient grade change than the 40 : 60 case. The two grades are considered to be sufficiently similar that the average composition (50%) would actually satisfy the specifications of either grade. Specifically, this work considers an overlapping case where the old grade is satisfied by any composition containing less than 60% new grade, while any composition above 40% new grade satisfies the new grade.

In this work, the intermixed length is calculated from the simulated composition profiles, based on satisfying the grade specification along both the slab centerline and surface. Other interior compositions should lie between these two extremes, so the grade specification should be met everywhere. The procedure is illustrated in Figure 7 a) for the example of a 10 : 60 grade specification. The old grade is satisfied only when $C < 0.1$ (10%) everywhere, while the new grade is satisfied so long as $C > 0.6$ (60%).

The position of the meniscus at the time of ladle open is designated as distance along the strand, $z = 0$. As seen in Figure 7, intermixed steel is created in both the old grade ($z < 0$) and the new grade ($z > 0$). In the old grade, new steel penetrates deep down the centerline of the pure solid shell of old grade, because the rate of turbulent diffusion and mass convection exceeds the casting speed. Thus, the centerline is critical in evaluating the grade specification in the old grade.

The displaced old grade mixes to contaminate the new grade. The surface is the critical place to evaluate the grade specification of the new grade, because it solidifies before the residual old grade becomes diluted.

For each of these 10 different cases, 14 different parametric studies were performed, based on the standard conditions (Table II) for simple ladle change grade transitions on a two-strand slab caster. These standard conditions differ only slightly from those of the typical small and large tundish operations where measurements were obtained for model validation. Table III explains the changes made for each of the 14 other casting conditions investigated. The calculations assume identical tundish flow and casting conditions on each strand. Each change in conditions was made independently; which is not always the case in a real casting operation.

Table II Standard Casting Conditions for Parametric Study

Input condition	Small tundish	Large tundish
Slab thickness, T	.203 m	.203 m
Slab width, W	.978 m	1.000 m
Number of strands, #	2	2
Minimum tundish weight at ladle open, M_{min}	5 tonnes	15 tonnes
Steady tundish weight, M	10 tonnes	45 tonnes
Time holding tundish weight after ladle open before refilling, t_{wh}	0 s	0 s
Total time for tundish weight to increase to steady state, t_{wu}	120 s	180 s
Volume fractions: dead, f_d	40%	57%
Back-mixing box 1, f_{m1}	40%	10%
Back-mixing box 2, f_{m2}	15%	15%
Plug flow (total), f_p	5%	18%
Minimum casting speed at ladle open, V_{cmin}	0.64 m/min	0.5 m/min
Steady casting speed, V_c	1.0 m/min	1.5 m/min
Time to ramp down speed prior to hold at low, t_{vd}	5 s.	480 s
Time at low speed, t_{vmin}	0 s	240 s
Time to ramp speed back up to steady state, t_{vu}	300 s	180 s
Cooling conditions (Appendix I)	slow	fast

Table IV presents the tonnes of intermixed steel that must be scrapped for both strands, calculated from the MIX1D model results. Each number in this table is calculated from the intermixed length, based on slab dimensions and the average density of the steel (7.6 tonne/m^3). The intermixed length is the distance along the final steel product that fails to satisfy the specifications of either the old or the new grade, as explained in Section 7. Negative numbers denote the tonnes of slab length that could satisfy either grade, which is only possible for overlapping grade specifications.

9. RESULTS OF PARAMETRIC STUDY

Effect of composition specification

The intermixed length is naturally more affected by the severity of the grade change than by any other parameter. For 0.2m thick strands, the tonnes of intermixed steel ranges from a maximum of 18 - 83 tonnes for the most stringent (10 : 90) specification to only 0 - 8 tonnes for the overlapping (60 : 40) specifications. This finding emphasizes the importance of optimizing the sequence schedule to avoid casting dissimilar grades together as much as possible.

Naturally, the most stringent 10 : 90 case always has the longest intermixed length and highest tonnage of steel to downgrade for a given set of casting conditions. As the specifications become more lenient, less product requires regrading, which is seen by moving across any row in Table IV.

The overlapping case (60 : 40) has the least mixing, as expected. In fact, it might seem surprising that intermixed steel can be produced at all, when the grade specifications overlap. This situation arises solely from the composition differences through the thickness of the strand. At some distance down the strand, the surface might be too low to meet the new grade specification while the center is too high to meet that of the old grade.

Table III Conditions for parametric study with MIX1D model

#	Casting condition(s) changed	Small tundish	Large tundish
1	None	Standard	Standard
2	Keep tundish weight constant	M_{min} = 10 tonnes	M_{min}=45 tonnes
3	Further decrease tundish weight at ladle open	M_{min} = 1 tonnes	M_{min} = 10 tonnes
4	Delay refilling tundish weight	t_{wh} = 240s, t_{wu} = 900s	t_{wh} = 180s, t_{wu} = 720s
5	Change tundish: (increase dead and decrease mix)	f_{m1}=5%, f_d=75%	f_{m1}=5%, f_{m2}=5%, f_d=72%
6	Change tundish: (increase mix and decrease dead)	f_{m2}=55%, f_d=0	f_{m1}=67%, f_d=0
7	Change tundish: (increase plug and decrease mix)	f_p=40%, f_{m1}=5%	f_p=33%, f_{m1}=5%, f_{m2}=5%
8	Keep casting speed constant	V_{cmin}=1.0 m/min	V_{cmin}=1.5 m/min
9	Keep casting speed reduced longer both before and after ladle open	t_{vd} = 300s, t_{vmin} = 900s, t_{vu} = 300s	t_{vd} = 600s, t_{vmin} = 900s, t_{vu} = 600s
10	Combine changes (from runs 2,6,8) to prolong mixing	M_{min}=10, V_{cmin}=1.0, f_{m2}=55%, f_d=0	M_{min}=45, V_{cmin}=1.5, f_{m1}=67%, f_d=0
11	Increase slab width	W=1.6 m	W=1.6 m
12	Decrease slab width	W=0.6 m	W=0.6 m
13	Increase slab thickness	T=0.40 m	T=0.40 m
14	Decrease slab thickness	T=0.10 m	T=0.10 m

Table IV Results (tonnes of intermixed steel produced for conditions given in Table III)

Small Tundish	Grade Specification $C_{old} : C_{new}$				
#, Condition	10 : 90	10 : 60	40 : 90	40 : 60	60 : 40
1, Standard	26.8	18.8	18.9	10.8	3.5
2, constant M	28.4	20.0	20.0	11.4	3.7
3, lower M	24.7	18.1	16.9	10.4	4.2
4, delay M	25.4	18.8	17.5	10.8	4.2
5, f_d=75	24.4	18.1	16.9	10.5	4.2
6, f_{m1}=55	29.0	19.7	20.6	11.3	3.5
7, f_p=40	24.6	18.2	17.0	10.6	4.3
8, V_{cmin}=1.0	28.7	20.7	20.3	12.2	4.8
9, delay V_c	24.6	16.6	17.8	9.6	2.9
10, combine	38.9	23.5	27.8	12.4	-2.4
11, W=1.6	43.4	32.0	30.6	19.2	8.4
12, W=0.6	17.8	11.3	12.4	5.9	1.0
13, T=0.40	100.0	86.9	64.3	51.2	28.0
14, T=0.10	12.5	6.2	10.1	3.9	0.3

Large Tundish	Grade Specification $C_{old} : C_{new}$				
#, Condition	10 : 90	10 : 60	40 : 90	40 : 60	60 : 40
1, Standard	27.0	17.1	19.2	9.3	1.4
2, constant M	33.9	22.4	23.8	12.2	1.3
3, lower M	25.1	16.2	17.7	8.7	2.0
4, delay M	23.8	16.8	16.7	9.6	2.7
5, f_d=72	23.5	16.0	16.3	8.9	2.5
6, f_{m1}=67	58.0	18.5	48.8	9.6	-1.2
7, f_p=33	23.2	16.1	16.2	9.1	2.8
8, V_{cmin}=1.5	29.9	21.6	19.4	11.1	2.8
9, delay V_c	25.3	14.5	18.5	7.7	0.4
10, combine	83.3	39.5	63.6	19.8	-7.4
11, W=1.6	39.0	28.1	27.7	16.8	6.7
12, W=0.6	21.3	10.4	15.3	4.3	-1.9
13, T=0.40	111.3	88.1	69.3	45.6	20.1
14, T=0.10	16.8	6.6	14.0	3.9	-0.8

It is even more interesting to note that the conditions that generally reduce the amount of intermixed steel are often detrimental for this overlapping case. This opposite direction of the trends means that the best way to handle grade changes depends on the composition specifications. For this reason, the development of an optimal strategy for handling overlapping grades will be discussed in a separate section. The following sections focus on minimizing intermixing for relatively stringent cases, typical of radical grade changes.

Effect of stringent to lenient grade order

When two grades have the same relative grade specification, (e.g.. 10 : 90 or 40 : 60), then the model predicts that the order in which they are cast should not matter. This is because mixing is dominated by turbulent flow, so all elements should diffuse in a roughly equal manner (according to their concentration).

When two grades which have very different tolerances for mixing with the other must be cast together in a sequence, however, the order in which they are cast can make a difference. This section considers the question of whether it is better to cast the stringent grade before the lenient grade (10 : 60) or vice versa (40 : 90). Previous work by Damle and Sahai[8] has suggested that casting from "stringent to lenient", (10 : 60) is better.

The present model predictions can be evaluated by comparing the 10 : 60 and 40 : 90 columns in Tables III and IV. There is no consistent trend. For most of the runs, the stringent to lenient specification (10 : 60) indeed produces less intermixed tonnage than the lenient to stringent (40 : 90). This is particularly true for the large tundish, where this finding applies to all but 3 of the runs in Table IV. Mixing in the tundish is characterized by a long tail before the asymptote at C=1 is reached. This is seen in Figure 5. This means that much steel must exit the tundish before the old grade remaining in the tundish is diluted enough to satisfy a stringent new grade. The first steel to solidify is near the submerged entry nozzle, so the composition leaving the tundish controls the surface composition of the slab. Thus, there is less intermixed length along the surface (which controls the new grade), when the lenient grade is cast last. Because a large tundish contains more steel than the strand, tundish mixing dominates the intermixed length. If mixing along the center does not change much, it is better to cast the stringent grade first.

Unfortunately, a stringent old grade is worse at the center by about the same extent that a stringent new grade is worse at the surface. This means that casting the stringent grade first

(10:60) may decrease intermixing at the surface at the expense of increasing intermixing at the center. Composition along the center is controlled by mixing in the strand, which determines the intermixed length of the old grade. When mixing in the strand dominates the total intermixed length, it is better to cast from lenient to stringent (40 : 90). This is the case for most of the runs with the small tundish, and all of the large slab sizes, including thicker molds (run 13) or wider molds (run 11). In addition, higher casting speed increases the metallurgical length, which extends mixing along the centerline. Decreasing the tundish volume at ladle open (run 3) again increases the importance of strand mixing, particularly for the small tundish. For these cases, the lenient grade should be cast first (40:90).

These two balancing effects can be understood by comparing Figures 7 a) and b). Casting the stringent grade last (Fig. 7 b) decreases centerline mixing but increases surface intermixing. Although the amount of intermixed steel does not change much, the location of the intermixed slab is translated much further up the strand (towards the new grade) for this 40 : 90 case. This could have serious consequence if measures were not taken to track the new location of this intermixed steel.

Often the effect of strand mixing (increasing intermixed length for the stringent to lenient case in the centerline of the old grade) almost exactly cancels the tundish effect (reducing intermixed length at the surface of the new grade). In these cases, the order of casting the stringent and lenient grades does not matter very much.

Effect of tundish weight history

The weight of steel left in the tundish at the time of ladle open greatly affects the intermixed length. In general, lower tundish weight tends to decrease intermixing. Factors include lowering the tundish weight at ladle open (compare runs 2 and 3), delaying the time before refilling the tundish (compare runs 1 and 4), and lowering the maximum tundish weight (compare small and large tundish results).

These trends hold for all of the grade specifications investigated except the overlapping case. The importance of the lower tundish weight history depends greatly on the severity of the grade change: there is less benefit for a lenient new grade.

The effect of varying tundish weight at ladle open (for the same steady weight of 45 tonnes) is illustrated for the large tundish in Figure 8. Increasing the tundish weight at ladle open from

15 to 45 tonnes is seen to extend the intermixing range considerably. In a real operation, the intermixing would be even greater, because the tundish plug flow fraction would likely decrease as well. This increase in intermixed length is the reason why many operations drain the tundish down before opening the new ladle, despite the quality problems such as reoxidation and slag entrainment that can be encountered.

The magnitude of this effect depends on the size of the tundish. For the small tundish, the effect of tundish weight history is much less. In fact, draining the tundish to only 1 tonne (run 3) improves mixing by less than 4 tonnes (13%), relative to leaving the weight constant at its steady value of 11 tonnes throughout casting (run 2). This finding simply shows that mixing in the strand controls the intermixed length once the tundish weight is low enough.

In addition to lowering the minimum and maximum tundish weights, delaying the refilling is also beneficial. Holding the weight low after opening the new ladle and / or a slower filling rate to steady state (run 4) both tend to shorten the intermixed length. The effect is relatively minor, however. Refilling gradually over 12 - 15 minutes, including a 3-4 minute hold after ladle open reduces the intermixed tonnage by only a few tonnes, relative to the 2-3 minute total refilling time for standard conditions. As expected, the effect is greater for the larger tundish.

A slower filling rate makes little difference to intermixing after a long hold time. If the hold before refilling is long enough to drain old grade from the tundish, this indicates there is no added benefit from slow refilling. Deciding how long to wait before refilling the tundish should depend on the extent of the mix: stringent new grades benefit from holding a low tundish level longer before refilling; lenient new grades can refill quickly with no difference in intermixed length.

Effect of tundish parameters

Another important set of casting conditions is the volume fractions of the tundish (mixing, plug, and dead). These are controlled physically by the tundish shape and flow control devices. For example, the addition of weirs, dams, and impact pads tend to increase the plug flow and / or mixing fractions, while they generally decrease the volume fraction of the dead zones.

There are far more possible combinations of tundish operating conditions than can be investigated in this work. Plant measurements are required to calibrate the volume fractions to match the concentration profiles produced for a given tundish configuration. These volume fractions change with casting conditions and grades being cast: for example, higher pour temperature increases buoyant flow. Three runs were performed to illustrate the general effects of major increases to the fractions of dead volume (Run 5), mix volume (Run 6), and plug volume (Run 7). The results show that changing the volume fractions has little effect on intermixing for lenient grade specifications of the new heat, regardless of tundish size. This is understandable because the volume fractions primarily influence the surface composition, which affects the new grade mixing length.

Increasing the dead volume (run 5) decreases intermixing. This is because the volume of the tundish is effectively decreased. The extreme case examined in this run makes the "large" and "small" tundishes behave almost the same, as mixing in the mold now dominates both cases. Increasing dead volume is not recommended, however, because a smaller effective volume has more quality problems, such as poor flotation of entrained slag and inclusions due to "short circuiting". Furthermore, dead volumes are often not truly "dead", and slow fluid exchange with a "dead" volume can prolong the tail of the concentration curve. This increases intermixing length, particularly for a stringent new grade on a large tundish.

Increasing the mixing volume (run 6) by decreasing the dead volume, greatly increases intermixing. The magnitude of the effect for stringent new grades depends on tundish size, however. The intermixed tonnage more than doubles for stringent new grades cast in the large tundish.

Increasing the plug flow volume (run 7) by decreasing the mixing volume, decreases intermixing, particularly for stringent new grades in the larger tundish. The beneficial effect of impact pads found by Rasmusen [13] to reduce intermixing in a steady, large tundish operation may be due to this effect. Flow controls may also reduce turbulence and flow variability, which is helpful for both intermixing and steel quality. However, flow controls which increase mixing volume are predicted to aggravate intermixing unless the grade change is overlapping.

Effect of casting speed history

In general, casting at a slower speed for a longer time, both before, during, and after ladle open, tends to decrease the intermixed length and tonnage. This is due to shortened mixing lengths along both the centerline and surface. Slower speed shortens the centerline mixing length (cut at old grade) because species transport by turbulent mixing in the strand is decreased and the shell thickness is increased at any given distance down the caster.

If the composition history entering the mold from the tundish does not change, then the surface mixing length (cut at new grade) shortens in direct proportion to the drop in casting speed. However, slower speeds also tend to extend the transition time leaving the tundish, so improvement at the surface is not as great as expected.

Improving the centerline naturally nets the greatest improvement for stringent old grades (10:90 and 10:60). This improvement with delayed speed increase is one of the few trends that also holds true for the overlapping grade specification (60 : 40).

Run 8 shows that casting at steady speed increases the intermixed length by 2-3 tonnes, relative to the standard. Comparing runs 8 and 9 shows that reducing the casting speed from 1.0 to 0.5 m/min for 25 minutes (small tundish) decreases the intermixed tonnage by about 4 tonnes (20%), relative to steady casting with no slowdown. Greater savings are found for the large tundish. A long time at reduced speed is more beneficial than a quick drop to a very low speed.

Economic considerations must be made to decide whether the savings produced by reduced speed are worthwhile. The optimal choice of speed history should depend on the relative cost of slower production balanced with the benefit of producing less intermixed product. Slower casting speed has costs associated with lost production, in addition to maintenance to repair machine damage and possible steel quality problems (due to excessive bulging). If the caster is a rate-limiting step in plant productivity, it is probably not worthwhile to slow down for intermixing reasons alone.

Effect of section thickness

Increasing the slab thickness is detrimental to the length of intermixed steel for every tundish size and mixing criterion considered (runs 11 - 14). This is because the metallurgical length of the strand increases, allowing deeper penetration of intermixed steel into the centerline. Because thicker slabs also contain more tonnes per unit length, the effect on increasing intermixed tonnes is greatly compounded.

The consequence of this finding is that large bloom casting operations (thickness > 9”) should always experience longer lengths (and tonnes) of intermixed steel than slab casters. This is consistent with the results presented earlier during model validation. Thin slab casters and billet casters should have the least intermixing. This finding agrees with previous results, obtained without consideration of tundish mixing.[4]

The effect of decreasing the thickness is most beneficial for the small tundish case, which is dominated by mixing in the strand. Decreasing the thickness shortens the mixing length along the centerline. This shortens the overall intermixed lengths for the 10:60, 10:90, and 40:60 cases in the small tundish and for the 10:60 and 40:60 cases in the large tundish. This effect is largest for the small tundish cases, which are dominated by mixing in the strand. The result is a two-fold reduction in intermixed steel for the small tundish (comparing runs 1 and 14). Decreasing the thickness also decreases the intermixed tonnage for the large tundish operation. However, the effect diminishes as tundish mixing becomes more important.

The order of casting affects the importance of mold thickness. For the 40 : 90 specification, the thinner mold (run 14) actually has a longer intermixed length than for the standard case, (although it contains less tonnage). This is due to the large penalty imposed on intermixed surface lengths for the stringent new grade, while the centerline benefit is not sufficiently rewarded. This emphasizes the conclusion that casting the stringent grade before to the lenient grade (10 : 60) is crucial to minimize intermixing in thin slab casting.

Effect of section width

The effect of slab width is similar to that of slab thickness, but not as dramatic. Decreasing the slab width translates all of the concentration curves towards the new grade, lessening centerline mixing length at the expense of longer surface mixing. The net effect on the intermixed length is relatively small. It is important to consider that narrow slabs contain fewer tonnes of steel per unit length than wide slabs. Consequently, intermixed tonnage is greatly reduced with narrower slabs. This effect is greatest for the lenient grade changes (40:60). The combined effect of slab width and thickness reveals that for the same cross-section, thinner and wider slabs produce shorter intermixed lengths.

10. GRADE TRANSITION STRATEGIES

Based on the above study, three different strategies might be considered for optimizing mixed grade casting, depending on the severity of the grade transition. The best strategy depends on economic considerations, which include balancing the costs of lost production, scrap or downgrade cost per tonne, cost of measuring composition, and intangibles such as the likelihood and cost of not detecting out-of-specification steel.

Stringent casting (no downgrade possible)

Casting radical grade transitions when no downgrade market is available is the least desirable option. When this must be done, intermixed length should be minimized. First, an economic analysis should be performed to weigh the benefits of using grade separators and flying tundish changes, or even stopping / restarting the sequence. This calculation requires knowledge of the expected intermixed lengths for different casting conditions, which can be assisted by model calculations.[3] Table IV results show that some casting conditions (such as stringent grade changes with thick or wide slabs) would intermix most of a heat, so require one of these practices.

If it is determined that mixing in both the tundish and mold is the most cost-effective option, then casting conditions should be optimized to minimize intermixing, according to the results in Section 9. Specifically:

- start to reduce casting speed long before ladle open,
- keep speed slow as long as possible during ladle open,
- lower tundish weight at ladle open,
  (the time prior to ladle open does not matter),
- hold tundish weight and speed constant for several minutes after ladle open,
- ramp speed and weight up to steady state slowly,
- minimize mixing volume in the tundish,
- cast thin, narrow slabs if possible

An on-line model should be installed to control exactly where intermixing occurs (as a function of real-time measurement of grades and casting conditions) and to predict where the intermixed slab should be cut. Ideally, the torch cut-off should cut at these exact locations, after adding a short length of steel to each end of the intermixed slab as a safety factor. This requires a precise tracking system to match distance down the strand with the time of casting events, such as ladle open. The location of the cuts must be planned in advance, so that the lengths of the other slabs in the cast can be adjusted to satisfy the length requirements of every slab.

<u>Lenient casting (downgrade market available)</u>

When a slab fails to meet grade specifications, it is either downgraded or scrapped. When a market exists for downgraded slabs, the optimal strategy is usually to capture in a single slab, all of the steel which fails to satisfy either the new or the old grade.

In contrast with operations which must scrap intermixed slabs, downgrading requires more than simply minimizing the length of the intermixed steel. For example, the length of the intermixed slab likely must be within a restricted range. Thus, the optimal place to cut the intermixed steel cannot be decided on the basis of composition alone.

When a slab can be downgraded for composition reasons, this simply means that an application is available which can accept a greatly increased range of compositions. Such applications are more likely for less severe grade changes, where the composition specifications of the old and new grades are also likely to be more lenient.

The results for lenient transitions (Section 9) show that a typical slab caster only produces about 10 tonnes of intermixed steel (5 tonnes per strand) for 40 : 60 specifications. For many applications, this intermixed length should be relatively easy to capture within a single slab, if care is taken to identify the location of the intermixed region. Again, a calibrated on-line model is an asset to assist in this task, by accounting for changes in casting conditions that would lengthen and move the intermixed section of the cast strand.

To minimize the other quality problems that may arise during the grade transition, steady-state casting conditions should be met as much as possible. Thus, a tradeoff exists between maximizing steel quality and minimizing intermixed length. For this reason, casting conditions should be optimized to reduce the intermixed length only enough to make it fit within a single slab. The casting condition changes presented in the previous section can be applied as necessary to achieve this. Depending on the downgrade market, it might even pay to operate at steady casting conditions to optimize quality and produce two intermixed slabs.

<u>Overlapping casting (downgrade avoided)</u>

The best strategy to optimize grade transitions is to schedule heat sequences to produce overlapping grade specifications, such as the 60 : 40 case modeled in this work. When this is possible, then the entire philosophy for optimizing the casting conditions changes. The strategy should be to avoid scrapping and downgrading entirely.

The results in Table IV for the overlapping (60 : 40) case show that care must be taken to find casting conditions which avoid any positive intermixed region. A negative distance represents the safe region where the cut between slabs of adjacent heats can be made arbitrarily because the specifications of both grades are satisfied.

Most of the strategies which minimize the intermixed length for conventional stringent and lenient grade specifications tend to have the opposite effect on overlapping grades. This is illustrated in Figure 9, where the conditions of runs 1 and 10 are compared. Figure 9 a) shows that the standard large tundish conditions, which are reasonably optimized for a downgrading strategy, produce 27 tonnes of intermixed steel when subjected to a stringent (10 : 90) grade specification. For an overlapping grade change, however, these conditions produce 1.4 tonnes of intermixed steel. Although the latter intermixed section is short, it complicates dispositioning of the slabs. Most of the cases in Table IV produce about 1m or 2 tonnes of intermixed steel per strand for this 60 : 40 case.

Figure 9 b) illustrates the intermixing amounts for casting conditions optimized to reduce intermixing for the overlapping grade change. An overlap of 2.4 m (-7.4 tonnes) is produced, which satisfies either grade. The casting conditions found to achieve this (run 10) keep the tundish weight and casting speed constant at their steady values, increase the tundish mixing volume, and decrease the dead volume. However, these casting conditions extend the intermixed region of a stringent (10 : 90) grade change to over 83 tonnes.

Intermixing in overlapping grade changes is due to varying composition through the slab thickness. Composition differences between the surface and centerline are generally greater when the transition occurs over a short distance. These differences increase for lower tundish weight, larger cross sections (either thicker or wider slabs), and higher casting speed. The casting conditions which optimize overlapping grade changes (run 10) tend to minimize composition variations through the thickness.

Intermixing in overlapping grade changes should be avoided by employing casting conditions which extend the grade change. These include:

- increase tundish weight,

- do not reduce tundish weight at ladle open
- increase mixing volume of tundish
- decrease dead volume of tundish
- reduce casting speed
- decrease slab thickness
- decrease slab width

To avoid quality problems due to transients, casting should be steady state (constant tundish volume and casting speed), to the greatest extent possible. This same strategy also optimizes overlapping grade changes, with the exception of steady casting speed. If the grade transition is gradual enough, then entire slab lengths may have a composition range that falls between the "old" and "new" grades. These slabs might be able to satisfy a more stringent requirement for an intermediate composition. Overlapping grade specifications result from optimized scheduling and should be encouraged. They enable high productivity, while avoiding both quality problems due to transients and the need to downgrade or scrap slabs.

11. CONCLUSIONS

Based on calculations with a calibrated mathematical model, (MIX1D),[3] three different strategies for optimizing grade transitions in the continuous casting of steel slabs have been identified. They depend on the grade specification (stringent, lenient, or overlapping). The following conclusions can be applied to optimize grade transitions which involve non-overlapping grade specifications:

1) Grades with stringent specifications should be cast before lenient ones when tundish mixing dominates. This is the case for large tundishes, low casting speeds, and thin or narrow slabs.

2) Lenient grades should be cast before stringent ones when strand mixing dominates. This is the case for small tundishes, flying tundish changes, high casting speeds, and wide or thick slabs.

3) Lowering the tundish weight at ladle open, keeping it low, and then refilling it slowly all tend to reduce intermixing, particularly for large tundishes and stringent new grades, where tundish mixing predominates.

4) Tundish flow controls should be optimized (through plant and water model measurements) to minimize the mixing volume, particularly for stringent new grades on large tundishes.

5) Slowing down the average casting speed throughout the grade transition decreases the amount of intermixed steel.

6) A thinner slab produces much less intermixed tonnage in all cases. It even shortens intermixed length for most cases.

7) A narrower slab width produces less intermixed tonnage in all cases. The effect on intermixed length is minimal.

8) For the same cross-section, thinner and wider slabs produce shorter intermixed lengths.

The best strategy is to optimize scheduling to produce overlapping grades specifications. For this type of grade transition, the optimal casting conditions change completely:

1) Intermixing is caused by composition variations through the slab thickness, which are worse with thick or wide slabs, and high casting speed.

2) Intermixing is best avoided by casting at steady state, with a large tundish weight, minimal drop in tundish weight at ladle open, tundish flow controls which increase mixing volume and decrease dead zones, and low casting speed. This practice is also best for steel quality.

12. ACKNOWLEDGMENTS

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FIGURES

Fig. 1 Typical change of casting speed, tundish weight, and flow rates with time during a grade transition

Fig. 2 Schematic of continuous casting tundish and its six box model

Fig. 3 Schematic of three zone strand model

Fig. 4 Shell thickness growth profiles assumed in model

Fig. 5 Comparison of predicted concentration histories exiting tundish into mold with measurements for:
a) small tundish operation. b) large tundish operation c) bloom casting operation

Fig. 6 Comparison of predicted composition profiles along final product with measurements for:
a) small tundish operation b) large tundish operation. c) bloom casting operation

Fig. 7 Typical composition and intermix range output by MIX1D model for a small tundish operation (Table I)

a) 10 : 60 (stringent : lenient) grade transition b) 40 : 90 (lenient : stringent) grade transition

Fig. 8 Effect of weight of steel remaining in a large tundish at ladle open on calculated results (runs 1 and 2):

a) Concentration history exiting tundish b) Composition profiles in steel slabs

Fig. 9 Effect of casting conditions and intermixing criterion on amount and location of intermixed steel

a) Standard conditions (large tundish run 1) b) Steady casting conditions (large tundish run 10)

APPENDIX I SHELL THICKNESS RELATIONSHIPS

To calculate shell thickness, needed for the third submodel, a kt^n relationship was assumed between shell thickness, S, and solidification time, t_{sh}. Values for the parameters depend on section size, steel composition, and spray conditions. Typical values are given in Fig. 4.

$$t_{sh} = \left(\frac{S}{k_a}\right)^{\frac{1}{n_a}} \qquad S \leq S_b \qquad [A1]$$

$$t_{sh} = \left(\frac{S_b}{k_a}\right)^{\frac{1}{n_a}} \left(1 + \frac{n_b\, S}{n_a\, S_b} - \frac{n_b}{n_a}\right)^{\frac{1}{n_b}} \qquad S > S_b \qquad [A2]$$

FIGURES

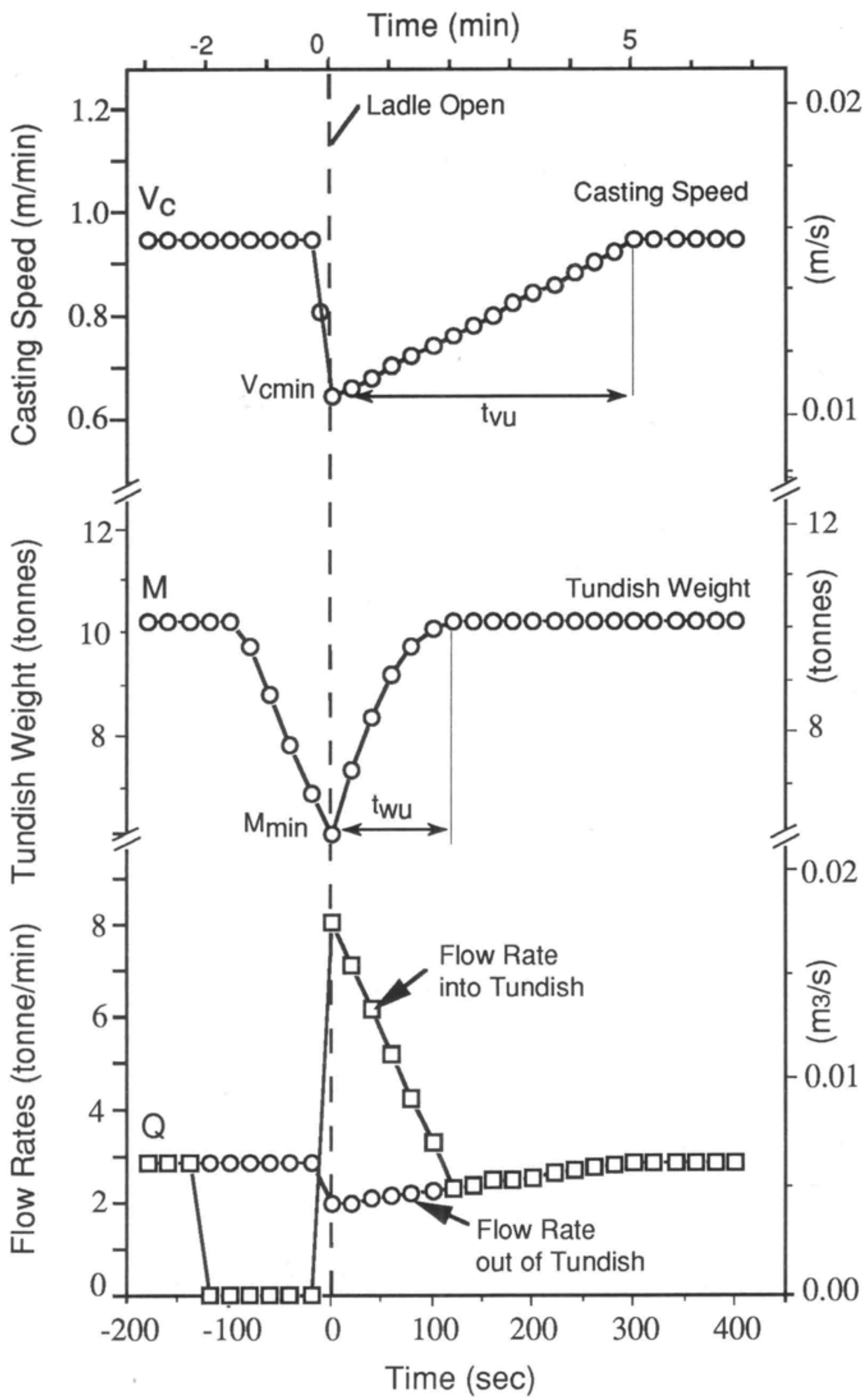


Fig. 1 Typical variation of casting speed, tundish weight and flow rates with time during a grade transition.

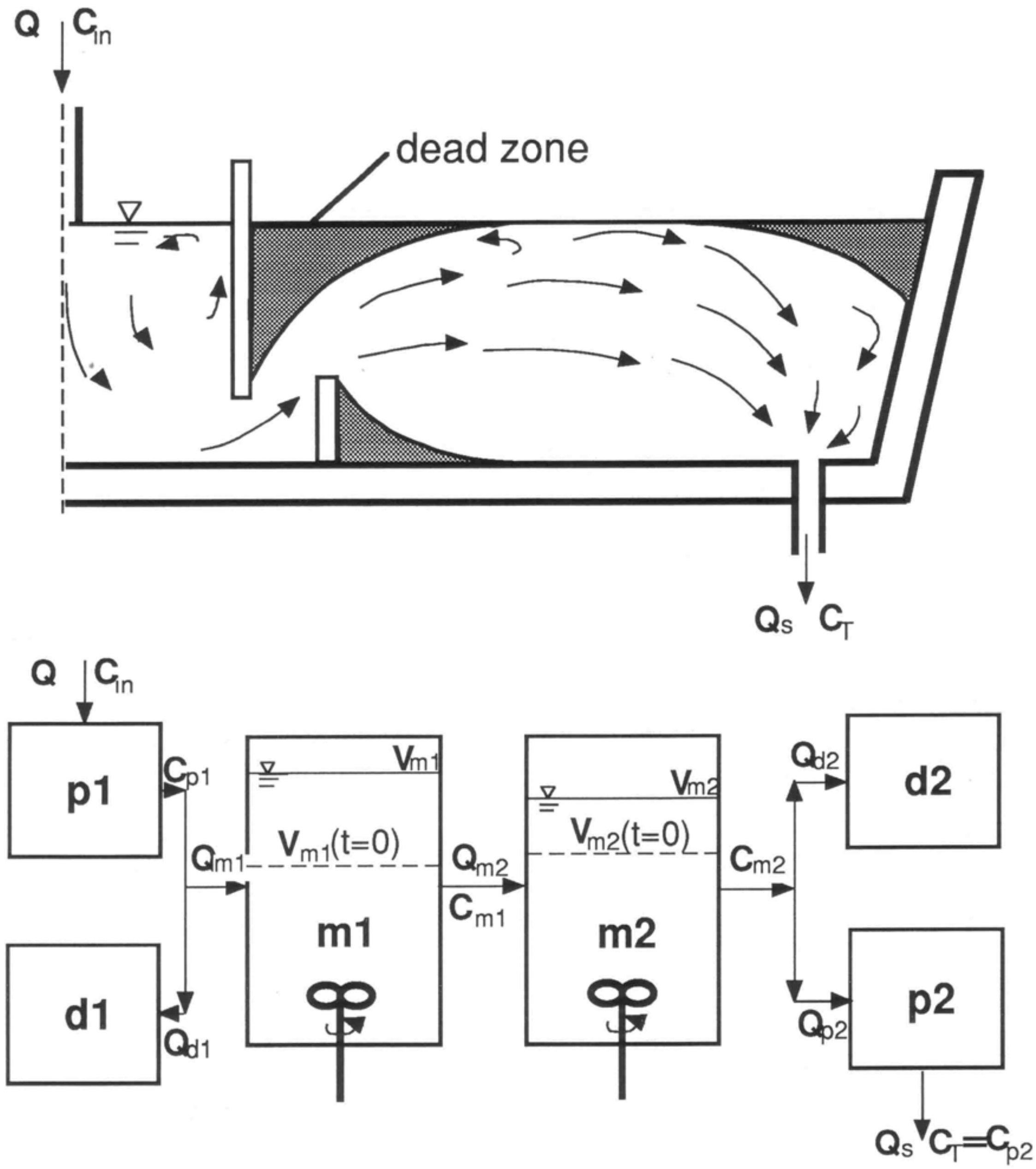


Fig. 2 Schematic of a continuous casting tundish and its six box model.

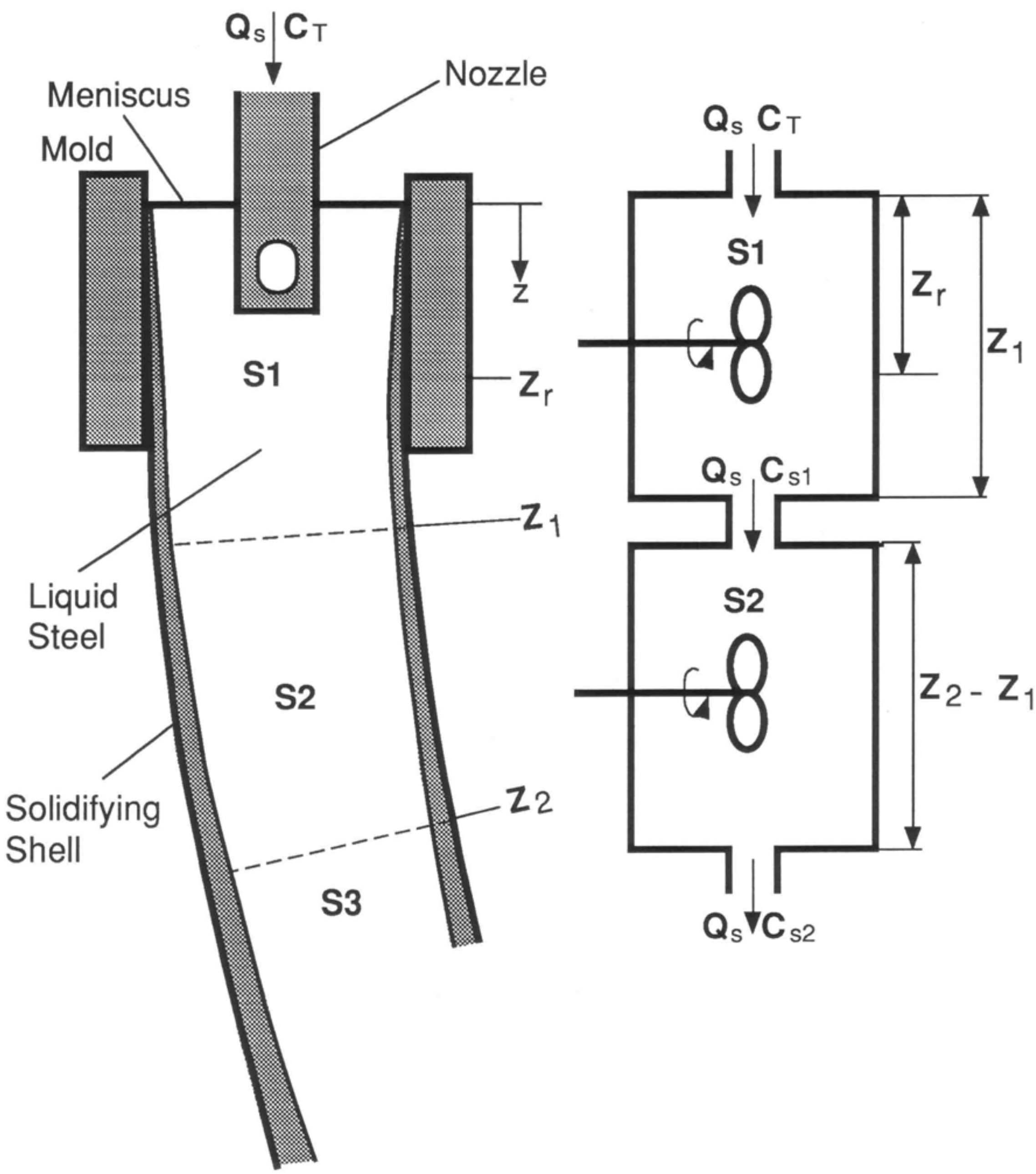


Fig. 3 Schematic of three box model of strand.

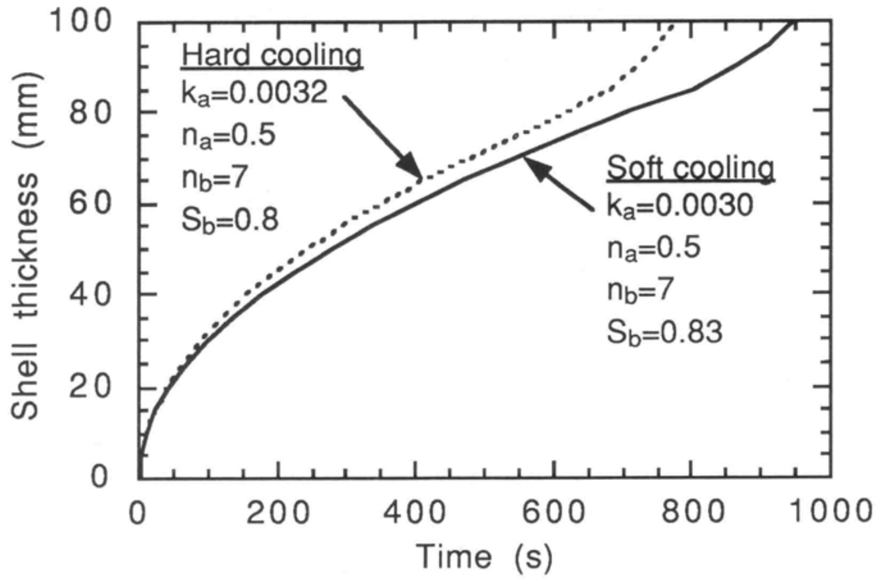


Fig. 4 Shell thickness growth profiles assumed in model

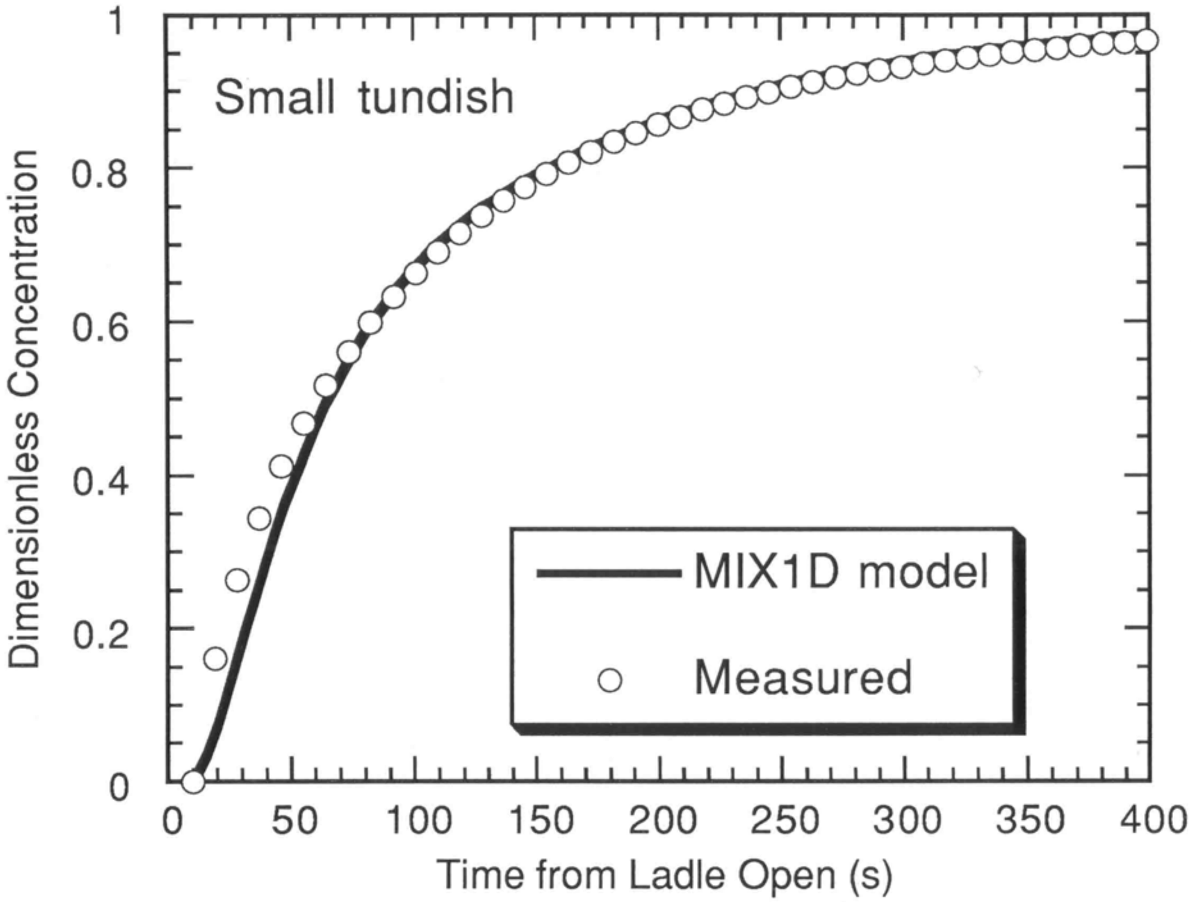


Fig. 5 Comparison of predicted concentration histories exiting tundish into mold with measurements for:
a) small tundish

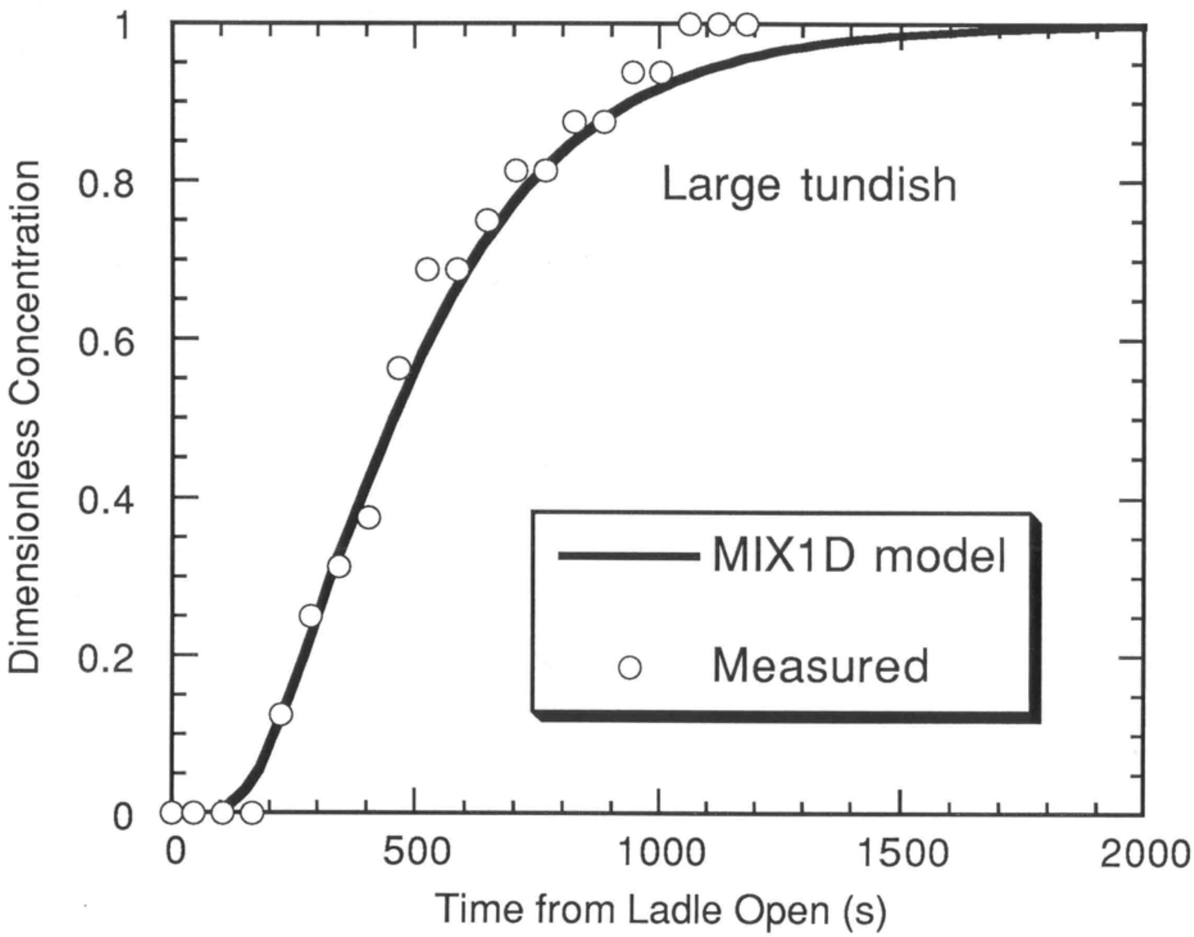


Fig. 5 Comparison of predicted concentration histories exiting tundish into mold with measurements for:
b) large tundish

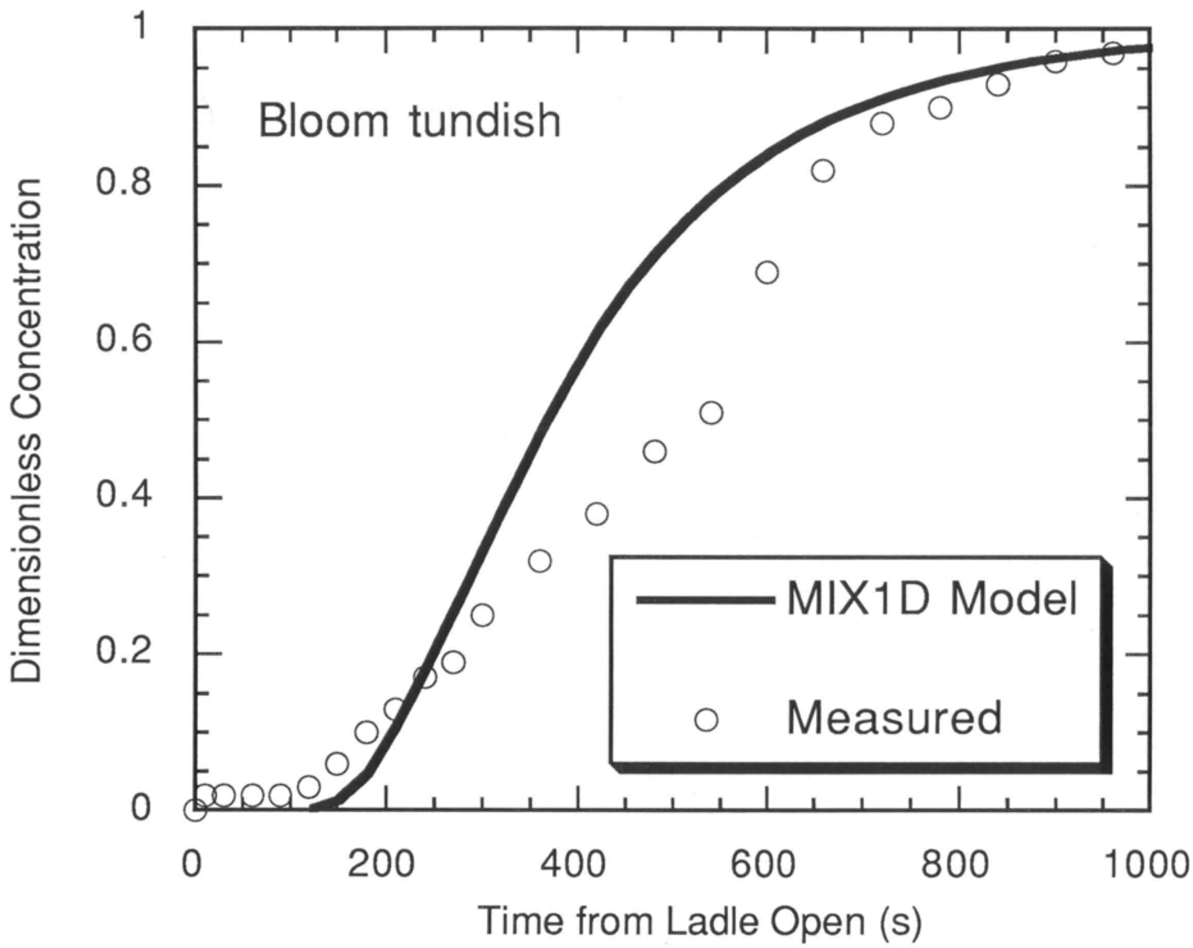


Fig. 5 Comparison of predicted concentration histories exiting tundish into mold with measurements for:
c) bloom

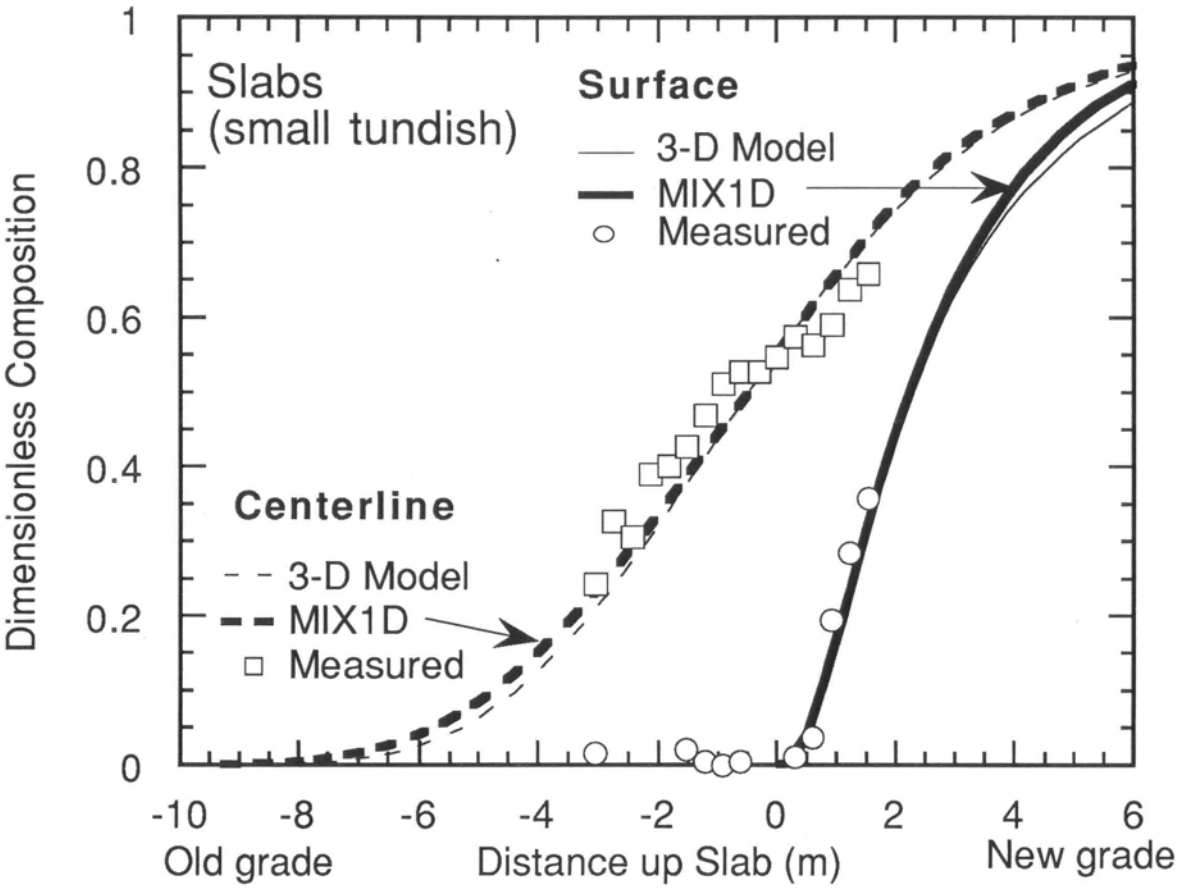


Fig. 6 Comparison of predicted composition profiles along final product with measurements
a) small tundish operation

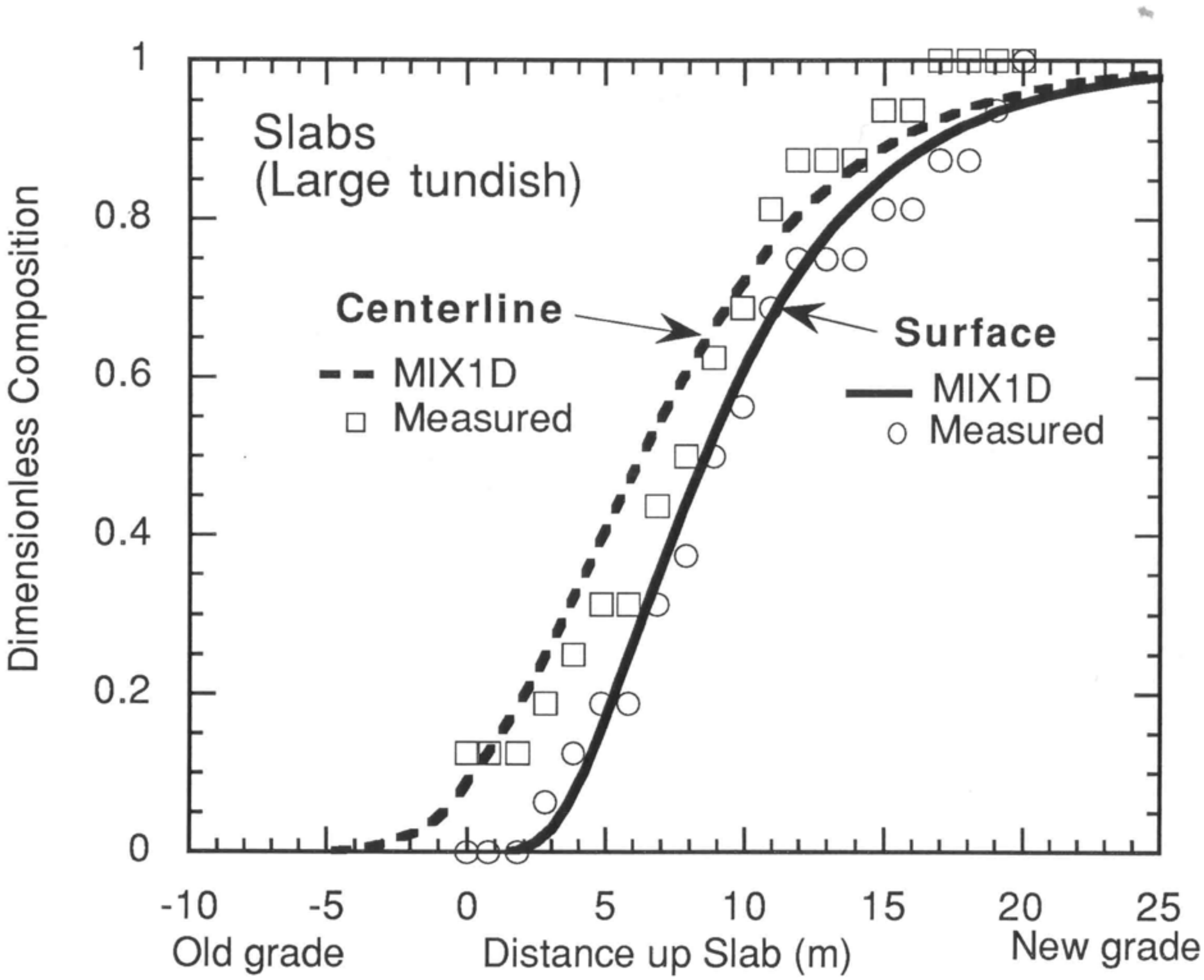


Fig. 6 Comparison of predicted composition profiles along final product with measurements
b) large tundish operation

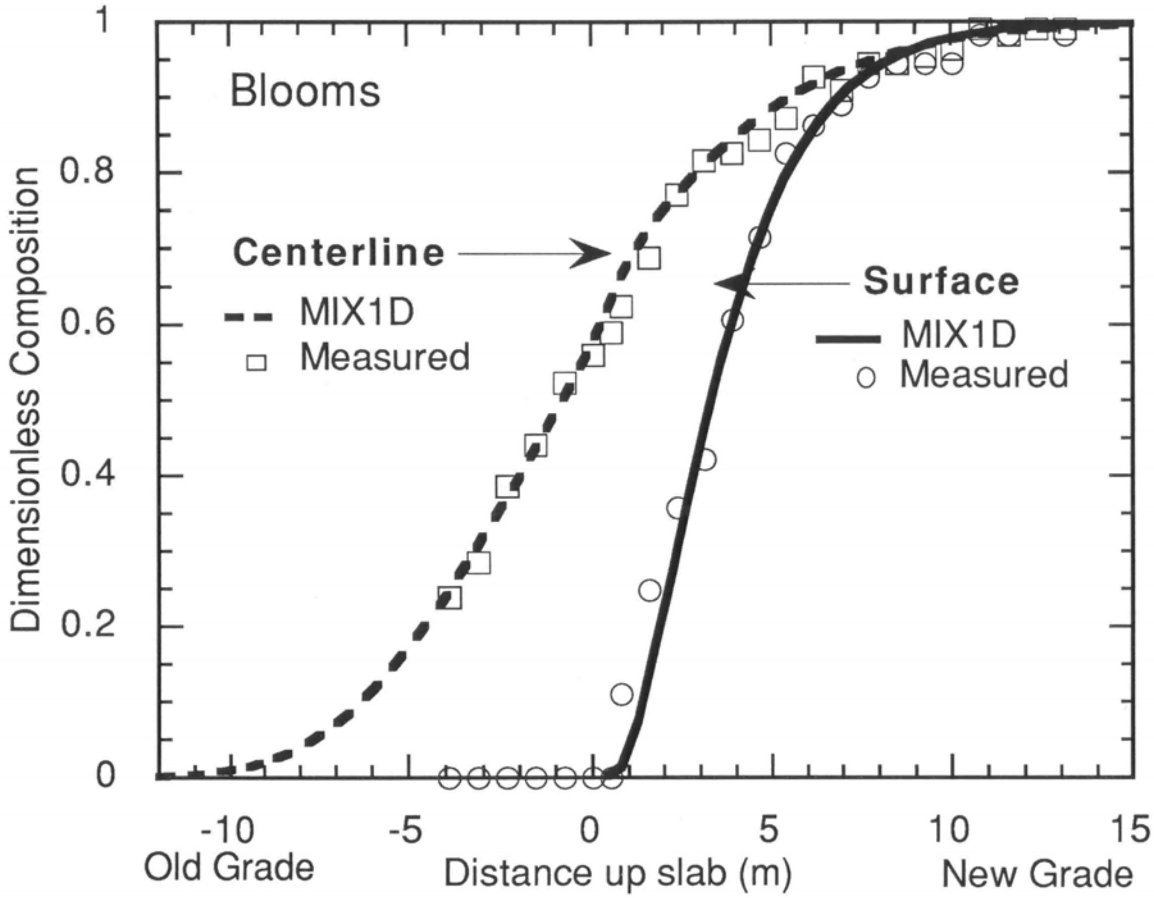
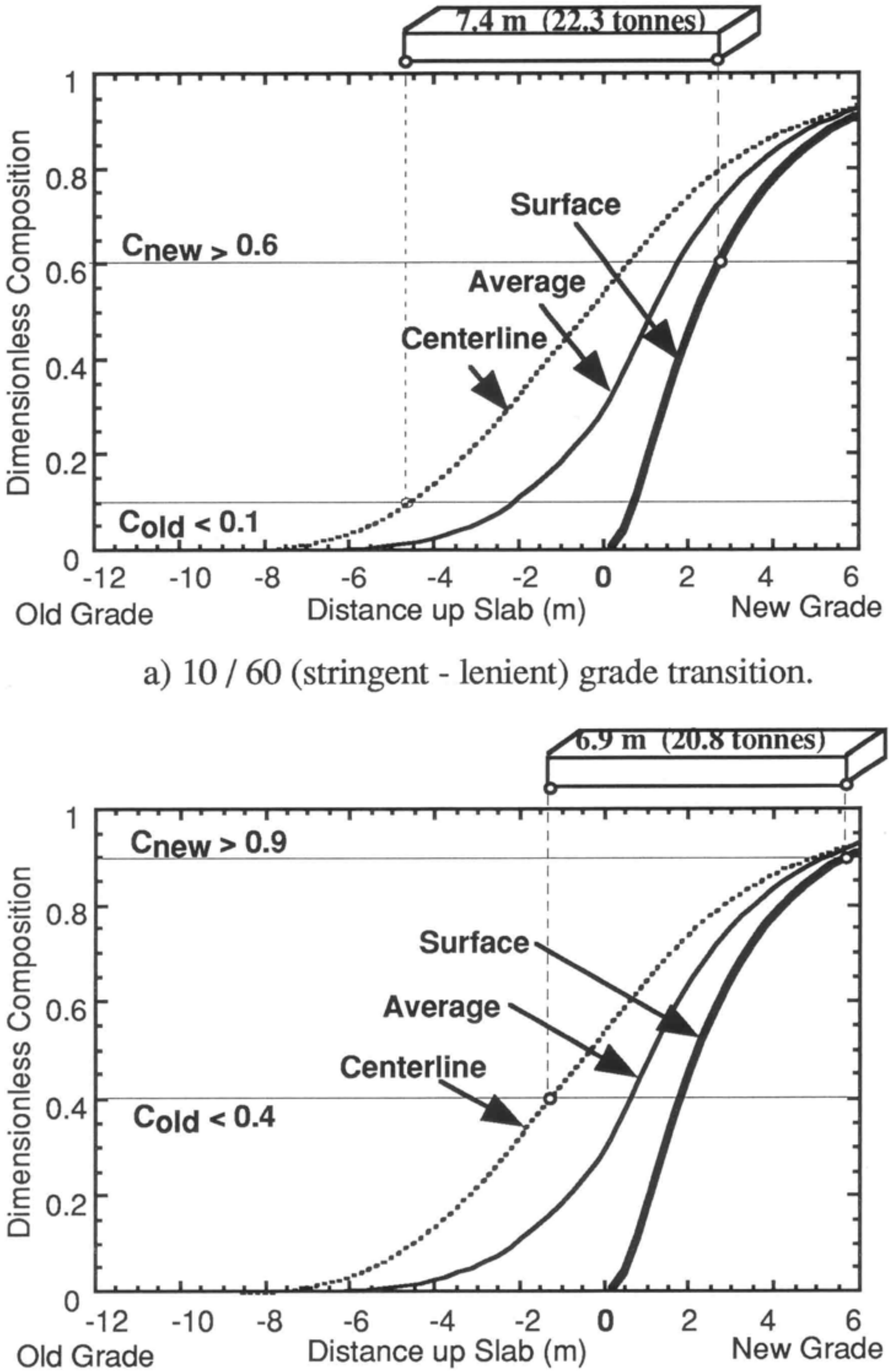


Fig. 6 Comparison of predicted composition profiles along final product with measurements
c) bloom casting operation



a) 10 / 60 (stringent - lenient) grade transition.

b) 40 / 90 (lenient - stringent) grade transition

Fig. 7 Composition and intermixing range output from MIX1D model for a small tundish operation (Table I)

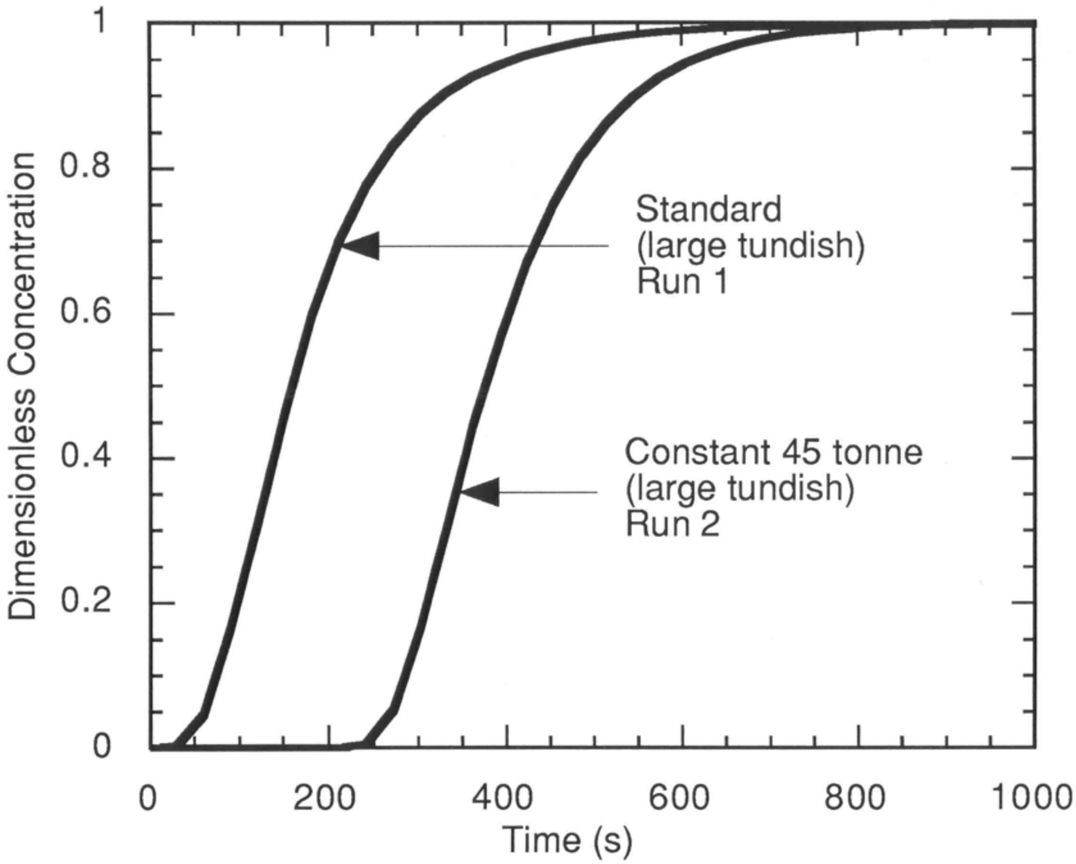


Fig. 8 Effect of weight of steel remaining in a large tundish at ladle open on calculated results (runs 1 and 2):

a) Concentration history exiting tundish

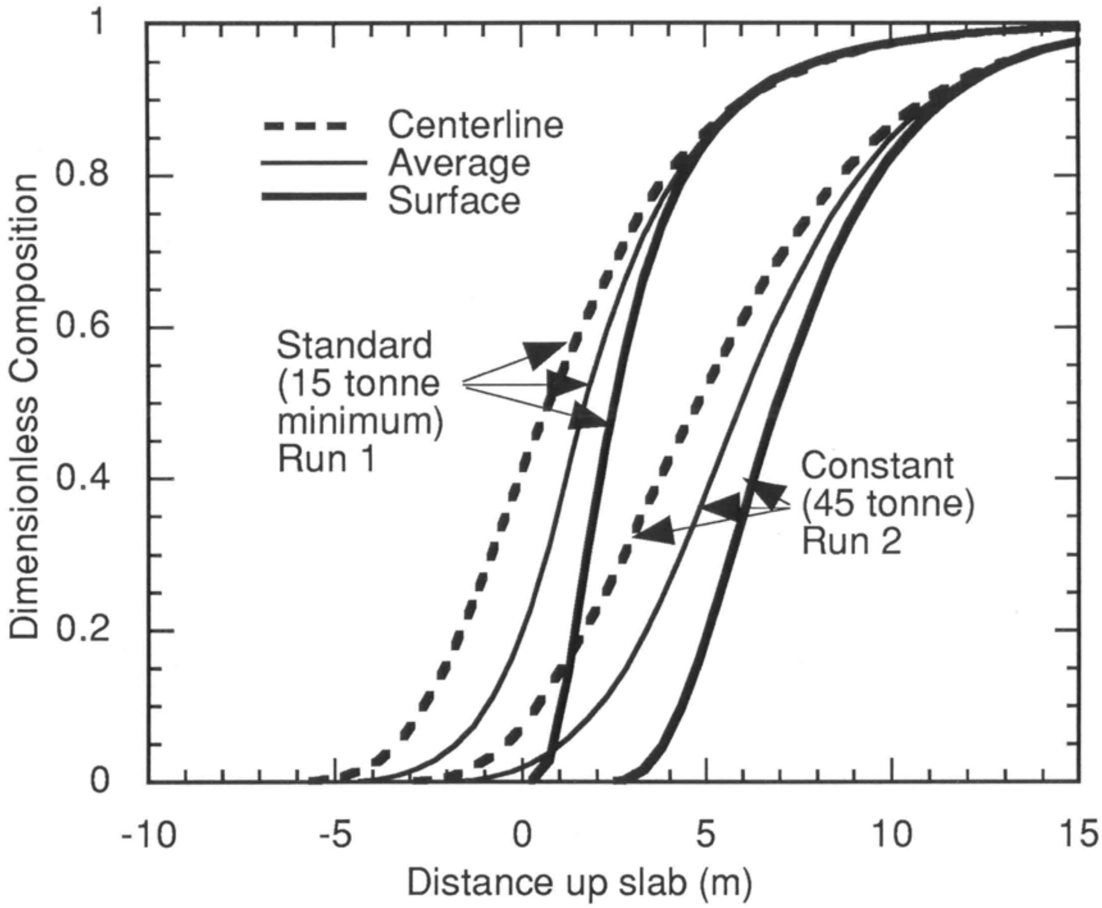


Fig. 8 Effect of weight of steel remaining in a large tundish at ladle open on calculated results (runs 1 and 2):
b) Composition profiles in steel slabs

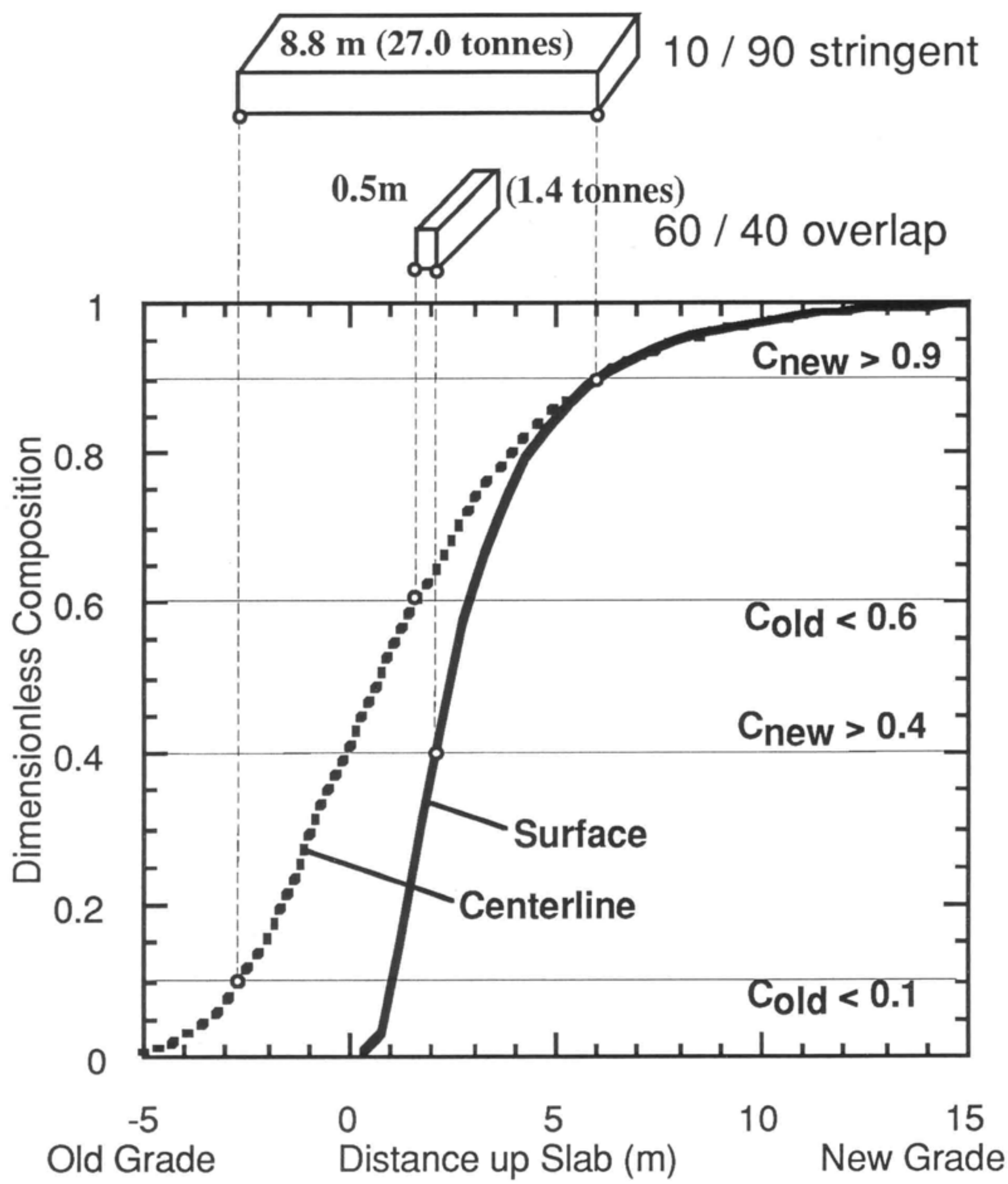


Fig. 9 Effect of casting conditions and intermixing criterion on amount and location of intermixed steel

a) Standard conditions (large tundish run 1)

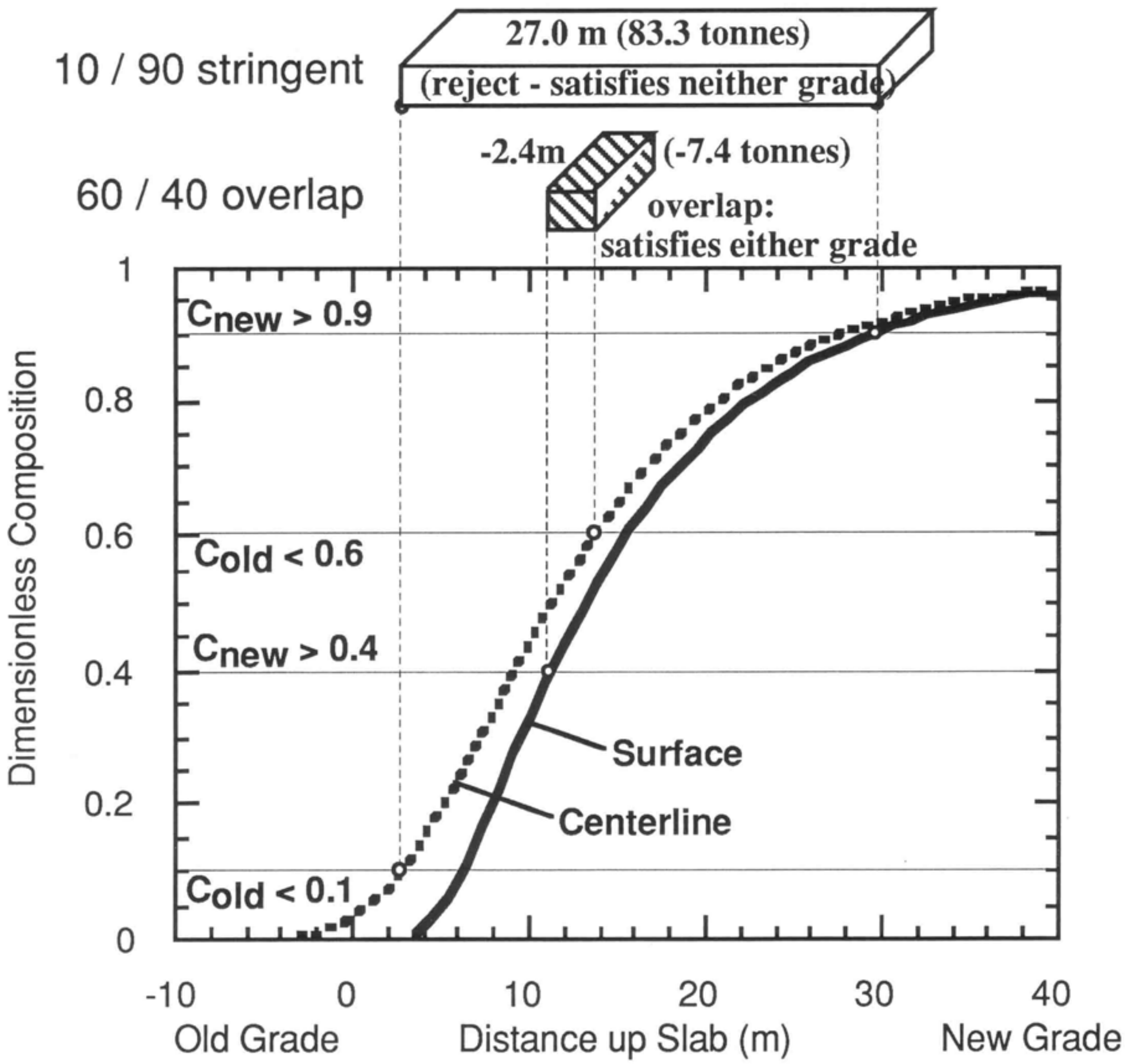


Fig. 9 Effect of casting conditions and intermixing criterion on amount and location of intermixed steel

b) Steady casting conditions (large tundish run 10)