Inclusion Behavior and Heat-Transfer Phenomena in Steelmaking Tundish Operations: Part III. Applications—Computational Approach to Tundish Design

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The attributes of various tundish designs and flow modifiers have been studied based on the computational and physical modeling efforts developed in parts I and II. The importance of thermal natural convection effects in such vessels has been demonstrated. Flow patterns and residual ratios (RR) for various tundish designs of equal volume and metal throughput showed that a conventional biflow, twin-strand, trough-type tundish fitted with flow modifiers allows for the greatest removal of inclusions, while a one-way flow, twin-strand, wedge-shaped tundish performs best in the absence of flow modifiers. More detailed analyses of the conventional trough-type tundish were performed to assess the effects of double-weir–double-dam and single-weir–double-dam arrangements. The effectiveness of steeply sloping sidewalls for enhanced removal of inclusions was demonstrated; however, this measure was associated with penalties in the form of greater metal temperature losses.

I. INTRODUCTION

IN part I, an experimental technique for the on-line measurement of particle concentrations in aqueous systems[1,2] was presented and used to compare the effectiveness of dam and weir arrangements in a full-scale aqueous model of a tundish for a single-slab or twin-bloom combicaster. The data were then matched with fully three-dimensional (3-D) descriptions of the isothermal flow fields and of buoyant particle dispersion, flotation, and separation. As particle predictions largely matched experimental data, the validity of the mathematical model with respect to full-scale aqueous models of tundish systems was confirmed.

In part II, the relevance of natural convection in real metal flow systems was demonstrated. Given the sophistication of the present model, 3-D fluid flow in any current tundish designs can now be simulated and detailed information concerning metal flow and the degree of inclusion separation can be obtained. The criteria for optimal tundish design are therefore addressed in part III.

Continuous casting tundishes are now regarded as one of the more important vessels in the steelmaking operation. Steelmakers appreciate the fact that deleterious inclusions of significant size exist in such vessels and that their residence time within the vessel must be extended as far as possible in order to allow the inclusions to float out. Most major steel companies are making use of ever larger tundishes and optimizing their shape and/or contained flow modification devices.

In the present article, flow fields and inclusion separation ratios for several tundish shapes of equal volume and equivalent metal throughput have been studied and computations on the effectiveness of various combinations of weirs, dams, and slopes of sidewalls have been performed in order to identify the more desirable shapes and designs now in current use around the world. Three designs were selected for modeling. Figure 1 illustrates type I, II, and III tundishes chosen for study, wherein the shaded volume represents the computational domain. Type I is a conventional two-way flow trough-type tundish. Type II is a one-way flow, twin-strand, trough-type tundish, and type III is a one-way flow, twin-strand, wedge-shaped tundish. The capacities of tundishes chosen for these comparisons were 70 tonnes. This translates into a volumetric capacity of 10.35 m^3. The volumetric flow rate chosen was 0.0214 m^3/s, equivalent to 9 tonnes/min, imposing a metal mean residence time (θ) of 8 minutes. These are relatively common tundish statistics for current slab-casting operations in steelmaking. The conventional trough-type tundish (type I) design has been studied by several researchers and is also in wide use. Type II and III tundishes have also been adopted at several steel plants, their shapes being a function of caster layout.

The present study concentrates on understanding the effect of tundish design on metallurgical quality by calculating the efficiency of these three tundish shapes and their various configurations of flow modifiers with respect to inclusion removal and metal quality. Metal quality is defined here as physical quality in terms of steel cleanness, temperature distribution, and product uniformity. It is anticipated that the present results will be helpful in the design of future tundish systems.

II. FORMULATION

A. *Mathematical Model*

The required set of differential equations was solved with appropriate boundary conditions in order to determine flow, turbulence, inclusion, and temperature

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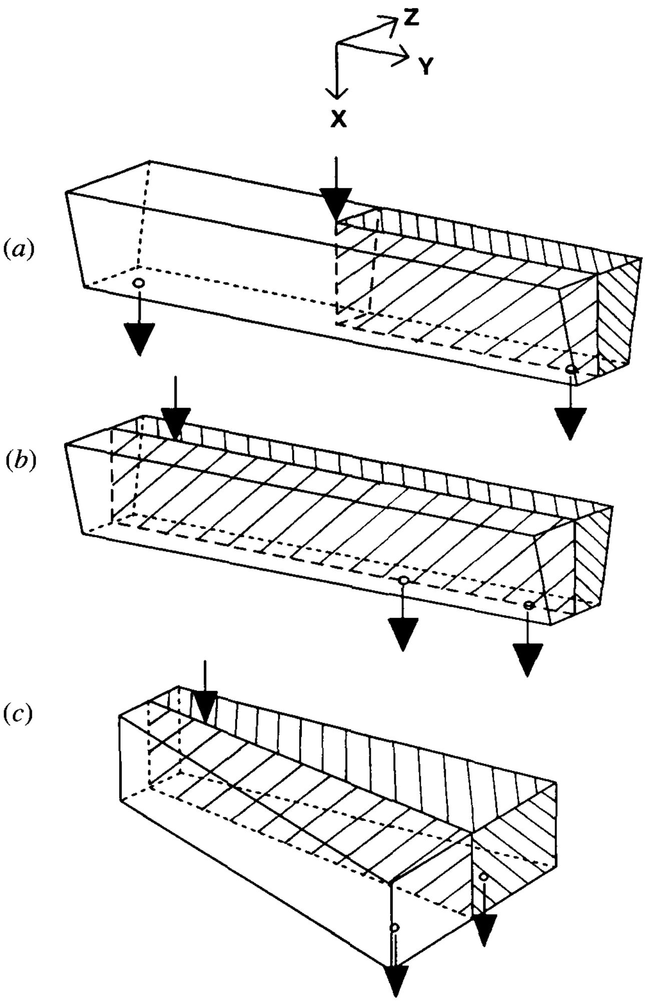


Fig. 1—Schematic diagrams for three generic types of tundish: (*a*) conventional trough-type tundish (type I); (*b*) one-way flow, twin-strand, trough-type tundish (type II); and (*c*) one-way flow, twin-strand, wedge-shaped tundish (type III).

fields. All these equations can be expressed in the general form:

$$\frac{\partial(\rho\phi)}{\partial t} + \text{div}\,(\rho u\phi) = \text{div}\,(\Gamma_\phi \text{grad}\phi) + S_\phi \qquad [1]$$

which allows convenient computational procedures to be adopted for their simultaneous solution. In Eq. [1], Γ_ϕ represents the exchange coefficients and S_ϕ is the source term. The quantities Γ_ϕ and S_ϕ are specific to the particular meaning of ϕ which can represent u, v, w, T, C, k, or ε. It is noted that the k-ε turbulence model of Launder and Spalding[3] was used to mimic the effects of turbulence on the flow. The explicit formulations of ϕ defined for motion (u, v, w), for turbulent properties (k, ε), for the dispersion of fine particles (C), and for the energy conservation (T) equation are listed in Tables I and II. Parts I and II of this series of articles provide more details of these procedures and equations.

B. *Boundary Conditions*

The rate of input of the vertically entering jet of steel from the ladle was assumed to be 4.5 t/min of steel per strand, giving a flowrate, Q, of 0.0214 m^3/s. At all the tundish wall boundaries, including any dams and weirs, standard wall functions were used in conjunction with nonslip boundary conditions. The boundary conditions required for the dispersion of particles assumed that inclusions within the fluid were impervious to all bounding surfaces apart from the free surface. Mathematically, this corresponds to zero flux at all bounding surfaces including weirs and dams.

At the free surface (which was considered to be flat) and at the symmetry planes, normal velocity components and normal gradients of all other variables (momentum and scalar transport properties) were taken to be zero. At the jet's entry from the ladle shroud, a flat velocity profile was assumed. At the free surface of the steel, ideal conditions for the absorption of inclusions were assumed. Since the volume fraction of the inclusion particles is small, these particles do not influence flow and turbulence behavior of the liquid steel.

In calculating surface heat losses from the steel, it was assumed that these were radiative in nature, with or without absorbant slag. The slag was assumed to be liquid, 3-cm thick, and motionless.

Table I. Definitions of ϕ, Γ_ϕ, and S_ϕ in Equation [1]

Conservation of	ϕ	Γ_ϕ	S_ϕ
Mass	1	0	0
Momentum—x, y, z	u, v, w	μ_{eff}	$\frac{\partial}{\partial x_j}\left(\mu_{\text{eff}}\frac{\partial u_j}{\partial x_j}\right)$
Kinetic energy	K	$\frac{\mu_{\text{eff}}}{\sigma_k}$	$G - \rho\varepsilon C_D$
Dissipation rate	ε	$\frac{\mu_{\text{eff}}}{\sigma_s}$	$\frac{g}{k}(C_1 G - C_2\rho\varepsilon)$
Inclusion particles	C	μ_{eff}	0
Temperature	T	μ_{eff}	0

Table II. Values of Constants in K-ε Turbulence Model

C_1	C_2	C_D	σ_k	σ_g
1.43	1.92	0.09	1.00	1.30

C. *Numerical Solution Procedure*

The METFLO computer code[4,7] was used for solving turbulent flows and heat and mass transfer within such tundishes. There, finite difference equations were derived from governing differential equations, as shown in Eq. [1] and Tables I and II. The resulting set of equations was solved simultaneously using an implicit finite difference procedure referred to as the SIMPLE algorithm.[5] On the basis of symmetry arguments, one-quarter of the conventional trough-type tundish (type I) and a half-section of the one-way flow, twin-strand, trough-shaped (type II) and the one-way flow, twin-strand, wedge-shaped (type III) tundishes were considered for computations. Input conditions and parameters employed in the computation are summarized in Tables III, IV, and V. Orthogonal cartesian grids were

Table III. Input Data Used for Calculations

Melt temperature (°C)	1575
Melt volumetric flow rate (m^3/s)	0.0214
Melt viscosity ($kg/m \cdot s$)	0.0067
Melt density (kg/m^3)	7000
Inclusion density (kg/m^3)	3000

selected. Curved and inclined walls, as well as dams and weirs, were specified by blocking off cells, either partially or completely, to fluid flow.

Figure 2 shows how the model's predictions for vertical velocity components in the type I tundish vary with grid spacing. A 24 × 40 × 16 grid produced results essentially identical to those for the standard 17 × 40 × 16 grid. Grid sensitivity analyses were also performed for the type II and III tundishes. It was shown that 17 (vertical) × 40 (longitudinal) × 16 (transverse) grid configurations for type I and II tundishes, as well as a 17 (vertical) × 40 (longitudinal) × 20 (transverse) grid for the type III configuration, produce results that are insensitive to grid and time configurations. All the computations were carried out on a CRAY-1S* supercomputer, the programs requiring about a million words in memory and execution times of 1 to 2 hours for steady-state flow fields. About 1 hour of execution was needed for describing the transient dispersion of particles, following a step input change in the inclusion density at the inlet (shroud) nozzle.

*CRAY-1S is a trademark of Cray Research, Inc., Minneapolis, MN.

III. RESULTS AND DISCUSSION

A. *Comparison of the Three Types of Tundish*

1. *Fluid flow*

Figures 3 through 5 illustrate flow fields for the three designs of tundish under consideration in the absence of flow modifiers. In all cases, a primary recirculation zone

Table IV. Data Used for Three Designs of Tundish

Shape	Type I Conventional Trough-Type	Type II Adjacent Ported Trough-Type	Type III Adjacent Ported Wedge-Shaped
Tundish volume (m^3)	10.350	10.350	10.350
Volumetric flow rate (m^3/s)	0.0214	0.0214	0.0214
Tundish length (m)	7.120	6.000	4.750
Tundish depth (m)	1.200	1.200	1.200
Surface width in inlet side (m)	0.682	0.711	0.605
Surface width in outlet side (m)	0.682	0.711	1.210
Weir location from inlet (m)	1.650	2.950	2.325
Dam location from inlet (m)	1.750	3.050	2.425
Weir gap (m)	0.280	0.280	0.280
Dam height (m)	0.360	0.360	0.360

Table V. Data Used for Parametric Studies for the Type I Tundish

Configurations	NFM-0	NFM-10	NFM-20	NFM-30
Tundish volume (m^3)	10.35	10.35	10.35	10.35
Volumetric flow rate (m^3/s)	0.0214	0.0214	0.0214	0.0214
Tundish length (m)	7.12	7.12	7.12	7.12
Tundish depth (m)	1.2	1.2	1.2	1.0
Surface width (m)	0.580	0.682	0.791	0.861
Taper of sidewall (deg)	0	10	20	30

Configurations	SW	SD	SWSD	SWDD	DWDD	DWDDR
Tundish volume (m^3)	10.35	10.35	10.35	10.35	10.35	10.35
Volumetric flow rate (m^3/s)	0.0214	0.0214	0.0214	0.0214	0.0214	0.0214
Tundish length (m)	7.12	7.12	7.12	7.12	7.12	7.12
Tundish depth (m)	1.2	1.2	1.2	1.2	1.2	1.2
Surface width (m)	0.682	0.682	0.682	0.682	0.682	0.682
Taper of sidewall (deg)	10	10	10	10	10	10
First weir location from inlet (m)	1.20		1.20	1.00	1.20	1.20
First dam location from inlet (m)		1.41	1.41	1.20	1.41	1.41
Second weir location from inlet (m)					2.15	2.36
Second dam location from inlet (m)				2.25	2.36	2.15
First weir gap (m)	0.28		0.28	0.28	0.28	0.28
First dam height (m)		0.36	0.36	0.36	0.36	0.36
Second weir gap (m)					0.28	0.28
Second dam height (m)				0.18	0.36	0.36

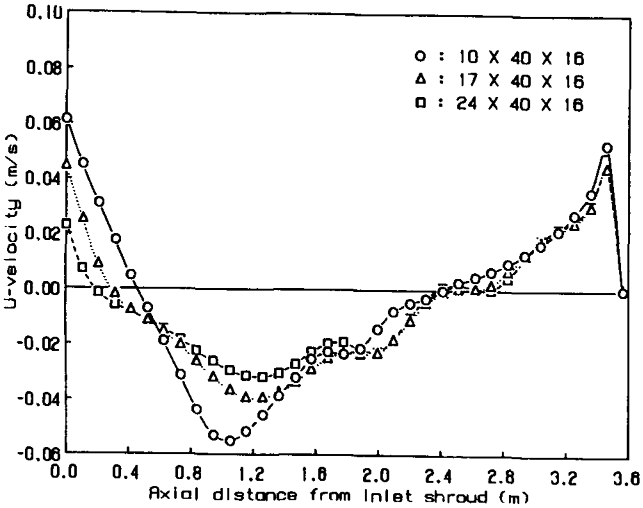


Fig. 2—Velocity component changes *vs* various grid configurations.

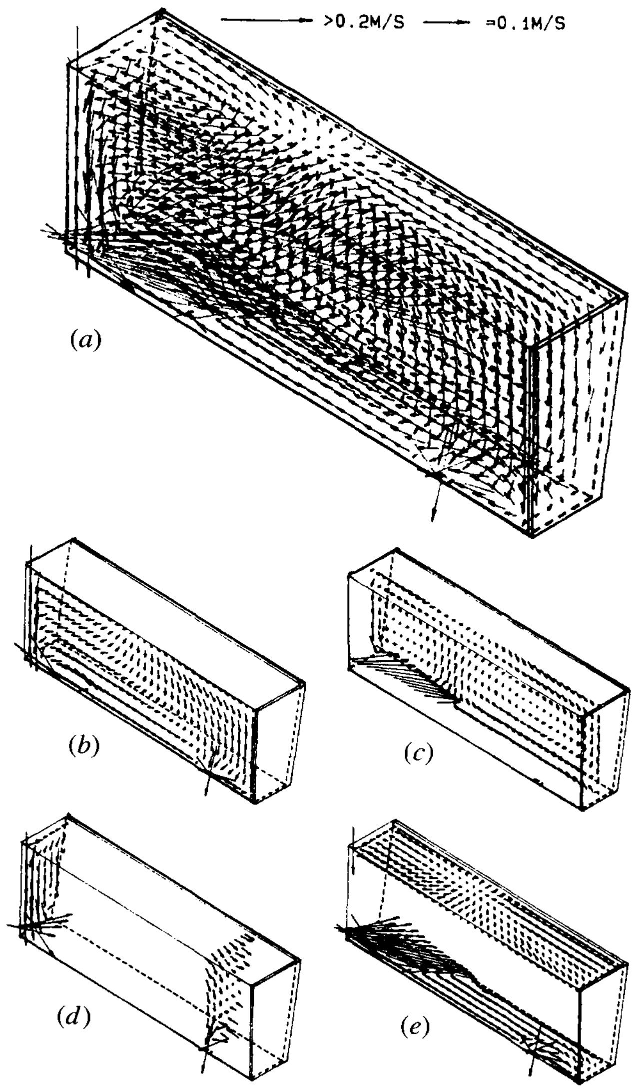


Fig. 3—Perspective view of the 3-D flow patterns in conventional trough-type tundish (*a*) without flow modifiers, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view, and (*e*) horizontal free surface and bottom plane view.

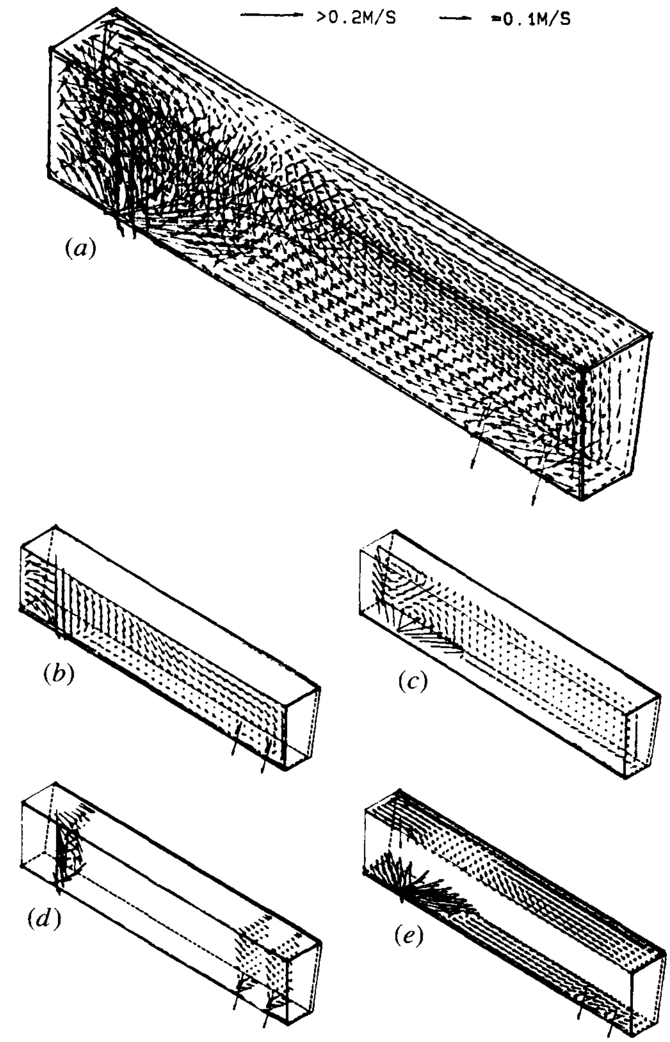


Fig. 4—Perspective view of the 3-D flow patterns in adjacent ported trough-type tundish (*a*) without flow modifiers, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view and (*e*) horizontal free surface and bottom plane view.

in the vicinity of the plunging jet is generated. The effect of natural convection is marked by a zone of secondary recirculation in the longitudinal sense, with steel moving down the outside and endwalls. The effect is greater the further the travel from the entry region. Owing to the diverging flow in the adjacent ported wedge-shaped (type III) tundish, a rotating flow in both the axial and transverse planes generates a relatively complicated spiral type of flow. It is emphasized that these flow fields correspond to equal volume–equal flow rate conditions.

The role of dams and weirs is illustrated in Figures 6 through 8. In all cases, their effect is to first direct steel from the primary recirculating zone toward the surface for enhanced inclusion removal. The steel stream then flows down the sidewalls and end walls, largely as a result of natural convection, with a fraction of the flow exiting while the remaining major portion recirculates across the tundish floors and back toward the surface.

2. *Dispersion of particles*

The fact that flow fields have a bearing on the physical quality of steel being produced is of great significance.

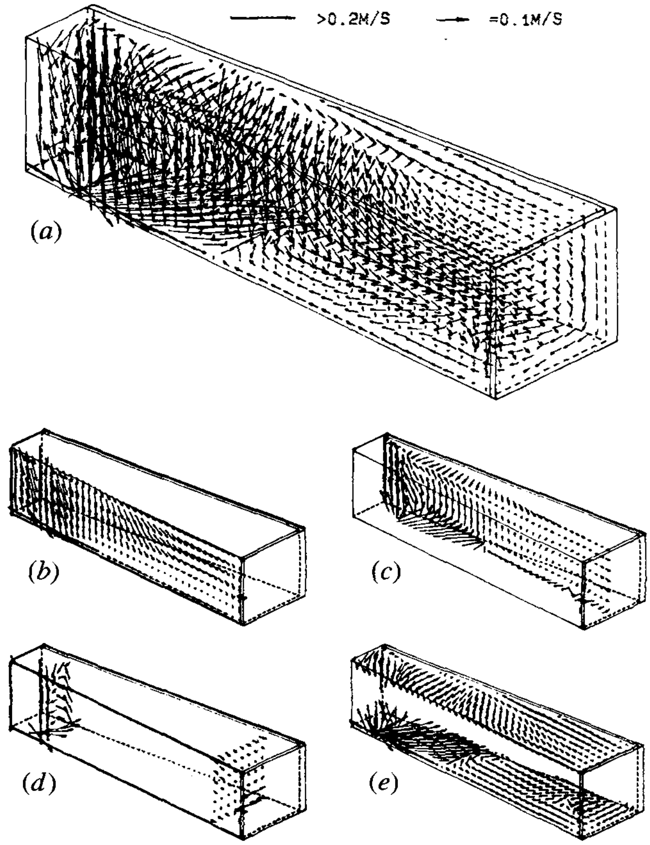


Fig. 5—Perspective view of the 3-D flow patterns in adjacent ported wedge-shaped tundish (*a*) without flow modifiers, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view, and (*e*) horizontal free surface and bottom plane view.

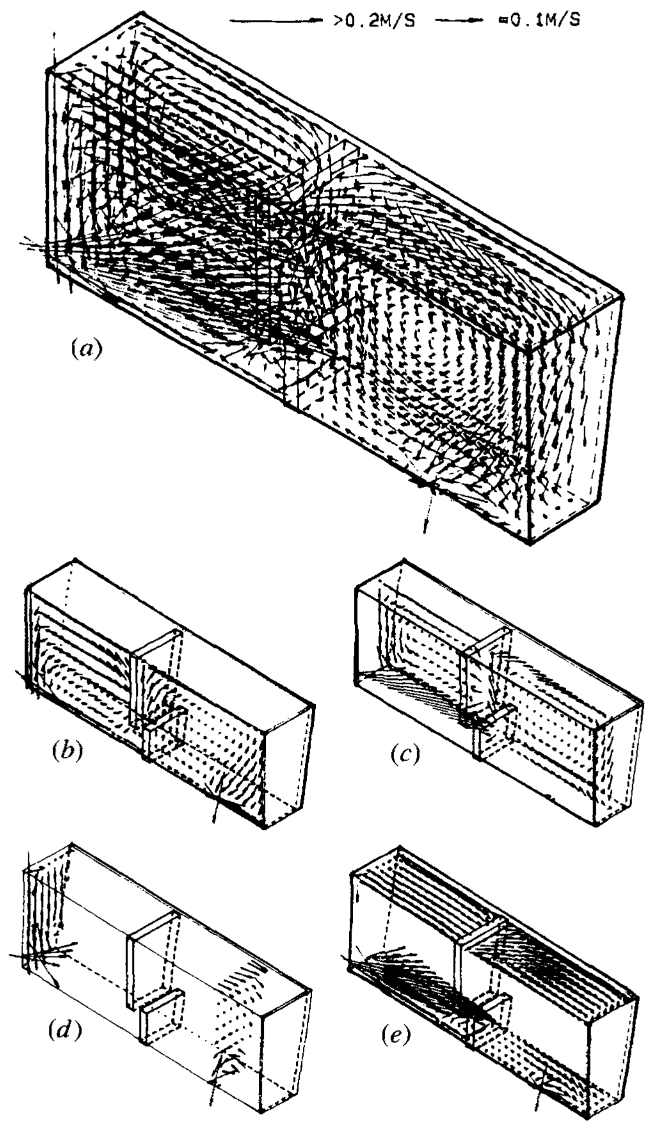


Fig. 6—Perspective view of the 3-D flow patterns in conventional trough-type tundish (*a*) with flow modifiers, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view, and (*e*) horizontal free surface and bottom plane view.

Figure 9 provides a plot of the residual ratios of inclusion particles *vs* time from their initial introduction as a steady concentration source into a conventional trough-type tundish without flow modifiers. Four curves are plotted corresponding to different Stokes rising velocities. The residual ratio is defined as the total number of particles leaving per unit mass *vs* the total number of particles entering the tundish per unit mass, or the number density of particles exiting the tundish to the number density of particles in the entry feed to the tundish. Taking the density of molten steel as ρ_s = 7000 kg/m^3 and the average density of the inclusions as ρ = 3000 kg/m^3, together with g = 9.8 m/s^2 and μ = 0.006 kg/ms, one obtains from Eq. [10] in part I a Stokes rising velocity of u_s = 1 mm/s for 53 μm and 3 mm/s for a 91 μm particle in molten steel at about 1565°C. Similarly, Stokes rising velocities of 5 and 7 mm/s correspond to particles of 117- and 139-μm diameter, respectively. Inclusions with diameters ranging between 50 and 150 μm are typical for molten steel.[6]

From Figure 9, it is seen that there is no difference in the residual ratios for particles of different sizes during the initial period of about 5 minutes following the loading of the melt with inclusions. Beyond this time, the curves separate, with each curve attaining a steady-state value. The steady-state residual ratio is significantly greater for smaller particles, since smaller particles are more easily entrained by molten steel flowing to the exit in view of their low rising velocities. It is also interesting to note from Figure 9 that the smaller particles take longer to reach their steady-state residual ratio than one might have anticipated. From the input data, the nominal mean residence time of this work is 8 minutes and transient effects can last up to three nominal residence times following a change in inclusion concentration levels.

Figure 10 provides a plot of the residual ratio of inclusion particles *vs* their Stokes rising velocity, following their initial introduction as a steady concentration source into each of the tundishes. Four curves are plotted, two for the type I and III tundishes and another two for the type II tundish. These computations refer to the behavior of inclusions with no flow modifiers.

From Figure 10, one can note a slight difference in the residual ratios for small inclusions according to the shape of tundishes. As seen, the adjacent ported trough-type tundish gave the best results on account of enhanced

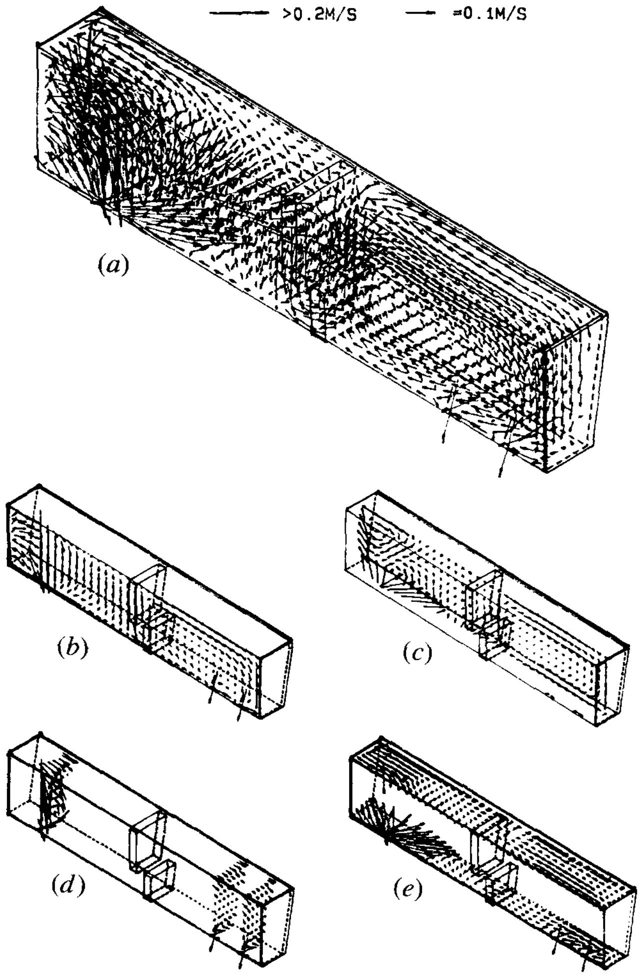


Fig. 7—Perspective view of the 3-D flow patterns in adjacent ported trough-type tundish (*a*) with flow modification, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view, and (*e*) horizontal free surface and bottom plane view.

recirculation toward the top surface, thereby giving more chance for the inclusions to float out.

Figure 11 shows four curves corresponding to three different shapes of tundish with flow modifiers. As seen, this is in total contrast with Figure 10. The presence of a dam and weir had a significant effect on residual ratios, the float-out of larger particles being considerably enhanced. These computations confirm the value of flow modifiers. Of the three tundish designs, the conventional trough-type tundish gave the best improvement in residual ratios over those with no flow modifiers. While it is generally agreed that the use of flow modifiers is required for the improvement of steel quality, their precise placement and arrangement are difficult to assess on the basis of plant investigations alone. The present model was therefore used to assess various design strategies for the enhanced removal of inclusions.

B. *Design Variables for the Conventional Trough-type Tundish (Type I)*

Various design modifications were studied, including steel throughput, inclination of sidewalls, and their dam/weir arrangements.

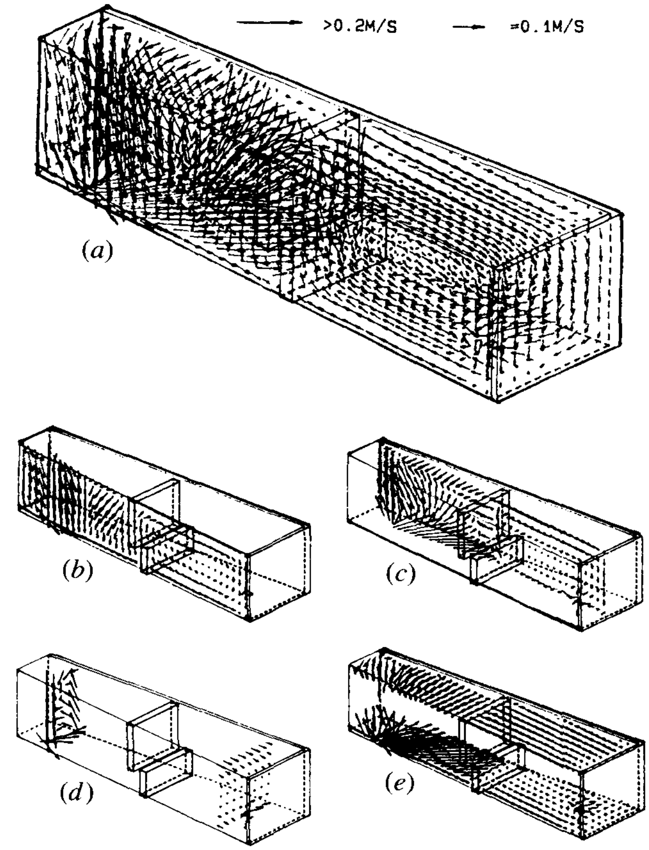


Fig. 8—Perspective view of the 3-D flow patterns in adjacent ported wedge-shaped tundish (*a*) with flow modifiers, (*b*) longitudinal view in central inlet plane, (*c*) longitudinal intermediate plane view, (*d*) inlet and outlet transverse plane view, and (*e*) horizontal free surface and bottom plane view.

1. *Steel throughputs—casting rates*

As would be expected, a slower casting rate leads to longer melt residence times within the tundish whether there are flow modification devices or not. As seen from Figure 12(a), which is in the absence of flow modifiers,

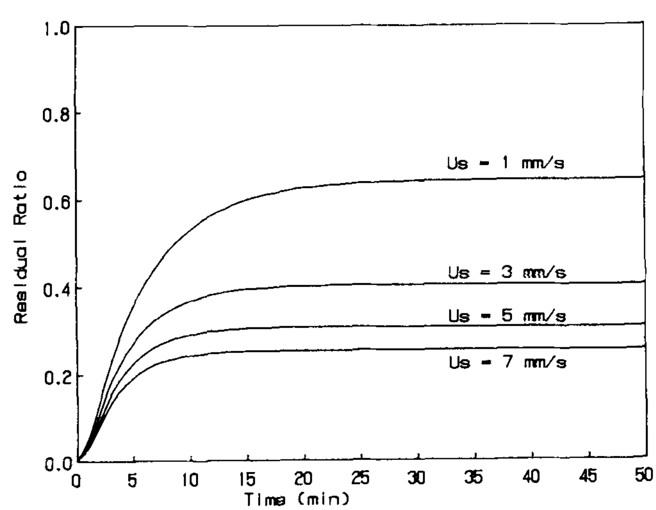


Fig. 9—Residual ratios against time in conventional trough-type tundish without flow modifiers.

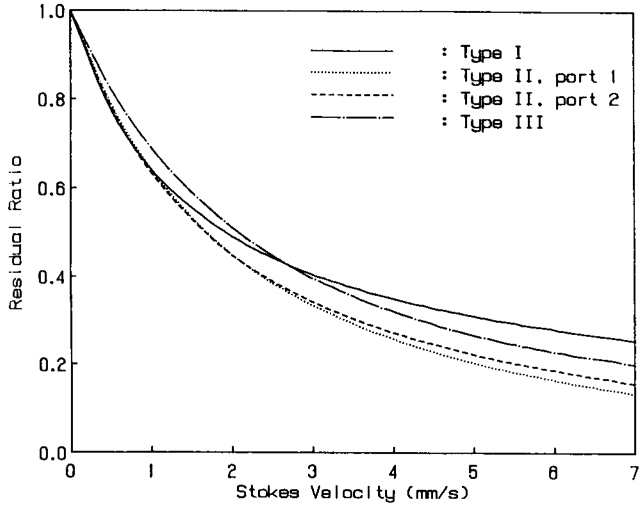


Fig. 10—Residual ratios against Stokes velocities for three designs of tundish without flow modifiers.

the greater opportunity afforded inclusions to float out resulted in lower residual ratios for all sized studied. When flow modifiers are in place (in the case of SWSD in Table V), it can be seen from Figure 12(b) that those can reduce this sensitivity to melt velocity appreciably.

2. *Inclination of sidewalls*

Figure 13 demonstrates quantitatively the beneficial effects of inclined sidewalls for removing inclusions. Curves corresponding to four different slopes of tundish sidewalls show that the best results are induced by using less steeply inclined sidewalls. These improvements were obtained at the expense of increased heat losses, the average metal temperature in the tundish being 1564°C with the 30 deg slope of sidewall, or some 2°C lower than that of a standard 10 deg sloping sidewall. This can be deduced from Figure 14 which presents isotherms along the central vertical plane of tundishes with slopes of (a) 10 deg and (b) 30 deg. The tundish with a

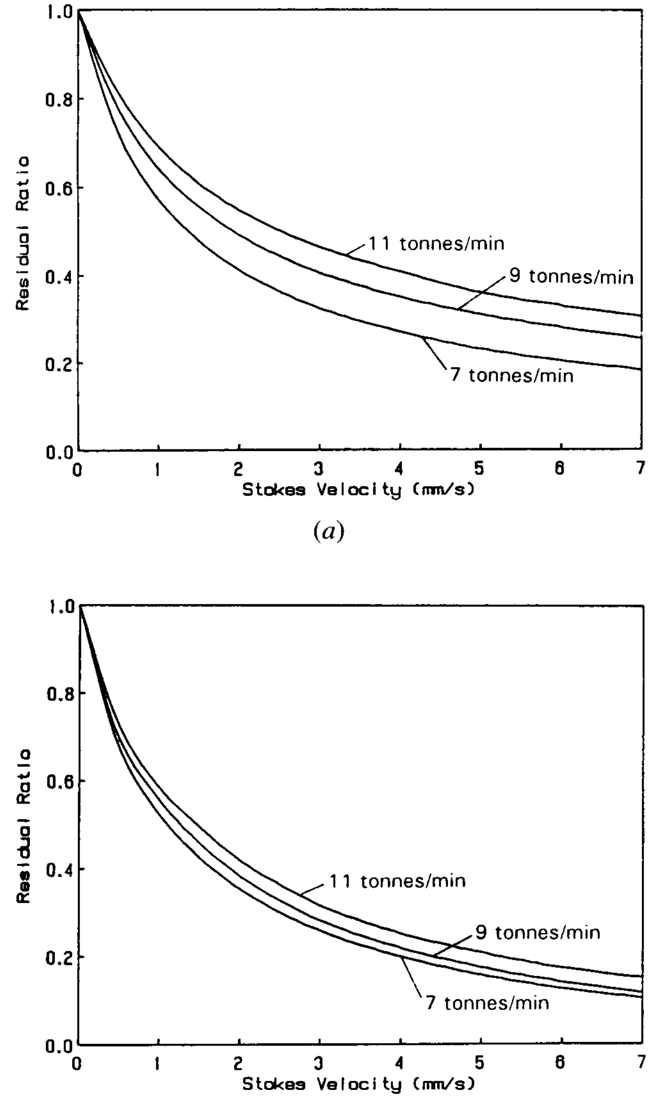


Fig. 12—Residual ratios against Stokes velocities for three steel throughputs in conventional trough-type tundish. (*a*) 7, 9, and 11 tonne/min in the absence of flow modifiers; (*b*) 7, 9, and 11 tonne/min in the presence of flow modifiers.

30 deg sloping sidewall exhibited lower surface temperatures as well as less uniform transverse temperatures. These higher heat losses are incurred as a natural consequence of the higher surface area/volume ratios of strongly sloping tundishes. However, when flow modifiers are in place, the effect of sidewall slope becomes much less marked.

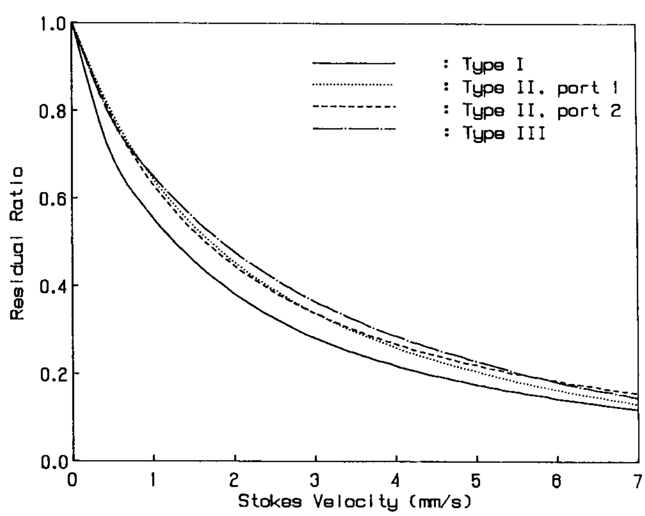


Fig. 11—Residual ratios against Stokes velocities for three designs of tundish with flow modifiers.

3. *Combinations of weirs and dams*

In Figure 15, residual ratios for different combinations of weirs and dams are shown. It is clear that residual ratios can be enhanced by employing flow modifiers. However, for a single weir (SW) or single dam (SD), residual ratios are only enhanced for a dam. A single weir did not aid inclusion float-out. As seen in Figure 16(a), the flow of melt after a dam leads to an upwardly flowing stream and recirculation. By contrast,

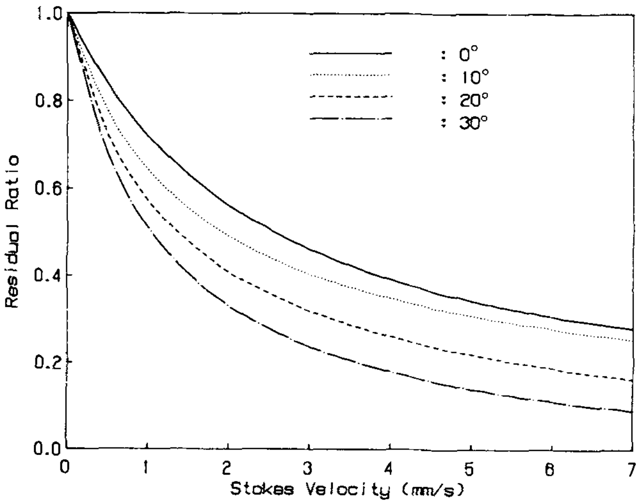


Fig. 13—Residual ratios against Stokes velocities for different slopes of sidewall in conventional trough-type tundish (NFM).

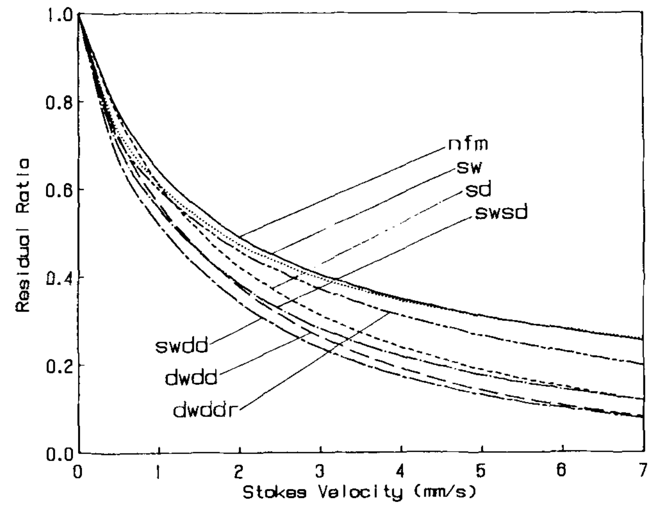
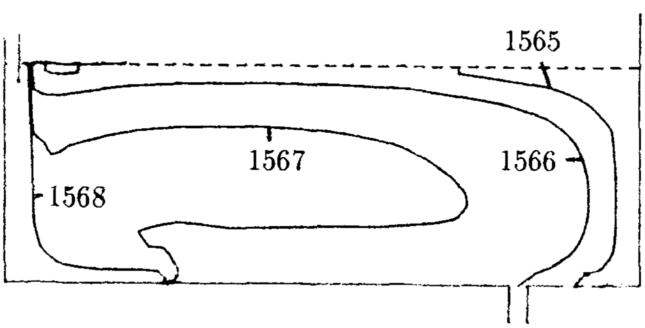


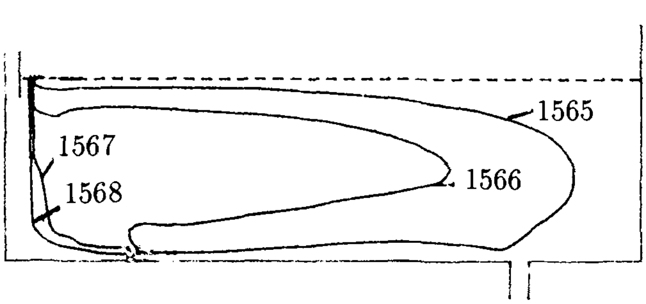
Fig. 15—Residual ratios against Stokes velocities for several combinations of weirs and dams in conventional trough-type tundish.

a weir generates a small recirculation zone of limited extent with the opportunity for the float-out of particles reduced. When a single weir and dam (SWSD) are used together, there is a marked improvement in metal quality.

Another option is to use a series of dams and weirs to optimize tundish performance. Computations were therefore run on the CRAY-1S using a second weir and dam combination. The mnemonic SWDD represents a single weir and double dam, DWDD represents a double weir and double dam, while DWDDR is for a double weir and double dam, with the second weir and dam reversed. In the SWDD, the second dam was set to half



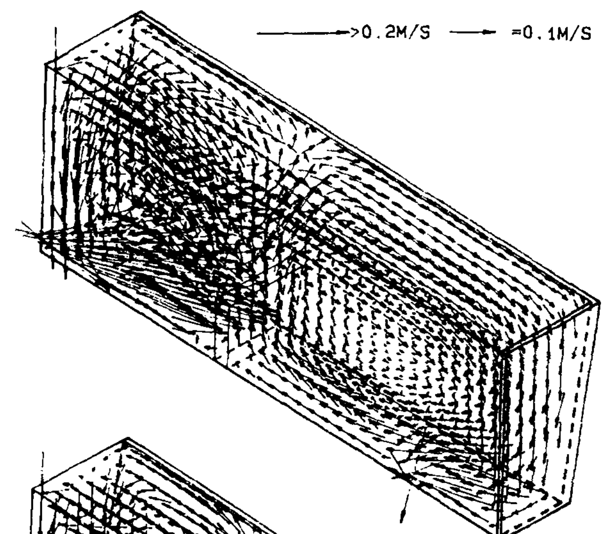
(*a*)



(*b*)

Fig. 14—Isothermal curves for different slopes of sidewall in conventional trough-type tundish (no flow modifiers): (*a*) 10 deg slope and (*b*) 30 deg slope.

(*a*)



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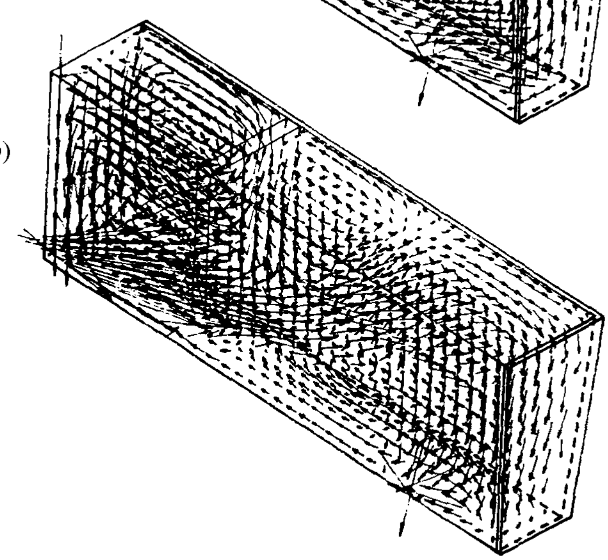

Fig. 16—Perspective view of the 3-D flow patterns in conventional trough-type tundish: (*a*) with a dam (SD) and (*b*) with a weir (SW).

the height of the first dam and placed quite far away from the first dam.

From Figure 15, it can be seen that a SWDD arrangement (SWDD) gave the lowest residual ratio (or the greatest improvement in metal quality), this being some 10 to 20 pct better than the case without flow modifiers (NFM).

4. *Spacing of weirs and dams*

Our present study suggests that the distance between a weir and dam is not particularly important, there being very little difference in residual ratios. This is apparent through study of Figure 17.

Figures 18(a) and (b) (SWDD and DWDD, respectively) show that an upflow is generated after each dam. While these should have positive effects from the point of view of inclusion separation ratios, computations show the SWDD arrangement to be even better for improved metal quality (for the set of conditions under study). A DWDDR configuration was also studied (not shown here). In that design, the placements of the second weir and dam were reversed. Separation ratios were found to be adversely affected by this procedure.

C. *Limiting Solutions—Theory and Practice*

Given the variability in the design of tundishes from one steel plant operation to another, it is useful to analyze these tundish flows in terms of those theoretical limits that are potentially within reach. (Here, we discount the use of filters or inclusion agglomeration techniques.) Thus, in order to optimize inclusion flotation, theory dictates that a plug-flow, or linear reactor, represents the best opportunity to achieve this result.[7] Indeed, if the rising velocity of an inclusion is taken to be u_s and the full depth of liquid in the tundish is taken to be H, then provided the residence time, θ, of steel in such a tundish exceeds the quotient, H/u_s, 100 pct elimination of such inclusions is possible. If not, the residual ratio is simply given by the expression

$$R = 1 - \frac{u_s L}{vH} \qquad [2]$$

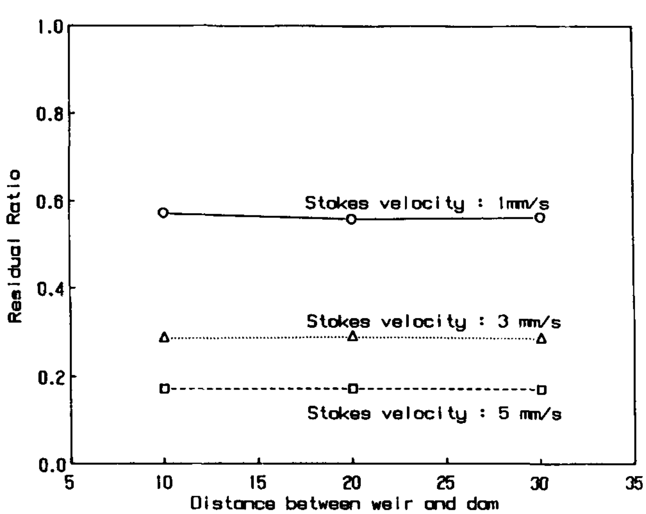

Fig. 17—Residual ratios against gaps between weir and dam for SWSD configurations in conventional trough-type tundish.

Here, L is the length of tundish and v is the uniform fluid velocity in the ideal plug flow tundish.

At the other operational extreme is the well-mixed reactor, for which the residual ratio of inclusions would be

$$R = \frac{1}{1 + u_s LW/Q} \qquad [3]$$

For a rectangular tundish, the flow rate $Q = v(WH)$, so that this expression simplifies to

$$R = \frac{1}{1 + u_s L/vH} \qquad [4]$$

Finally, one can imagine flow in a tundish that is ideally linear in the axial sense but well mixed in the vertical sense as a result of thermal natural convection

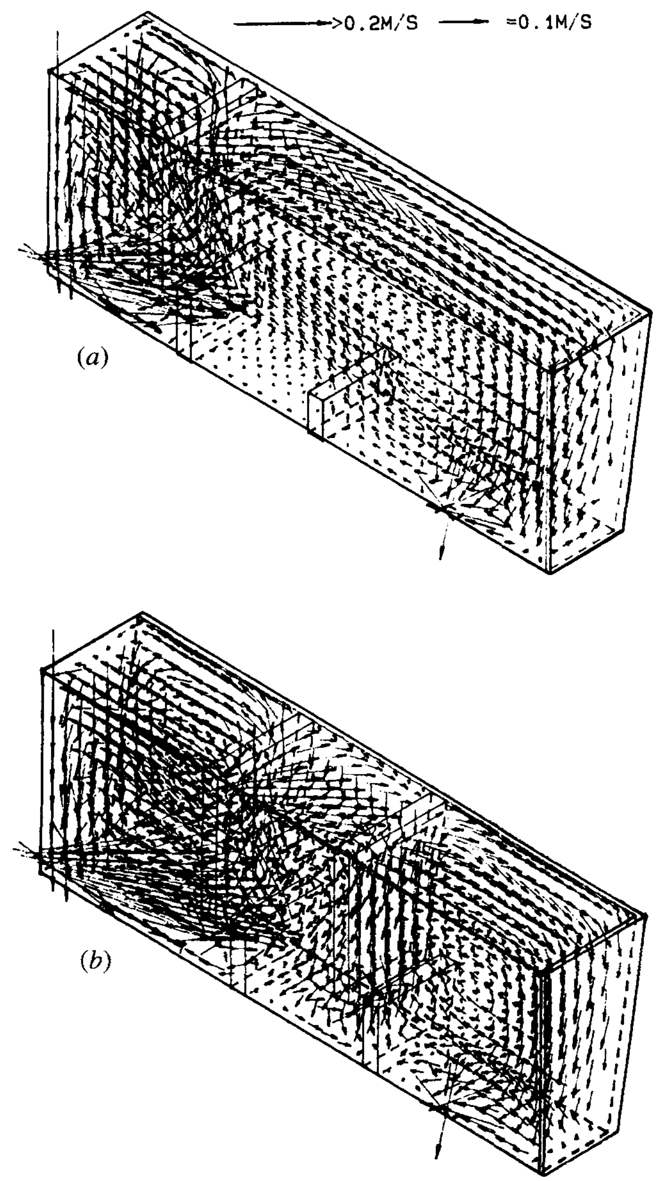

Fig. 18—Perspective view of the 3-D flow patterns in conventional trough-type tundish: (*a*) with SWDD and (*b*) with DWDD.

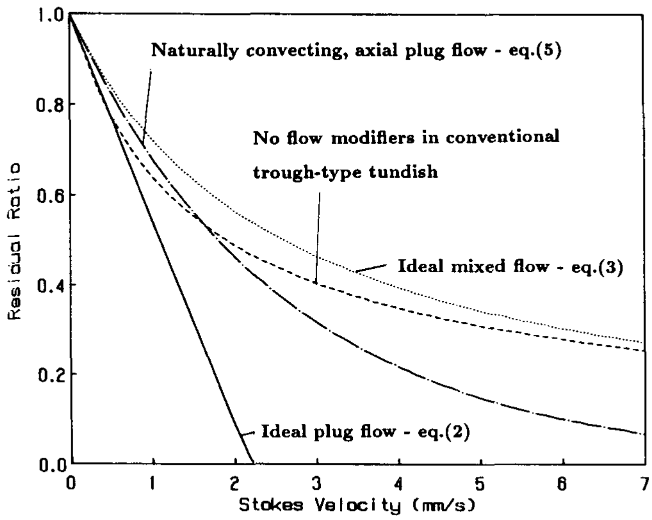

Fig. 19—Comparison of residual ratios against Stokes velocities predicted by ideal limiting solutions (ideal mixed, plug, and axial plug–vertically mixed flow) and differential model (NFM) in conventional trough-type tundish.

processes. Again, one can readily demonstrate that the appropriate expression for R would be

$$R = e^{-u_s L/vH} \quad [5]$$

Residual ratios for these three extremes of reactor vessels are presented in Figure 19, along with those computed for flows in a conventional trough-type tundish. As expected, we see from Figure 19 that the ideal plug flow reactor gives the best result for inclusion separation, followed by a plug reactor (tundish) incorporating vertical mixing. An ideal, well-mixed reactor (tundish) would yield the least satisfactory result for inclusion flotation. The computational results for the tundish arrangement without flow modifiers, plotted in this figure, are seen to most closely approximate an ideally mixed reactor, indicating the need for the types of flow modification devices considered in the present text.

As a general comment, Eq. [2] demonstrates that the lowest residual ratios can be achieved for a low velocity flow through a long shallow tundish. In the production of superalloy melts in electron beam melting furnaces, this is the configuration used. By this means, residual inclusions less than about 5-μm diameter can be assured. On the other hand, for avoiding vortexing flows and slag entrainment and for handling ladle changes and minimizing heat losses, current designs involving deep tundishes make eminent sense. Nonetheless, a greater understanding of the origin of the large alumina clusters typically found in tundishes[8] is needed, as well as their coalition and removal mechanisms, before one can claim to have a full appreciation of factors concerned in the optimal hydrodynamic design of tundishes.

IV. CONCLUSIONS

1. Three designs of tundish have been tested (computationally) to help identify an optimum design and arrangement of flow modifiers.
2. Of the three types of tundish, the conventional trough-type tundish with flow modifiers exhibited the best improvement in residual ratios.
3. In terms of sidewall slope, for a conventional trough-type tundish, inclusion separation is better but temperature uniformity worse for a 30 *vs* 10 deg slope.
4. For a conventional trough-type tundish, a double dam arrangement showed the greatest potential for enhancing metal quality.
5. While increased metal throughput can adversely affect metal quality, since there is less time for inclusions to float out, flow modifiers can appreciably reduce this sensitivity to melt velocity.
6. Transient effects can typically last up to three nominal residence times following a change in inclusion concentration levels for inclusions in the 40-μm size range.

NOMENCLATURE

d	inclusion diameter (m)
g	gravity (m/s^2)
H	tundish depth (m)
K	turbulence kinetic energy in unit mass (m^2/s^2)
L	tundish length (m)
Q	flow rate (m^3/s)
R	residual ratio (−)
S_ϕ	source term ϕ
u_s	stokes velocity (m/s)
u	x-direction velocity component (m/s)
v	y-direction velocity component (m/s)
w	z-direction velocity component (m/s)
W	tundish width (m)
ρ	inclusion density (kg/m^3)
ρ_s	density of molten steel (kg/m^3)
ϕ	dependent variable
μ	viscosity of molten steel (kg/m/s)
Γ_ϕ	exchange coefficient ϕ
ε	energy dissipation rate per unit mass (m^2/s^3)
θ	residence time (s)

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