Numerical Calculation of Fluid Flow in a Continuous Casting Tundish

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The deposition of deoxidation and reoxidation products in continuous casting tundish nozzles results in poor surface quality of the cast product and in extreme cases, disruption of the operating schedule. Since the flow of steel in the tundish is central to the behavior of nonmetallic inclusions in the tundish, the details of the flow field are determined numerically by appropriate solutions of the equations of change. The effects of the changes of the internal configuration of the tundish and various casting parameters on the computed velocity fields, particle trajectories, and particle residence times are investigated. The conclusions drawn from the computed results are compared with the results of various independent water model studies.

I. INTRODUCTION

IN the past several decades, continuous casting of steels has emerged as a widely used technology in modern steel plants. Since the improved yield and operating cost benefits of the continuous casting process are now well recognized, the process will play an increasingly important role in the production schedule of most steelmaking companies in the foreseeable future. A schematic diagram of the continuous casting tundish is shown in Figure 1. An important operating problem in continuous casting is the deposition of nonmetallic materials in tundish nozzles resulting in a reduction in the metal pouring rate through the nozzles. This reduction in the metal flow rate from the tundish to the mold is a serious problem in maintaining a steady production rate and may also result in poor surface quality of the product. In extreme cases, the buildup of the oxide products continues until complete blockage of the nozzle occurs, thereby disrupting the operating schedule.

The mechanisms of nozzle blockage have been discussed by Duderstadt *et al.*[1] and also in detail by Singh.[2] Singh established that the primary reason for the nozzle blockage was the alumina deposition. Schwerdtfeger[3] found that the inclusions deposited at the nozzle orifice did not form *in situ*. The buildup of corundum in the continuous casting nozzle was investigated using a radioactive isotope by Shevchenko.[4] Ono *et al.*[5] found that the deposition was a mixture of Al_2O_3, SiO_2, Fe_2O_3, MnO, and other deoxidation products. The importance of the reoxidation of steel in the continuous casting process was emphasized by several investigators.[6-10] As a result of these studies, it is now generally accepted that the nozzle blockage is caused by the deposition of relatively fine deoxidation products and somewhat coarser reoxidation products.

Earlier efforts to alleviate this problem can be placed into several categories. Significant efforts were made in preventing the reoxidation of steel by stream protection[10-14] and also in improving designs of the tundish nozzles to minimize deposition.[1,2,12] Other efforts to alleviate this problem included modification of the deoxidation process to acquire a liquid deoxidation product,[6,27,28] injection of Al wire downstream of the tundish nozzle to reduce deposition,[15] refining of steel using ceramic filters,[16] and use of "atmosphere-controlled" tundishes.[17] Although the earlier work was useful in highlighting several aspects of this multifaceted problem, the deposition of the nonmetallic particles is still a serious problem in the industry today.

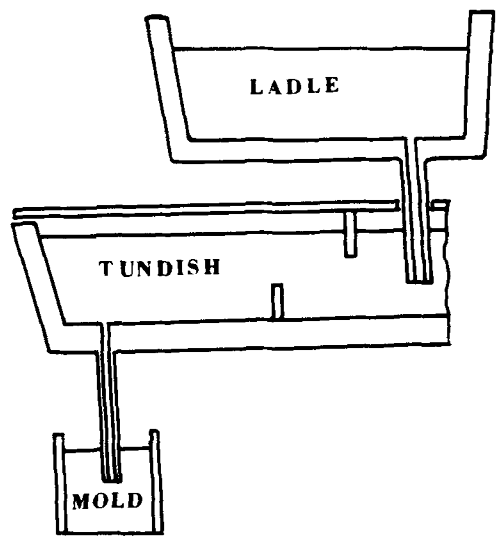

Fig. 1 — A schematic diagram of a continuous casting tundish.

The nonmetallic particles are transported through the tundish by way of the flow field in which the particles are entrained. Removal of particles is accomplished by one or both of the following mechanisms: (a) direct interaction of particles with steel/slag interface and removal into the slag or attachment to refractories and (b) by collision with other particles, growth, and removal of relatively large particles by flotation from the flowing metal stream. Since the rate processes identified with both these mechanisms are related to the fluid flow field in the tundish, the details of the fluid flow field are central to a study of the removal of nonmetallic inclusions in a continuous casting tundish. Although the literature related to the problem of nozzle blockage is a testimony of both the importance and the complexity of the problem, only a limited amount of information on the hydrodynamics of the tundish, obtained by means of water modeling, is available in the literature.[18-20,30,31]

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The effects of placement of weirs and baffles in the tundish and of the variation of casting rates and the liquid metal depth in the tundish on the velocity fields, particle residence times, and trajectories are discussed in this paper. The conclusions drawn from the computed results are compared with the results obtained from independent water model studies.

II. MATHEMATICAL MODELING

For the computation of fluid flow in the continuous casting tundish certain assumptions are made to ease the complexity of the task. First, since the velocity variation along the width of the tundish is substantially lower in comparison with the corresponding variation along the other two directions, the velocity field is represented in two directions: along the length of the tundish and the depth of the molten metal. Secondly, the flow is assumed to be isothermal, incompressible, and steady. Since the flow field is inertia dominated, the contribution of natural convection on the overall flow field is neglected. The assumption of steady state, *i.e.*, that the liquid metal holdup in the tundish does not change with time, is made for simplicity. Furthermore, the thickness of the slag layer is considered to be small, and it is assumed that the existence of a slag layer does not influence the fluid flow field in the metal phase significantly.

The equations used for flow predictions are the equation of continuity and the equation of motion in two dimensions. These equations are well documented in standard textbooks[22] and are not presented here. However, since the turbulent flow conditions must be incorporated into the governing equations by way of the effective viscosity, μ_{eff}, a means of computing μ_{eff} is indicated here. In the present computational approach, Prandtl's mixing length hypothesis is employed to compute the turbulent viscosity, μ_t. The general form of the equation can be written as[21]

$$\mu_t = \rho l^2 \left|\frac{\partial u}{\partial y}\right| \qquad [1]$$

where ρ is the density of the medium, l is the mixing length, and $|\partial u/\partial y|$ is the absolute value of the velocity gradient along a direction perpendicular to the direction of flow. The mixing length is defined as

$$l = 0.4d \qquad [2]$$

where d is the distance to the nearest wall. The effective viscosity μ_{eff} is determined as

$$\mu_{\text{eff}} = \mu_t + \mu \qquad [3]$$

where μ is the molecular viscosity of the molten steel. An outline of the calculation scheme and the testing procedure of the numerical scheme undertaken prior to its application for the current work are described in the Appendix.

III. RESULTS AND DISCUSSION

Since the internal configuration of the tundish and the operating parameters affects the flow field, flow conditions favorable for the removal of nonmetallic inclusions may be achieved by modifying the tundish geometry or by adjusting selected casting parameters within acceptable limits.

The computed velocity field in a continuous casting tundish with no restrictions to flow is presented in Figure 2. The data used for the calculations are presented in Table I. Molten steel enters from the top left-hand corner and advances downward with a large velocity. A secondary recirculation pattern is observed close to the free surface near the stream entrance. The computed flow field when a weir is installed near the inlet stream is illustrated in Figure 3. In the entry region, the fluid flow pattern is similar in nature with the fluid flow field observed previously in Figure 2. However, there are several features that may be noted. A relatively larger region of recirculation is noted near the entry region in Figure 3; the magnitude of the velocity, as the stream turns, remains high, as is expected with the smaller area available for flow due to placement of the weir.

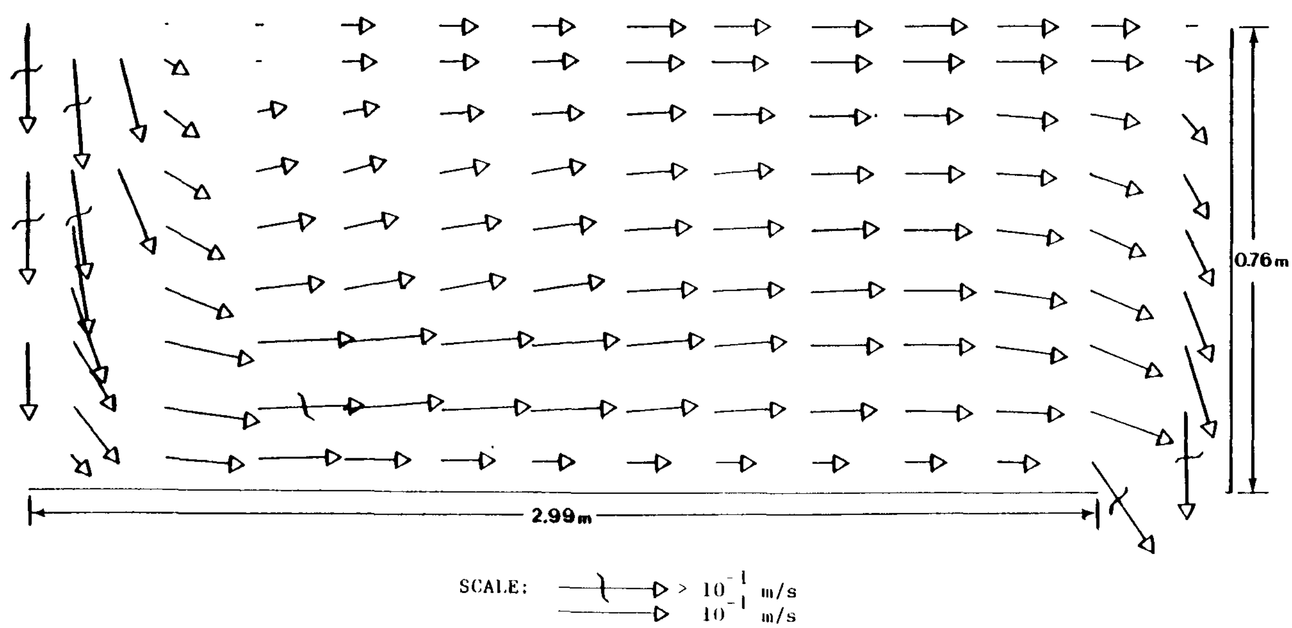

Fig. 2—Computed flow pattern in the tundish with no restrictions at the normal casting rate

Table I. **Data Used for Calculations**

Density of steel	7100 kg/m^3
Viscosity	3.0 kg/m-s
Tundish length	3.38 m
Depth of liquid metal in tundish	0.76 m
Height of dam	0.28 m
Depth of immersion of weir	0.38 m
Inlet velocity	1.54×10^{-1} ms^{-1}

The effect of placement of a dam at the bottom of the tundish is depicted in Figure 4. The flow pattern in the entry region is again similar to the other two cases. The placement of the dam in this case, however, produced significant changes elsewhere in the tundish. First, significant recirculation is observed on the backside of the dam. Secondly, the fluid is accelerated as it is forced to proceed up and above the dam. These special features of flow were also noted when velocity calculations were performed with both a weir and a dam placed in the tundish. Kemeny *et al.*[18] in their water model study with a dam and a weir configuration observed that upon exiting the pouring area under the weir, fluid is forced toward the surface of the liquid by the dam. They argued that this action promotes good contact between the slag and metal thereby enhancing the separation of nonmetallic particles.

A. *Lower Casting Rate*

While altering the internal configuration of the tundish can directly influence the intensity and direction of the flow

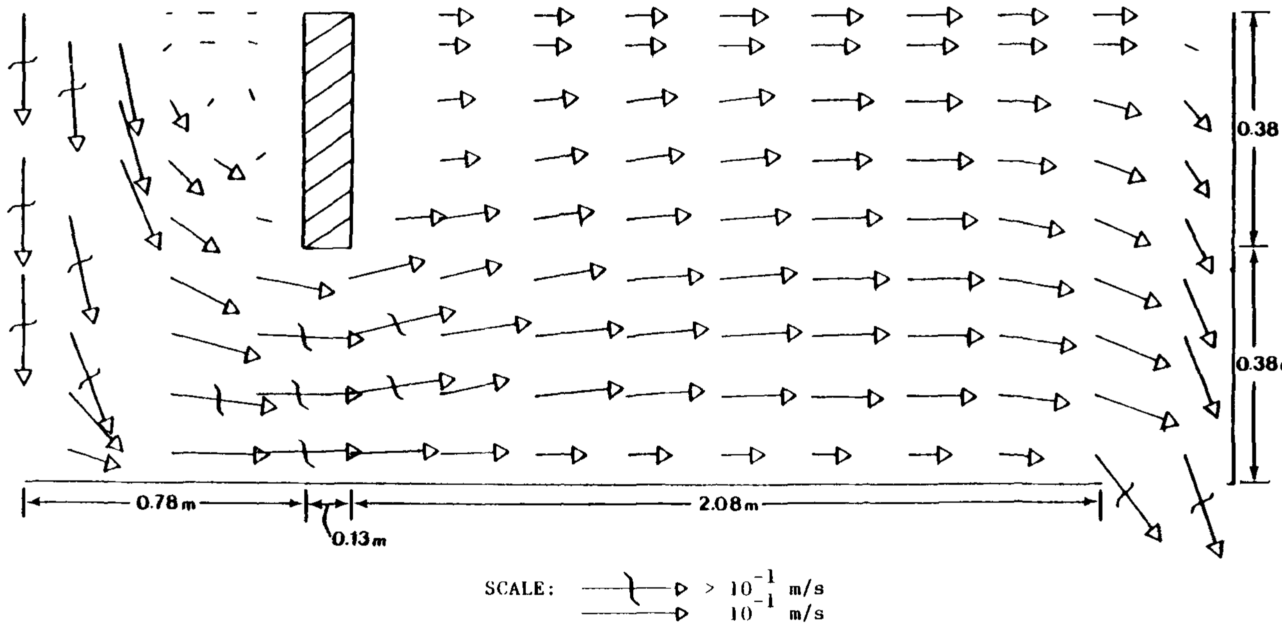

Fig. 3—Predicted flow pattern in the tundish with an upper weir

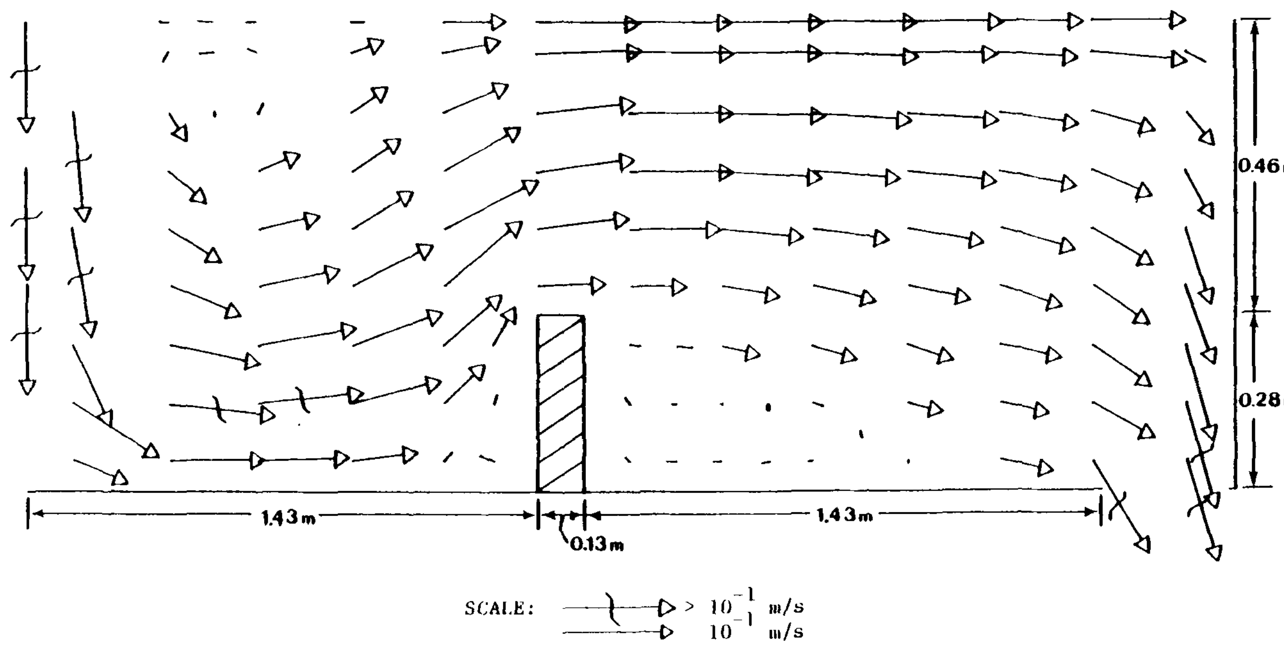

Fig. 4—Computed velocity field in the tundish with a lower dam

field, a more subtle effect may be produced with the variation of a casting parameter. The casting rate was reduced by 40 pct, and the velocities for the test cases involving the single weir, single dam, and the weir and dam combination were recalculated. An examination of the velocity fields revealed that the general nature and direction of flow did not change with the reduction of the casting rate. To illustrate this point, the computed flow field for the case with an upper weir and a reduced casting rate is presented in Figure 5. The flow patterns are almost exact with those produced by the normal casting rate. The magnitudes of the velocity vectors, however, have been reduced, as would be expected, and are represented in this diagram. It may be of interest to note that Harris and Young[20] under optimized conditions also found that the flow patterns are not sensitive to changes in flow rates. With the reduction in magnitude of the velocity field (Figure 5), a corresponding increase in particle residence time should be achieved. The magnitude of the velocity gradients will also change, ultimately affecting the collision rate of the nonmetallic particles. Before the overall contribution to inclusion removal can be determined, however, both the residence time and the mean velocity gradient must be considered. This will be accomplished in a subsequent section.

B. *Lower Liquid Level in Tundish*

A more direct effect on the flow field can be obtained by lowering the liquid metal level in the tundish. The computed flow field when the metal level was reduced by 50 pct with both the weir and the dam present in the tundish is shown in Figure 6. The relatively small cross sectional area for the net

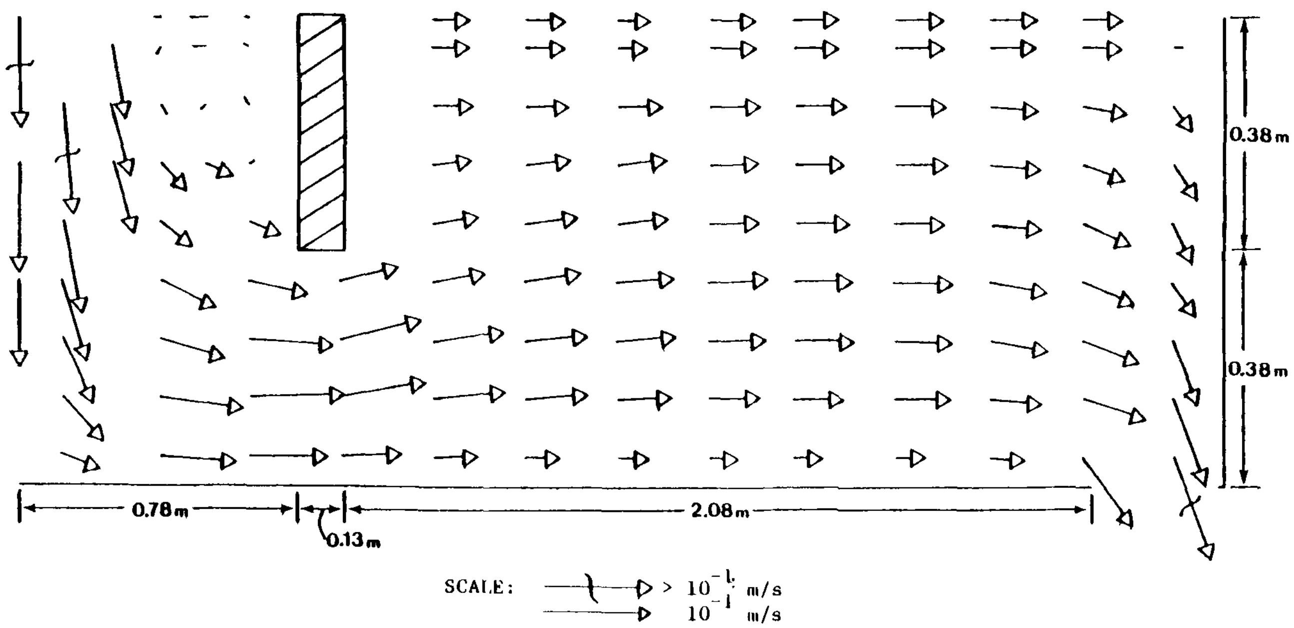

Fig. 5—Computed flow pattern in the tundish with an upper weir and at a reduced casting rate.

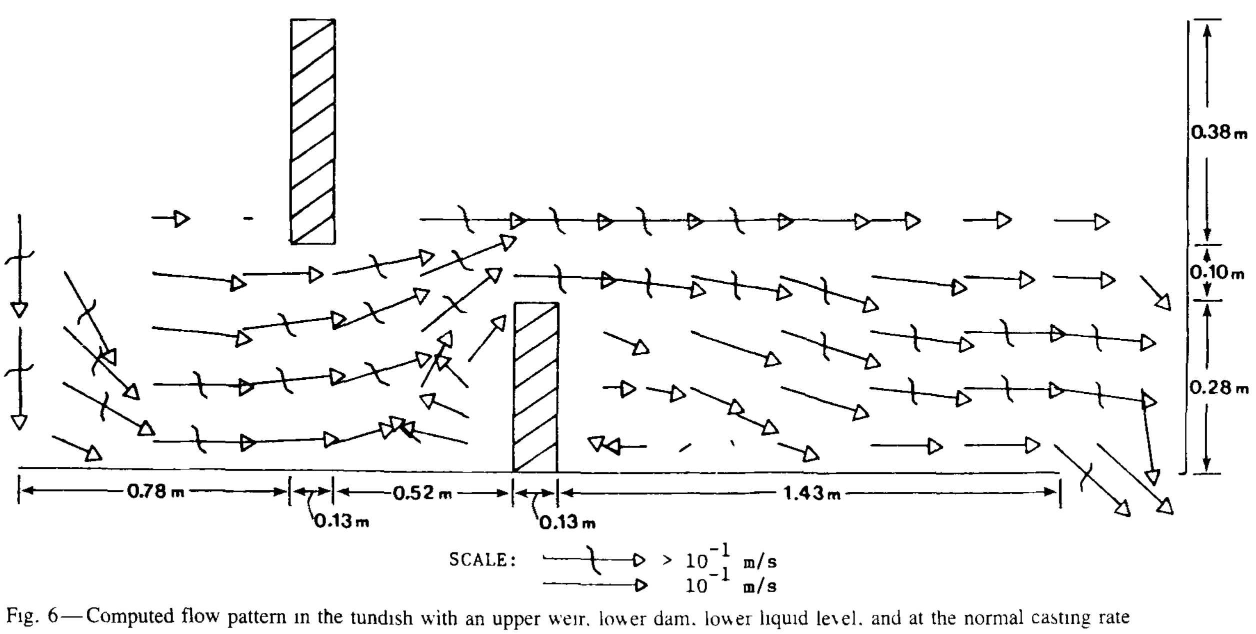

Fig. 6—Computed flow pattern in the tundish with an upper weir, lower dam, lower liquid level, and at the normal casting rate

flow in this case results in fairly large velocities in the tundish. Furthermore, as the metal is forced up and above the dam, significant acceleration of metal flow is observed. Furthermore, a strong recirculation is again observed on the backside of the dam.

C. *Particle Trajectories*

The circulation of molten steel is rather limited in certain regions of the tundish. These isolated or 'dead' regions reduce the working volume of the tundish. Calculation of particle trajectories allows estimation of the 'active' volume of the tundish. A particle tracking technique, described in the Appendix, has been used to estimate the particle trajectories. It is assumed that the degree of slip between the nonmetallic particles and the liquid steel is small compared to the velocity of steel in the tundish.

As a result of the interaction of falling stream of steel from the ladle into the tundish, the center region of the tundish is very strongly agitated. In this investigation, a large number of particles are assumed to be present in the impact region as soon as the liquid metal stream impinges from the ladle into the tundish. The paths of various particles are determined by a numerical technique described in the Appendix.

Figure 7 illustrates the effective particle working area in a tundish with no restrictions. Particle residence times for different particle trajectories are also indicated. It is observed from this diagram that a good portion of the tundish volume is used (active) for the transport of nonmetallic particles in this instance. The effect of the single weir is shown in Figure 8. The area for particle movement has been reduced significantly as the particles tend to follow the flattened profile produced by the weir, with the upper area of the tundish relatively inactive. The effective particle area is again reduced significantly in the single dam case as illustrated in Figure 9. Movement of the active area, however, is toward the tundish liquid surface with the lower area of the tundish inactive.

It is observed from Figure 10 that the weir and dam combination significantly reduces the particle working area. The upper and lower sections of the tundish are inactive with a

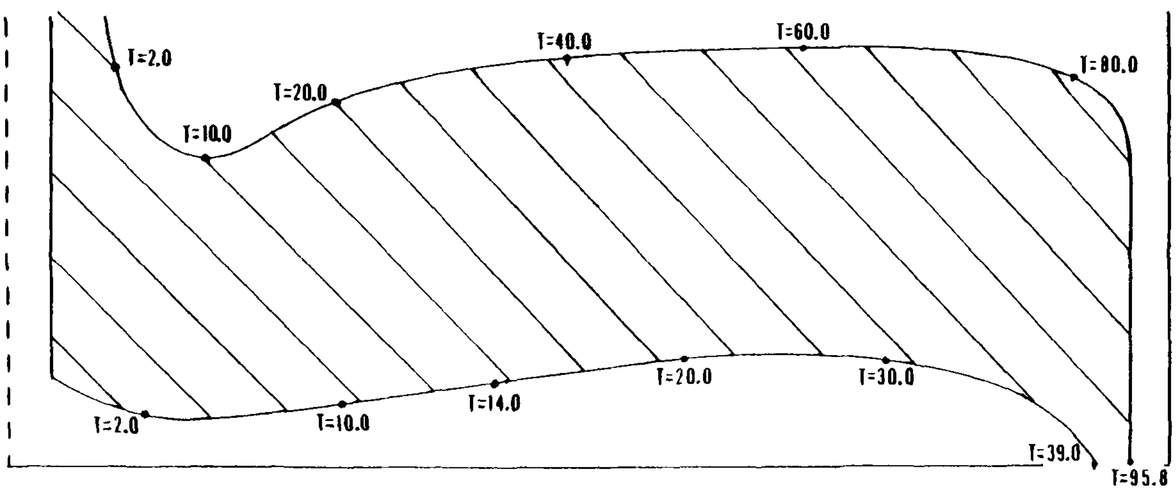

Fig. 7—Particle trajectories and residence times in the tundish with no flow restrictions.

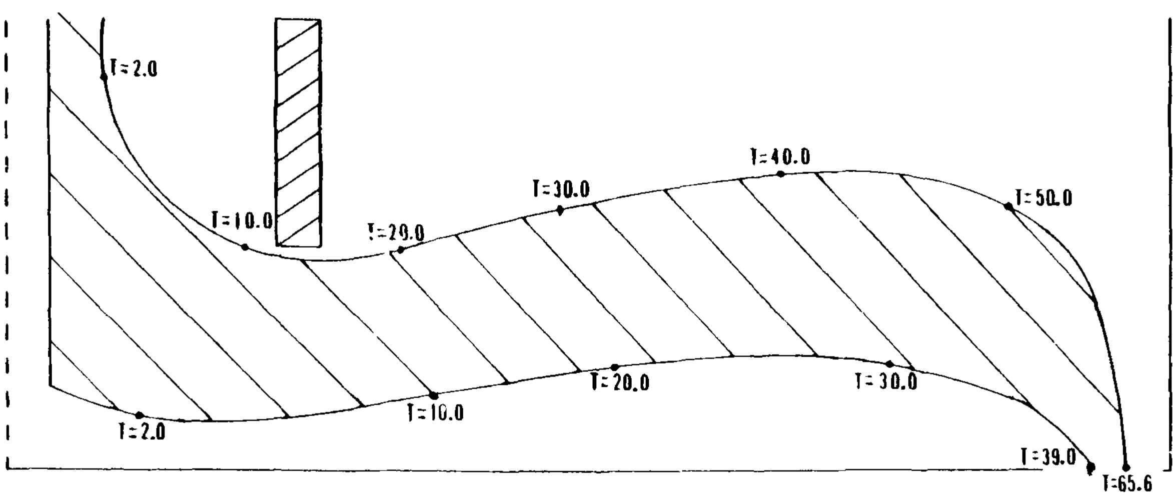

Fig. 8—Particle trajectories and residence times in the tundish with an upper weir.

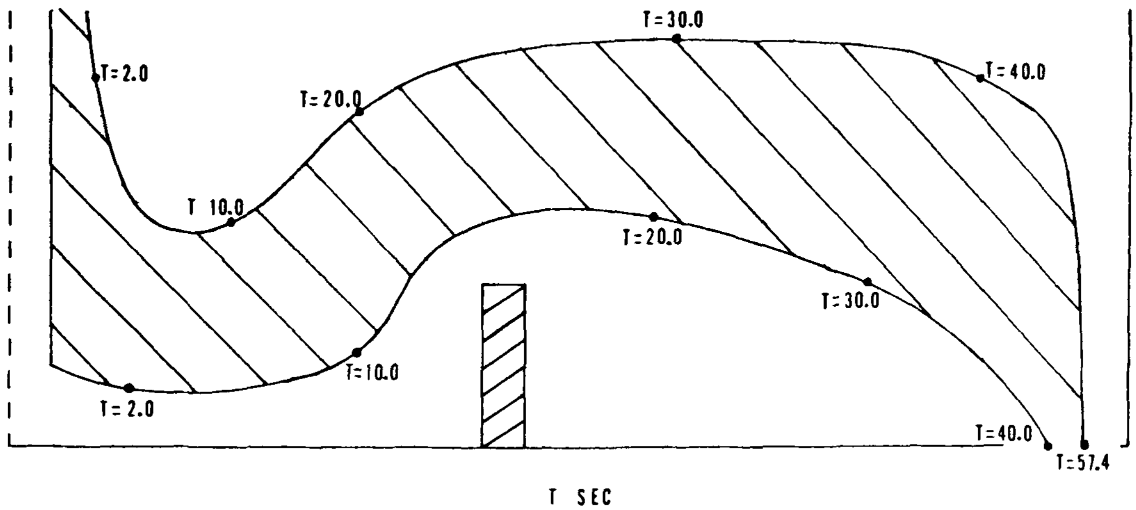

Fig. 9—Particle trajectories and residence times in the tundish with a lower dam.

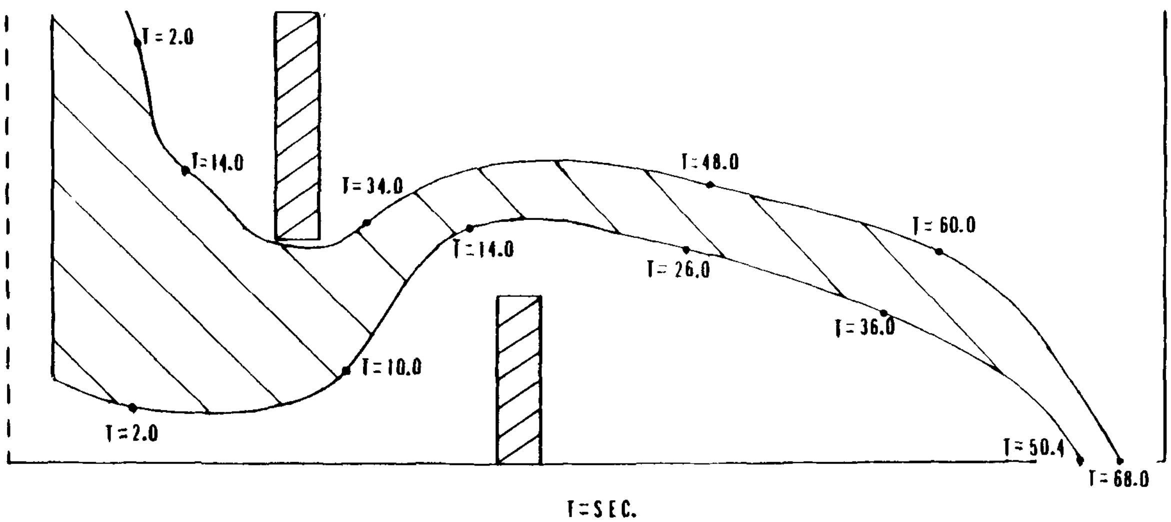

Fig 10—Particle trajectories and residence times in the tundish with an upper weir and lower dam

narrow middle section producing the active region. The active flow paths of liquid steel in the tundish, depicted in Figures 7 through 10, indicate that the liquid metal packets tend to flow in fixed paths. This observation was also made by Schmidt[23] from water model studies. Furthermore, from the dye injection studies Schmidt[23] observed that the fixed path is not the geometrically shortest path, an observation that is consistent with the particle paths presented in Figures 7 through 10. As mentioned before, because of the velocity fluctuations, particles may be transported from the active areas into the inactive areas, thus creating a bigger region than depicted in the illustrations. The results, however, are thought to be useful on a comparative basis, since actual observation in an operating system is difficult, to say the least.

D. *Residence Time*

The effect of geometry, casting rate, and tundish level on particle holding time was examined. The mean residence time has been computed and is presented in Table II. In examining the mean residence time data it may be of interest to review the computed results on particle trajectories (Figures 7 through 10) and velocities. It is observed from Figures 7 through 10 that as more restrictions are installed in the tundish, the particles have to travel longer distances

Table II. Mean Residence Time (s)

Casting Parameter	No Restriction	Upper Weir	Lower Dam	Weir and Dam
Normal casting rate	58.1	52.0	46 0	52.2
Lower tundish level	—	35.8	—	27.4
Reduced casting rate	—	71 7	60.6	63.0

in the tundish. However, as flow restrictions are introduced in the tundish, velocities are increased and the increased velocities tend to compensate the effects of longer particle trajectories. The computed mean residence time values indicate that the mean residence times are influenced by the internal configuration of the tundish. Furthermore, the differences between the minimum and maximum residence times indicated in Figures 7 through 10 clearly depend on the internal configuration of the tundish.

As the casting rate was reduced, the computed mean residence times in all cases increased, but not necessarily by the same amount. In the single weir instance, the increase was noted to be 38 pct while the single dam arrangement resulted in a 32 pct increase. The increase in residence time is expected since the field velocity values are lowered. Lowering the tundish level at the normal casting rate reduces the residence times since the velocities are much higher. This is primarily due to the reduction in available area for fluid movement.

E. *Steel Cleanliness*

The cleanliness of steel is related to the rate of collision of nonmetallic particles and the residence time of particles in the tundish. The number of collisions per unit volume per unit time between two particles of radius r_1 and r_2, $C(r_1, r_2)$ is expressed as:[24]

$$C(r_1, r_2) = W(r_1, r_2)n(r_1)n(r_2) \quad [4]$$

where $W(r_1, r_2)$ is a rate constant defined by Eq. [4] and $n(r_1)$ and $n(r_2)$ are the number of particles per unit volume of size r_1 and r_2, respectively.

$$W(r_1, r_2) = \frac{4}{3}(r_1 + r_2)^3 \text{ Grad } V \quad [5]$$

To establish a means of distinguishing the contribution of the internal configuration of the tundish and various casting parameters on the steel cleanliness, a cleanliness factor is formulated. Possible recapture of inclusions by molten steel is not considered. Since for given particle density and size in the tundish the collision rate is proportional to Grad V, the cleanliness factor, F, is expressed as the product of the residence time, T, and the integrated velocity gradient:

$$F = T\int_0^x \int_0^y |\text{Grad } V|\, \partial y\, \partial x \quad [6]$$

The cleanliness factors for various test cases are presented in Table III. The tundish arrangement that indicates the most desirable conditions for particle collision, growth, and removal is the dam and weir combination at the normal casting rate. While the residence time was increased with the reduction in casting rate, this positive feature was outweighed by the decrease in the mean velocity gradient. Likewise, as the mean velocity gradient was increased by the reduction in the tundish level, this was overshadowed by the decrease in residence time. A satisfactory result was, however, achieved with both variables, casting rate, and liquid metal level in tundish at some intermediate value and with the dam and the weir incorporated into the tundish. This conclusion compares favorably with results acquired in recent investigations by Harris and Young.[20] It was found that a dam and weir configuration resulted in a significant reduction in the percentage of slabs downgraded for aluminates. Furthermore, Schmidt[23] found that introduction of dams, weirs, and wall inserts produced significantly improved flow symmetry in a multi-strand tundish. However, he indicated the importance of cost and maintenance considerations of these modifications.

IV. CONCLUSIONS

A computational scheme has been developed to simulate turbulent flow of molten metal, trajectories of nonmetallic inclusions, and particle residence times in a continuous casting tundish. The scheme has been used in several test cases involving modification of tundish configuration and casting parameters.

The computed results indicated that the introduction of dams and weirs in the tundish changed both the trajectory of the nonmetallic particles and the active volume of the tundish. The particle residence time was influenced by the introduction of flow restrictions in the tundish. The internal configuration of the tundish significantly affected the spread of particle residence times in the tundish. Placement of dams and weirs in the tundish resulted in increased gradient of mean velocities and thus improved the probability of collision of nonmetallic particles. A reduction in level of liquid metal in the tundish increased the magnitude of the mean velocity gradient but did not actually improve the probability of achieving cleaner cast product (cleanliness factor) since the particle residence time was significantly reduced. Of the various tundish configurations studied, the dam and weir combination provided the optimum computed cleanliness factor.

APPENDIX

Outline of numerical scheme

A. *Calculation of Velocity Fields*

The finite difference equations derived from the equations of continuity and the two equations of motion in x and y directions were solved by a line-by-line solution scheme.[25] A fairly extensive documentation of the calculation scheme and a computer program are available in the thesis[26] on which this paper is based. The salient features of the scheme are presented below.

Table III. Cleanliness Factor, F (m^2)

Casting Parameter	No Restriction	Upper Weir	Lower Dam	Weir and Dam
Normal casting rate	14.1	14.7	16.0	19.8
Lower tundish level	—	10.6	—	12.5
Reduced casting rate	—	15.1	15.8	16.9

(a) Uniformly spaced, fixed rectangular grids (15×10) are used.
(b) The calculations are started with an assumed (guessed) velocity and pressure distributions.
(c) A line is selected and the momentum equations are solved for all finite difference cells on this line by means of a tri-diagonal matrix algorithm.
(d) Since the pressure values are not known, the calculated velocities do not usually satisfy the equation of continuity. A pressure correction equation is developed from the continuity and linearized momentum equations.
(e) The pressure correction equation is then solved for corrections to the pressure field.
(f) The velocities are corrected accordingly.
(g) Appropriate boundary conditions at the line ends are applied.
(h) A new line is selected and steps (b) through (g) are repeated. The procedure is continued until the end of the flow domain is reached. This completes one interaction cycle.

The convergence of the numerical scheme is checked by examining the magnitude of the mass and the momentum imbalance normalized with respect to the input mass and momentum values, respectively.

The boundary conditions for the calculations include prescriptions of no-slip boundary conditions on all solid surfaces including the locations where dams and weirs are placed. At the free surface, no shear or mass is transferred across the interface. In the entry and the exit regions the vertical velocity values are prescribed on the basis of the casting rate; horizontal velocities are assumed to be negligible.

B. *Testing of the Numerical Scheme*

Prior to the application of the numerical scheme for the calculations reported in this paper, the scheme was examined for accuracy. The computer program was used to simulate simple laminar flow in a pipe for which an analytical solution of the governing equations is available. Excellent agreement was achieved between the numerical predictions and the analytical results.

C. *Particle Residence Time and Trajectory*

For the calculation of particle residence time and trajectory it is assumed that the small nonmetallic particles move with the molten steel. An outline of the procedure is presented below.

1. At time $t = 0$, the location of the particles are known (x, y). The new particle position after a very small time increment t is given by:

$$x\big|_{t=\Delta t} = x\big|_{t=0} + \Delta t u\big|_{x,y} \qquad [A.1]$$

$$y\big|_{t=\Delta t} = y\big|_{t=0} + \Delta t v\big|_{x,y} \qquad [A.2]$$

where u and v are the velocities in the x and y directions, respectively.
2. The procedure was repeated during the entire period of the particle's stay in the tundish.

The residence time of an individual particle was computed by summing all the small time increments required for the particle to transit the tundish. The mean residence time is determined by adding all the residence times for various particles and dividing the sum by the total number of particles.

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