

Beckermann, C., "Water Modeling of Steel Flow, Air Entrainment and Filtration," in Proceedings of the 46th SFSA Technical and Operating Conference, Paper No. 3.6, Steel Founders' Society of America, Chicago, IL, 1992.

Water Modeling of Steel Flow, Air Entrainment and Filtration

**Christoph Beckermann
Associate Professor
Department of Mechanical Engineering
The University of Iowa
Iowa City, Iowa 52242**

September 1992

Abstract

This paper presents an analysis of water modeling of steel pouring to study (1) air entrainment and (2) filter effectiveness to remove reoxidation inclusions. In the first part, a review is presented of the physical processes and parameters important in air entrainment in free-surface flows. Then, the use of a water system to model air entrainment in steel pouring is analyzed. Attention is focused on an one-to-one, full-scale model of the casting system. It is shown that the similarity requirements reduce to proper matching of the so-called Z parameter which contains only liquid properties. Large uncertainties in the value of Z for the steel system and a lack of knowledge of the dependence of the air entrainment rate on Z suggest small-scale experiments using metals. Nonetheless, if the Z parameter can be matched, the air entrainment rate in the model will be the same as during pouring of liquid steel. Additional similarity requirements regarding air transport, oxidization and detrainment are also discussed. There is little hope in water modeling of the oxidizing reactions in the steel system.

The second part analyzes the usefulness of water modeling to simulate the removal of reoxidation inclusions from the molten steel using a ceramic filter. It is found that the flows of the liquid steel and the inclusions through the casting system and the filter can be well simulated by using an one-to-one, full-scale water model, the same filter, and simulated inclusions of the same size and shape as the reoxidation products. Due to the purely mechanical nature of the entrapment process for particles larger than 100 μm , it can then be expected that the filtration efficiency in the steel system and water model is the same. In addition, the similarities in the flows permit the use of a water model to study the inclusion transport and the effect of the filter on laminarizing the flow. Limitations and uncertainties in water modeling of steel filtration are also discussed.

I. AIR ENTRAINMENT

1. Introduction to Air Entrainment

The design of pouring techniques in steel casting must take into account the entrainment of air at the liquid steel surface. Air entrainment during pouring leads to reoxidation of the steel and, ultimately, inclusions in the casting. This section describes the major physical mechanisms important in air entrainment, while the basic parameters are introduced in Section 2. Water modeling of air entrainment in steel pouring is analyzed in Section 3, and the use of other modeling fluids and geometrically scaled systems is discussed in Sections 4 and 5, respectively.

Figure 1 illustrates opportunities for air entrainment during pouring. The supply of air may be

- unlimited (from the atmosphere) as for the stream between the ladle and the mold; or
- limited as in the runners and mold cavity, which is connected to the atmosphere by the risers.

There are many flow configurations which cause air entrainment. Generally, entrainment can take place all along the free surface (surface aeration) or locally at a surface discontinuity (local aeration) [1]. Surface aeration may be present along the high-speed metal stream from the ladle. The flow turbulence and shear forces of the surrounding air give rise to surface disturbances which lead to air entrainment. These disturbances grow and cause air entrainment along the jet surface and, in many cases, a complete disintegration of the jet. The major entraining mechanisms are overturning surface waves and fluid droplets being projected above the surface and then falling back. In penetrating the fluid surface, the droplets drag air into the fluid. Also the mechanism of air entrapment in vortices as described below contributes to entrainment.

Flow configurations leading to local air entrainment are always connected with some sort of surface discontinuity. These include plunging-jet type configurations, such as those encountered in the pour basin and sprue and as the metal enters the mold cavity. Plunging jets are characterized by the fact that air entrainment takes place locally at the intersection of the free jet with the metal surface. The momentum of the jet causes air to be entrained in the highly turbulent shear layer induced by the jet surface. Entrainment takes place mainly in relatively distinct vortices with longitudinal axes nominally perpendicular to the flow direction. This type of entrainment may be enhanced by the development of turbulence on the jet surface prior to impingement. Other local aeration configurations include so-called surface-rollers in nearly horizontal flows, such as jets impinging on rigid walls, zones of flow separation in the wake of bluff bodies or at abrupt expansions of the cross section as may be found in the runners and casting cavity, as well as transitions from free surface to conduit flow (sprue).

The process of air entrainment is subject to several limiting conditions: an inception limit, entrainment limit, air supply limit and transport limit. Each one of these may be the controlling factor [1]:

(i) Inception limit

For a given flow configuration, the flow conditions must be such as to generate a sufficiently large disturbance for air entrainment to occur. The inception limit depends strongly on the fluid properties and characterizes the condition that inertial reactions become large enough to overcome the resisting forces due to viscosity and surface tension. In general, a certain minimum velocity has to be exceeded, and the initiation of air entrainment is greatly enhanced by turbulent fluctuations of the approach flow.

(ii) Entrainment limit

The conditions of the approach flow govern the entrainment limit and are quantified by the Froude number (see below). A critical Froude number must be exceeded for air entrainment to occur. For higher Froude numbers, the approach flow provides the driving mechanism for air entrainment.

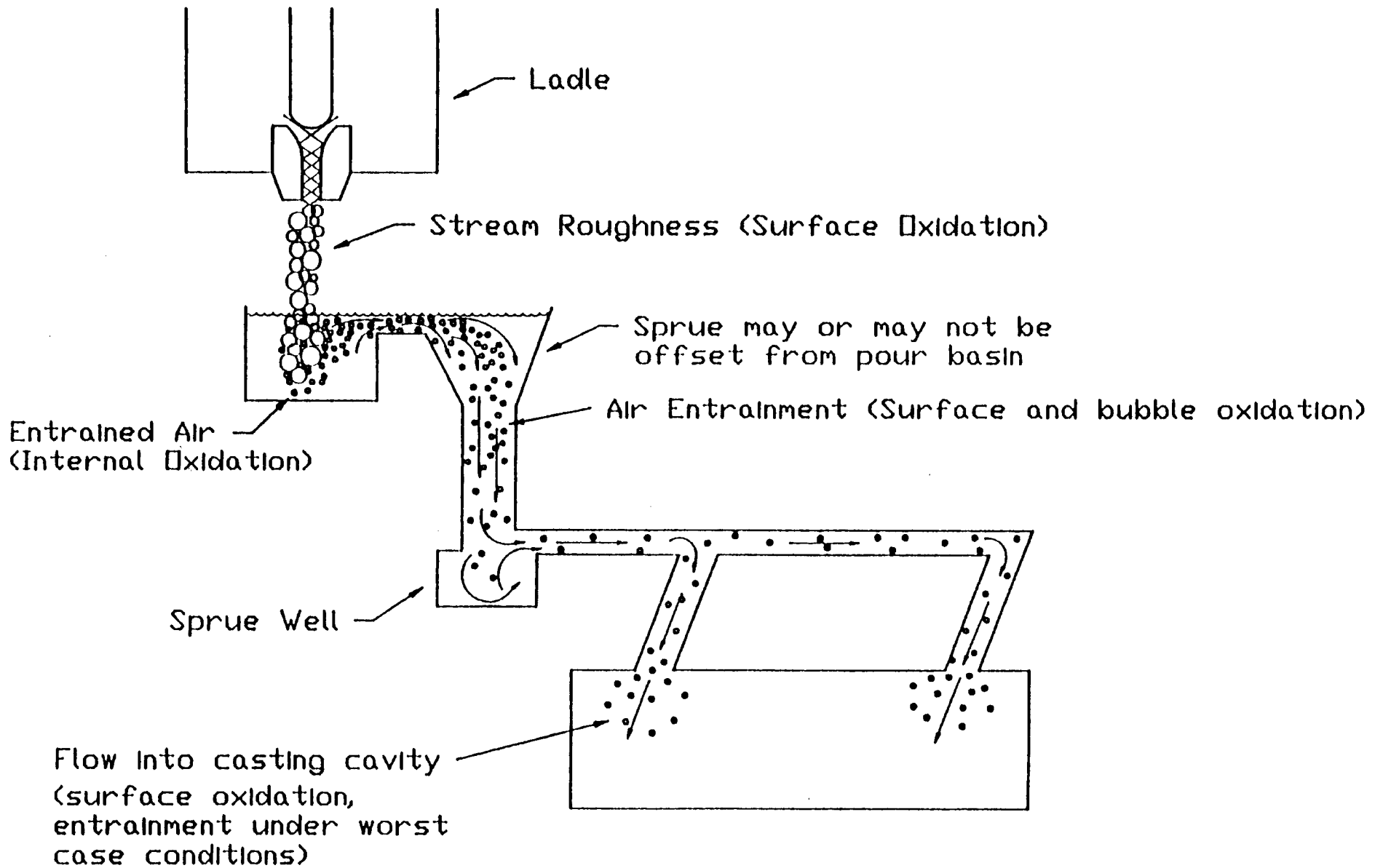


Fig. 1 Schematic Mold Illustrating Opportunities for Metal Oxidation During Pouring (from ref. [2]).

(iii) Air supply limit

In configurations such as the mold cavity, air is entrained from a limited enclosed air space, which is connected to the atmosphere by a duct (riser). In these cases, the supply of air to the point of entrainment into the metal requires an airflow through the system. This flow creates a pressure drop, which can limit the air supply rate and, hence, the air entrainment.

(iv) Transport limit

The transport capacity of the flow is governed by the downstream flow conditions (i.e., flow velocity and turbulence). All of the air which is entrained may not be transported by the flow and contribute to reoxidation of the metal, but may escape through the metal surface (detrainment). The transport capacity of the metal depends primarily upon the ratio between metal velocity and air bubble rise velocity. In relatively stagnant metal bodies, the transport capacity vanishes and the air bubbles will quickly rise to the surface and escape. In this case, the transfer of the entrained oxygen to the metal surface may not be complete and reoxidation will be less. Generally, the transport capacity increases with increasing velocity and turbulence intensity of the metal flow. For the high metal velocities encountered in typical steel pouring processes, the transport capacity and the oxidation rate may be sufficiently large for all of the oxygen in the entrained air to be transported to the metal surface and consumed in the oxidizing reactions. Air transport/escape and oxygen transfer/reaction are issues that need to be addressed in addition to the entrainment process. This is of importance in water modeling of steel pouring and is discussed in more detail in Section 3.

2. Analysis of Air Entrainment

2.1 Parameters Governing Air Entrainment

The dependent variable for air entrainment is the specific rate of entrained air, q_{ae} , per unit width of the flow surface. It can be described in terms of independent variables representing

- boundary geometry: reference fluid length l , geometric lengths
- fluid approach flow: reference velocity v , turbulence (Tu)
- air supply system: pressure difference ΔP
- fluid (metal) properties: density ρ , dynamic viscosity μ , surface tension σ , gravitational acceleration g .

The properties of air can usually be neglected. For example, the specific rate of entrained air can now be written as

$$q_{ae} = f(\text{geometry}; l; v; (Tu); \Delta P; \rho; \mu; \sigma; g) \quad (2.1)$$

A classical dimensional analysis leads to [3]

$$\frac{q_{ae}}{v l} = f\left(\text{geom. ratios}; (Tu); \frac{\Delta P}{\rho v^2/2}; \frac{v}{\sqrt{g l}}; \frac{v l}{\mu/\rho}; \frac{v}{\sqrt{\sigma/\rho l}}\right) \quad (2.2)$$

or

$$\beta_e = \frac{q_{ae}}{q} = f(\text{geom. ratios}; (Tu); Eu; Fr; Re; We) \quad (2.3)$$

where Eu is an Euler number, Fr is the Froude number, Re is the Reynolds number, and We is the Weber number. The latter quantity can be replaced by the parameter Z as

$$\beta_e = f(\text{geom. ratios}; (Tu); Eu; Fr; Re; Z) \quad (2.4)$$

where

$$Z = \frac{g \mu^4}{\rho \sigma^3} \quad (2.5)$$

The liquid parameter Z has the obvious advantage over the Weber number that it is a function of fluid properties alone and thus independent of the fluid velocity and length scale. For a given fluid it will remain constant, and all scale effects are concentrated in the Froude and Reynolds numbers.

2.2 Inception Limit

Air entrainment will commence when inertial and gravity forces override the resisting forces due to viscosity and surface tension. In the case where the environment is at atmospheric pressure ($\Delta P = 0$, unlimited air supply), the critical velocity v_c for onset of air entrainment will depend, for given approach flow conditions, on the fluid properties only:

$$f(v_c; \rho; \mu; \sigma; g) = 0 \quad (2.6)$$

These can be grouped in two dimensionless parameters

$$\frac{v_c^3}{g \mu / \rho} = f(Z) \quad (2.7)$$

Equation (2.7) indicates that the dimensionless critical velocity will depend on the liquid parameter Z , and the critical velocity is approximately constant for a given fluid. Experimental evidence for plunging water jets indicates that $v_c = 0.8$ to 1 m/s. No data are available for other fluids (such as steel), and the dependence of the critical velocity on Z has not been investigated.

If the approach flow is turbulent, two additional parameters must be introduced to characterize the intensity and the scale of the turbulent fluctuations. If v_t denotes the RMS of the velocity fluctuations and l_t is a turbulence length scale (of the eddies), then one arrives by dimensional analysis at

$$\frac{v_c}{g \mu / \rho} = f\left(\frac{v_t}{\mu^3 g / \sigma^2 \rho}; \frac{l_t}{\sigma^2 / \mu^2 g}; Z\right) \quad (2.8)$$

The experimental results for plunging water jets obtained by Ervine [4] indicate that v_c depends strongly on v_t , whereas the scale l_t of the large eddies is insignificant. However, for large turbulence intensities, as may be encountered in steel pouring, v_c is almost constant (independent of v_t too) for a given fluid. Hence, the value of 0.8 to 1.0 m/s for the critical velocity should apply to any plunging water jet, as long as the jet is still coherent at the point of impingement. This value also applies to other local aeration configurations where air entrainment is caused by vortices perpendicular to the flow direction. Again, no results are available for steel.

Finally, for surface aeration in high-speed flows, such as along the surface of the metal jet emanating from the ladle, equations (2.7) or (2.8) still hold, but the value of v_c must be expected to be much larger than the ones given above. Some information for water flows can be found in Ervine [4].

Generally, the critical velocity for the inception of air entrainment can be expected to be exceeded by the flows encountered in steel pouring. However, consideration of the inception limit provides information about the conditions that need to be met in order to eliminate air entrainment.

2.3 Entrainment Limit and Quantity of Air Entrained

Here, we consider limiting cases of the general relation for the quantity of air entrained given by equation (2.4). For a given approach flow, entrainment from the atmosphere ($E_u = 0$), a given fluid ($Z = \text{const.}$), and in the limit of fully turbulent flow ($Re \rightarrow \infty$), the entrainment rate per unit width becomes (Kobus, 1991):

$$q_{ae} = f(v; \rho; g) \quad (2.9)$$

These terms lead to a single dimensionless parameter, which must attain a constant value:

$$\frac{q_{ae}}{v^3/g} = \text{const.} \quad (2.10)$$

This relationship, together with $q = vl$, indicates

$$\frac{q_{ae}}{q} = \beta_e = \text{const.} \quad \frac{v^2}{g l} = \text{const.} \quad Fr^2 = K_e Fr^2 \quad (2.11)$$

where K_e is defined as an entrainment coefficient. Hence, in fully turbulent flow, K_e should attain a constant value for a given approach flow and a given fluid. For water, the value of K_e in equation (2.11) is of the order of 10^{-3} to 10^{-2} for a large variety of flow configurations [1].

Equation (2.11) has important implications for air entrainment during steel pouring. For geometrically similar castings and pouring systems, and if the steel flow is always fully turbulent, the relative air entrainment rate should ultimately become directly proportional to the square of the Froude number. As a simple example, consider a metal stream falling through a height H . Assuming the initial velocity in the ladle to be zero, the metal velocity at the point of impingement will be

$$v^2 = 2g H \quad (2.12)$$

Insertion into equation (2.11) yields

$$\beta_e = 2 K_e \frac{H}{l} \quad (2.13)$$

Recall that l is the reference length of the fluid and, thus, is related to the diameter of the metal stream. It can be seen that the amount of air entrained, relative to the metal flow rate, should be directly proportional to the height of the metal in the ladle above the point of impingement of the metal stream. On the other hand, it is inversely proportional to the diameter of the metal stream at the point of impingement. These may be important considerations in the design of steel pouring systems.

The above analysis also shows that for fully turbulent metal flows, the Reynolds number, an often quoted parameter, is not important in air entrainment. The flow can be considered fully turbulent when

$$Re > 10^5 \quad (2.14)$$

If the above condition is not met, the Reynolds number and the turbulence characteristics have to be added to the list of independent variables in equation (2.9), so that in the more general case we have

$$\beta_e = K_e(Re; Tu) Fr^2 \quad (2.15)$$

where Tu summarizes all relevant conditions of the approach flow, which include the velocity distribution and the turbulence intensity and scale. This scaling relationship is plotted in Fig. 2 for a given approach flow turbulence and a given fluid ($Z = \text{const.}$). It can be seen that for small Froude numbers, we reach the inception or entrainment limits below which no air entrainment takes place.

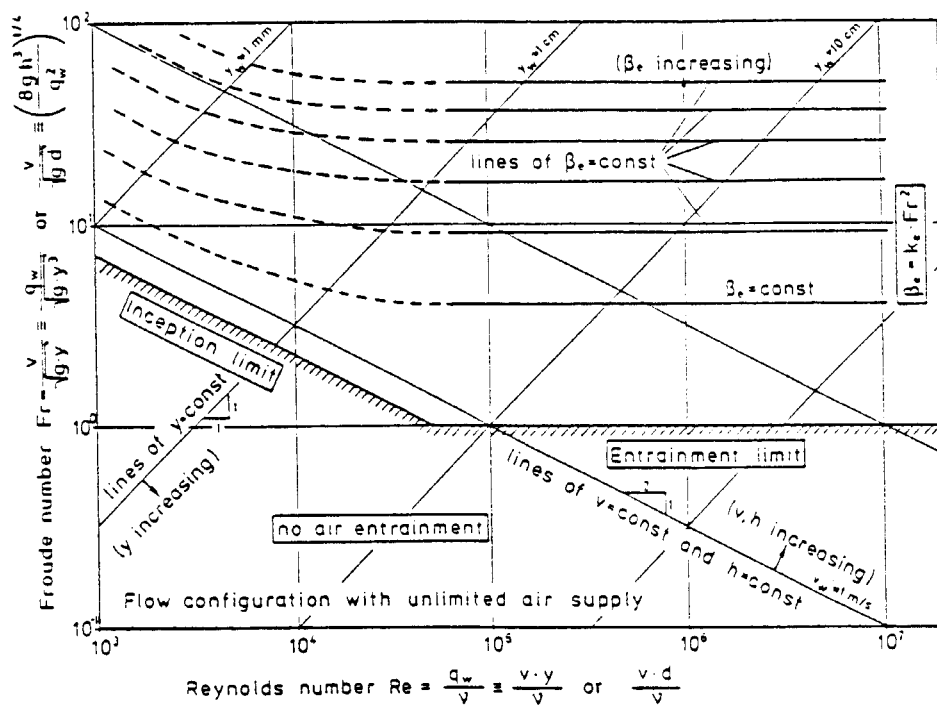


Fig. 2 Suggested functional relationship for the relative air entrainment for a given fluid and approach flow turbulence (from ref. [4]).

For smaller Reynolds numbers (i.e., velocities), the inception limit is important, while for fully turbulent flows ($Re > 10^5$) the entrainment limit is important, and the lines of constant β_e become horizontal according to equation (2.11). Figure 2 is only based on general similarity considerations and requires experimental verification. In addition, it should be kept in mind that such graphs can only be valid for a given flow configuration and a given fluid. Quantitative data are available for water flows in a variety of configuration (see, for example, Kobus and Koschitzky [4] for a recent review). However, to the author's best knowledge, no experiments have been performed to investigate the effects of the parameter Z on the entrainment coefficient K_e . Hence, the air entrainment rate can presently not be quantified for liquid metals and steel in particular. This lack of knowledge also causes considerable problems in water modeling of steel pouring, which is addressed in Section 3.

3. Similarity Considerations for Water Modeling

3.1 Modeling of Air Entrainment

The aim is to model air entrainment during pouring of steel using water. Complete similarity requirements are described by equation (2.4). The primary requirement is to have complete geometric similarity between the water model and the steel pouring system. Fortunately, water models can be constructed that are of exactly the same size and shape as the steel pouring system. Therefore, we will limit our attention to one-to-one, full-scale models. Extreme care should be taken to model all parts of the flow configuration correctly. In particular, if the air entrainment in the casting cavity is of interest, the internal geometry including the air supply/discharge system (e.g., risers) should be the same. Since most of the air entrainment takes place from the atmosphere with virtually unlimited air supply, the external pressure drop in the air flow, ΔP , is small. Then, for an one-to-one model the similarity requirement given by equation (2.4) reduces to

$$\beta_e = f((Tu); Re; Fr; Z) \quad (3.1)$$

The dimensionless parameters in equation (3.1) must be matched as closely as possible to achieve the same air entrainment rates in the water model and the steel pouring system. In an one-to-one model, both the reference fluid length, l , and velocity, v , will be the same for free surface, frictionless flows. Since, the Froude number does not contain any fluid properties, we have that

$$Fr_{model} = \frac{v}{\sqrt{gl}} = Fr_{casting} \quad (3.2)$$

is automatically satisfied in an one-to-one model.

However, the Reynolds number, Re , and the turbulence characteristics of the approach flow, (Tu) , depend on the kinematic viscosity of the fluid, $\nu = \mu/\rho$. Rough values of the relevant properties at typical pouring temperatures (1560 to 1600°C) are given by [5,6]:

$$\rho_{steel} = 7.0 \cdot 10^3 \frac{kg}{m^3}; \mu_{steel} = 6.5 \cdot 10^{-3} \frac{kg}{ms} \quad (3.3)$$

$$v_{steel} \approx 0.93 \cdot 10^{-6} \frac{m^2}{s}$$

and for pure water at 20°C:

$$\rho_{water} = 998 \frac{kg}{m^3}; \mu_{water} = 1.002 \cdot 10^{-3} \frac{kg}{ms} \quad (3.4)$$

$$v_{water} \approx 1.0 \cdot 10^{-6} \frac{m^2}{s}$$

Therefore, the kinematic viscosities of liquid steel and water are approximately the same. Since, the reference fluid length, l , and velocity, v , are also the same, we have that

$$Re_{\text{model}} = \frac{v l}{\nu} = Re_{\text{casting}} \quad (3.5)$$

and also for the turbulence properties of the approach flow

$$(Tu)_{\text{model}} = (Tu)_{\text{casting}} \quad (3.6)$$

Furthermore as mentioned in Section 2, for fully turbulent flow the mean flow characteristics and the turbulence structure become independent of viscosity and the Reynolds number. For a reference flow length and velocity of the orders of 0.1 m and 1 m/s, respectively, the Reynolds number is approximately equal to 10^5 . This indicates that the condition given by equation (2.14) is usually satisfied in steel pouring, and the flow in both the casting and the water model can be considered to be fully turbulent. Then, accurate matching of the Reynolds numbers (and the viscosities) is not required, since the air entrainment rate is independent of Re for fully turbulent flow (see Section 2). In summary, for an one-to-one, full-scale model the similarity requirement reduces to

$$\beta_e = f(Z) \quad (3.7)$$

In other words, the parameter Z should be the same in steel pouring and the water model. Recall that Z consists of fluid properties only. The surface tension of water at 20°C ($\sigma_{\text{water}} = 0.07275 \text{ N/m}$) is considerably lower than those encountered in steel pouring, which can range from about 1.5 N/m for steel to roughly 0.55 N/m for FeO with additions of MnO and SiO_2 [5, 6]. It is not entirely clear whether the steel surface can be assumed to be always covered by a liquid oxide layer during air entrainment, because such a layer would constantly be ruptured, folded and transported away, resulting in a surface renewal process. Nonetheless, with the definition of Z given by equation (2.5), the value for water at 20°C is

$$Z_{\text{water}} = 2.6 \cdot 10^{-11} \quad (20^\circ\text{C}) \quad (3.8)$$

The value of Z for steel is roughly

$$Z_{\text{steel}} = 7.4 \cdot 10^{-13} \quad (3.9)$$

which is about a factor of 35 lower than that of water. Taking the surface tension of FeO instead (but ρ_{steel} and μ_{steel}) we have

$$Z_{\text{steel, FeO}} = 1.5 \cdot 10^{-11} \quad (3.10)$$

which can be considered to be virtually the same as that of water. Such small differences are easily caused by temperature variations and the presence of impurities, oxygen, etc. in solution (see Section 4). Also note that the above differences/similarities in Z are not only caused by the surface tension (which is always very different from water), but are also due to the different densities and dynamic viscosities.

Whether the value given by equation (3.9) or (3.10) is more realistic is very important for satisfying the similarity requirement given by equation (3.7). Certainly if the oxide value is realistic, water is an excellent model fluid for studying air entrainment in steel pouring. On the other hand, air entrainment can be expected to be quite different if the surface tension of steel plays an important role. As noted in Section 2, both the inception limit and the air entrainment rate are directly dependent upon Z ; however, the exact functional relationships are not known. The sensitivity of the air entrainment rate

on Z could be clarified by conducting small-scale experiments with fluids having different Z values, such as low melting temperature metals or liquids other than water (see Section 4).

In conclusion, the above analysis shows that the similarity requirements for a full-scale, one-to-one water model of steel pouring reduce to proper matching of the Z parameter. In the presence of oxides at the steel/air interface, it appears to be possible to satisfy this last requirement. However, uncertainties exist with regard to the role played by the surface tension of steel and the dependence of the relative air entrainment rate on Z. It is suggested to conduct small-scale experiments to clarify the latter issue.

3.2 Additional Considerations for Similarity of Air Transport, Oxidization, and Detrainment

Reoxidation of steel can be considered to occur in three consecutive steps:

- mechanics of air entrainment (Section 3.1)
- mechanics of air transport away from the entrainment location
- transfer of oxygen to the metal surface, oxidizing reactions and detrainment of air

Whereas the similarities between steel pouring and water modeling in the mechanics of air entrainment (first item) were treated in the previous section, additional problems in achieving similarity arise for the latter two items. This section attempts to highlight these important issues.

After entrainment, small air bubbles form in the fluid. In turbulent flows, same measurements have shown that the bubble diameter, d_b , is typically less than about 1 mm (Kobus, 1991). The subsequent bubble transport is governed by viscosity through the turbulence characteristics and, hence, the Reynolds number of the flow. As shown in Section 3.1, Re and (Tu) are approximately the same in steel pouring and an one-to-one water model, implying that the bubble trajectory or residence time can be expected to be similar. An important quantity governing the transport capacity of the flow is the bubble slip velocity, v_b . This slip velocity corresponds to the rising velocity of a bubble in an infinite liquid. Small bubbles are almost spherical and the bubble Reynolds number (based on v_b and d_b) can be expected to be less than 100. Then, the parameter Z is of little importance and the bubble rise velocity is given by [1].

$$v_b = \frac{1}{12 \text{ to } 18} \frac{d_b^2 g}{\nu_{\text{fluid}}} \left(1 - \frac{\rho_{\text{air}}}{\rho_{\text{fluid}}} \right) \quad (3.11)$$

Since the bubble diameter, d_b , and the kinematic viscosity, ν_{fluid} , are approximately the same for steel and water, differences in v_b would be solely due to the density ratio. However, for water and air at 20°C:

$$\left(1 - \frac{\rho_{\text{air}}}{\rho_{\text{water}}} \right) = 0.9988 \quad (3.12)$$

whereas for steel and air at about 1600°C:

$$\left(1 - \frac{\rho_{\text{air}}}{\rho_{\text{water}}} \right) = 0.999973 \quad (3.13)$$

which is about the same. Thus, the bubble slip velocity, v_b , is the same in steel and water systems and can be estimated to be always less than about 0.3 m/s [1]. This indicates that not only the air bubble transport, but also the transport capacity and the detrainment rate are approximately the same in steel pouring system and the water model, which is encouraging. In the stream from the ladle and in the sprue, the flow velocity, v , can be expected to be much larger than the bubble slip velocity, v_b ,

implying that the transport capacity is large and the air bubbles will not escape (detrain). However, in the casting cavity the fluid will come to rest ($v \rightarrow 0$) so that the transport capacity vanishes. Then, all of the air which has not been absorbed by the steel/water will escape (detrain).

Some or all of the oxygen present in the entrained air will be transferred to the water/steel. For both the steel and the water systems, the rate of oxygen transfer depends on

- the contact area, i.e. the total surface area of the air bubbles
- the surface renewal rate, i.e. turbulent mixing, contact times, and bubble trajectories.

These two factors can be expected to be similar in the steel and water systems; due to the similarities in the fluid dynamics as discussed above. Other factors are, however, completely different. In the water/air system, the mass flux of oxygen depends on the concentration difference between air and water and, hence, water properties such as temperature, initial dissolved oxygen content, and impurities. On the other hand, in the steel/air system, the oxygen at the surface will be consumed in oxidizing reactions. Due to the large oxidation rate, it can be expected that in steel pouring much more of the oxygen will be consumed (perhaps all) than in the water model. Even if the water is saturated with oxygen after passing through the system, the amount of oxygen which is dissolved will be small relative to that remaining in the air. Quantitative comparisons would involve estimation of the oxygen transfer rates and the reaction rates, which is not possible at the present time. In fact, there is little hope that the oxidizing reactions in steel pouring can ever be modeled realistically using the water/air system.

The differences in the oxygen transfer between the steel and water systems may also influence the flow in the runners and in the casting cavity. Assuming that the oxygen is completely consumed by the steel, there will be somewhat more "gas" in the water system. In the more slowly moving fluid in the casting cavity, the effects of the bubbles on the flow field can, however, be quite pronounced. The entrained bubbles exert a buoyancy force on the surrounding fluid, which gives rise to bubble-induced flow [1]. If the total volume of the bubbles is less (as in the steel system), this effect will be smaller. Again, these differences cannot be quantified at the present time. Nonetheless, they should be carefully examined if the air entrainment rate in an actual steel pouring system is ever to be measured and compared to a water model.

4. Use of Other Model Fluids

As is evident from Section 3.1, the matching of the Z parameter between the steel and water systems may not be satisfactory. Therefore, it may be desirable to utilize different fluids to model air entrainment during steel pouring. Although a different fluid will usually not result in such a good match with the kinematic viscosity of steel and, hence, the Reynolds number, this is not important as long as the flows in both the steel casting system and the model are fully turbulent (see Section 2.3). As a first example, consider water at 60°C, instead of 20°C as in the previous section. The Z parameter and the kinematic viscosity become

$$Z_{\text{water}} = 1.6 \cdot 10^{-12} \quad (60^\circ\text{C}) \quad (4.1)$$

$$\nu_{\text{water}} = 0.47 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}} \quad (60^\circ\text{C}) \quad (4.2)$$

It can be seen that the above value of Z is only twice as large as the one for steel ($7.4 \cdot 10^{-13}$, eqn. 3.9), instead of a factor of 35 for water at 20°C. However, the kinematic viscosity is reduced by a factor of 2, implying that the Reynolds number will be twice as large as the one for the steel system. Again, this is acceptable since the flow is expected to be fully turbulent. Despite the large uncertainty in the Z value for steel, it can be concluded that heated water may be a better model fluid.

The addition of up to 10% weight of various inorganic solvents (salts, etc.) to water changes the surface tension by less than 3%, which is not significant enough to cause an appreciable change in Z . In fact, almost all nonmetallic liquids have a surface tension less than water [7], which will not result in the desired decrease to the low Z value of steel. Hence, the only way to reduce Z is to choose a fluid with a lower viscosity (see the definition of Z , eqn. 2.5). The resulting change in the Reynolds number must then be tolerated. Acetone at 20°C has a suitably low viscosity, but cannot be used in a plexiglass model (the same is true for alcohols). Oils, paraffins and glycerin have a much too large viscosity.

There are several metals that are liquid at room temperature; however, they are usually very expensive or hazardous. For example, consider gallium (melting point: 28°C, strongly undercooled, non-toxic). The values are

$$Z_{\text{gallium}} = 7.3 \cdot 10^{-14} \quad (4.3)$$

$$\nu_{\text{gallium}} = 0.34 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}} \quad (4.4)$$

The value of the viscosity can be tolerated, while the Z parameter is even lower than that of steel. Since gallium forms an oxide skin, the actual surface tension may be somewhat different. In conclusion, the use of gallium or gallium alloys should be considered. However, the high price of gallium will limit its use to small-scale exploratory experiments. In addition, liquid metals are opaque making proper visualization difficult.

5. Use of a Geometrically Scaled System

It is of interest to briefly discuss the use of a water model that is not a one-to-one, full-scale replica of the actual steel pouring/casting system. Again, complete similarity requirements are given by equation (2.4). The first requirement that must be satisfied is the equality of the geometric ratios. In other words, it is crucial that a scaled water model has exactly the same shape as the steel system. It has repeatedly been noted in the literature that small changes in the boundary shape can lead to large differences in the air entrainment rate [1]. For virtually unlimited air supply, the Euler number in equation (2.4) is not important (see above). Furthermore, no additional considerations are needed regarding matching of the Z parameter, since it contains liquid properties only.

As already noted, all of the scale effects are concentrated in the Reynolds and Froude numbers. From the definitions of these parameters (see eqs. 2.2 and 2.3) it is clear that they cannot be matched simultaneously for a scaled model where the reference fluid length, l , is not the same as in the actual steel system, because the kinematic viscosities of steel and water are approximately the same. However, matching of the Reynolds numbers is not important as long as the flows in both the steel and water systems are fully turbulent (see Section 2.3); therefore,

$$\text{Re}_{\text{model}} \text{ and } \text{Re}_{\text{casting}} > 10^5 \quad (5.1)$$

must be satisfied. Then, similarity considerations should concentrate on exact matching of the Froude numbers according to equation (3.2). For example, for a 1:2 water model (i.e., the steel system is twice as large as the water model), Froude scaling yields

$$l_{\text{model}} = 0.5 l_{\text{casting}} \quad (5.2)$$

$$\nu_{\text{model}} = \sqrt{0.5} \nu_{\text{casting}} = 0.707 \nu_{\text{casting}} \quad (5.3)$$

Hence, the water flow velocity must be regulated to be 70.7% of that of the liquid steel. Then, the relative air entrainment rate, β_e , in the 1:2 water model will be the same as in the steel system. Care should be taken that, with the reduced velocity and length, the model Reynolds number still exceeds 10^5 . If this is not the case, but a 1:2 water model is desired, the use of a model fluid with a lower viscosity should be considered. Note that a lower viscosity may also help in obtaining a better match in the Z parameter (see Section 4).

Although the above example shows that a properly scaled water model can be used, large scale factors are not recommended due to possible differences in (i) the turbulence characteristics of the flow and (ii) the subsequent air transport and detrainment. This is because the air bubble size and rise velocity are the same regardless of the boundary scale, but depend on the Reynolds number (see Section 3.2).

6. Summary and Conclusions

The basics of air entrainment have been reviewed and a dimensional analysis of the inception limit and amount of air entrainment has been presented. It is found that for a given fluid ($Z = \text{const.}$) and flow configuration, the relative air entrainment rate for fully turbulent flows ($Re > 10^5$) is directly proportional to the square of the Froude number, whereas the dimensionless critical velocity for the inception of air entrainment is constant.

An examination of the relevant dimensionless parameters and fluid properties suggests that an one-to-one, full-scale water model of the steel pouring system should be constructed. Then, the similarity requirements reduce to proper matching of the Z parameter. It is shown that water is an excellent model fluid for steel, if the surface tension of FeO and other oxides is used in the calculation of Z. However, if the surface tension of steel is important, large differences result in the Z parameter and, perhaps, the air entrainment rate. It is not clear which estimate of Z is more realistic in steel pouring. For this reason, it is suggested to conduct small-scale experiments using low-melting temperature metals in order to investigate the effects of oxidation on the magnitude of Z and the air entrainment rate.

Additional similarity requirements for air transport, oxidization and detrainment have also been discussed. While the air transport and detrainment can be expected to be similar in the steel and water systems, large differences exist in the transfer of oxygen to the steel/water. There is little hope to model the oxidizing reactions in steel using water, since the dissolution of oxygen in water does not involve a chemical reaction. In addition, the amounts of oxygen consumed will be quite different, which could lead to differences in the bubble-induced flow within the casting cavity.

Despite the above uncertainties and differences, water modeling of air entrainment during steel pouring appears to be a very promising tool. In particular, the use of heated water ($\approx 60^\circ\text{C}$) results in a better match of the Z parameter for steel. Other model fluids have either unsuitable properties or disadvantages in their use. Finally, a geometrically scaled water model must have the same Froude number as the steel system, while the flows in both the model and the casting must be fully turbulent. A large scale factor is not recommended due to differences in the Reynolds numbers and thus the air transport and detrainment.

II. FILTER EFFECTIVENESS TO REMOVE INCLUSIONS

1. Introduction to Filtration

The removal of inclusions formed by reoxidation of steel during pouring has potentially much merit. This section reviews the basics of filtration, while the use of water models to study filtration in steel casting is addressed in the subsequent section.

Reoxidation inclusions are believed to be larger than 1,000 μm , and attention in this study is limited to particles larger than 100 μm . They consist of liquid or solid oxides (MnO , FeO and SiO_2) which formed during the pouring process due to air entrainment. Porous ceramic media such as extruded alumina multi-cellular filters or alumina ceramic foams are candidate filters for refining steel melts in castings. The multi-cellular nature of these filters may also act as a flow laminarizer and reduce melt splashing. The mean pore size of these filters is of the order of 1 mm - roughly the same size as the inclusions of interest.

There are two types of filtration modes: (i) surface or cake filtration and (ii) deep bed filtration. Surface filtration ("sieving") relies on cake formation for particle retention, and hence the size of the filter pores must be of the same order or smaller than the particles. Thus, surface filtration is practical for the removal of large inclusions from the melt. On the other hand, deep bed filtration occurs within the filter medium on its internal surfaces. Each internal pore surface has a probability of retaining particles from the melt, and it can trap particles much smaller in size than the pores of the filter. Deep bed filters are commonly used in refining of aluminum melts and are found to be effective for the removal of dilute suspensions of inclusions in the size range of 1 - 30 μm , which is more typical of deoxidation products [8]. Obviously, a filter can act in both modes for inclusions that are of different sizes relative to the pores. Also, a depth filter can enter the surface or cake filtration mode with extended use due to the buildup of the internal surfaces. The aggregate of inclusions that form the "cake" in surface filtration acts as a "second" filter upstream of the original medium, which increases in depth and progressively restricts the flow.

Inclusion removal from liquids can be visualized as consisting of two serial steps: (i) transport of the inclusion to the filter surface and (ii) adherence or sintering of the inclusion to the filter surface due to secondary (Van der Waals) forces. The inclusions are transported by diffusion, direct interception, gravity and/or surface forces [9]. However, mechanical entrapment has been observed to be responsible for filtration of inclusions larger than about 30 μm , which is the case for reoxidation products. The deposited inclusions act as new filter sites for further capture of inclusions.

Filtration of steel melts in continuous casting has been addressed by Apelian and coworkers [8, 9, 11]. However, these studies concentrated on the removal of deoxidation and desulfurization products which are smaller than 100 μm . No study has been identified that is concerned with reoxidation products that are larger in size than 100 μm .

2. Water Modeling of Steel Filtration

There are three fundamental differences between steel and water filtration [8]. Firstly, steel does not wet the ceramic filter medium, while water does. Secondly, due to the high electrical conductivity of molten steel, electrokinetic forces between the inclusion and the filter surface are absent. Thirdly, certain inclusions in the steel system can sinter to the filter surface, while in low-temperature water systems the sintering process is absent. However, except during the priming process of the filter, none of the above factors are expected to be important, because of the purely mechanical nature of the entrapment process for particles larger than 30 μm .

As in the previous section, we concentrate on hydraulic models that are of exactly the same shape and dimension as the steel casting system. Furthermore, the same filter as well as particles of similar

shape and dimension as the reoxidation products should be utilized. Similarity of the flow is realized by matching of the Reynolds and Froude numbers. However, for a fluid/particle/filter system, a number of characteristic dimensions and properties need to be distinguished. The relevant parameters are discussed below.

Overall Flow:

$$Re = \frac{v l}{\nu} \quad (2.1)$$

$$Fr = \frac{v}{\sqrt{g l}} \quad (2.2)$$

where v and l are the characteristic velocity and length (i.e., cross-sectional diameter) of the approach flow, respectively, and ν is the kinematic viscosity of the steel/water, as in the previous section on air entrainment, the above parameters are automatically matched if an one-to-one, full scale model of the casting system is utilized and if the kinematic viscosities of steel and water are the same. Even if the kinematic viscosities are not exactly the same, a small difference is of little consequence if the Reynolds number is large enough for the flow to be fully turbulent ($Re > 10^5$), which is expected to be the case.

Filter Flow:

$$Re_f = \frac{v_f d_f}{\nu} \quad (2.3)$$

$$Fr_f = \frac{v_f}{\sqrt{g d_f}} \quad (2.4)$$

where v_f and d_f are the interstitial or pore velocity and hydraulic pore diameter of the filter, respectively. Again, for equal steel and water viscosities the above parameters can be exactly matched for an one-to-one model system. Note that the flow in the filter can be laminar, because $d_f \ll 1$. The transitional Reynolds number for a monolithic extruded filter is equal to 2300, whereas for a ceramic foam filter it is of the order of unity. As opposed to fully turbulent flow, in the laminar regime it is much more important to match the Reynolds numbers and, hence, the kinematic viscosities exactly. Fortunately, the kinematic viscosities of steel and water (at room temperature) match very well (see Section I), so that the filter Reynolds and Froude numbers can be expected to be the same in the water model as in the steel system.

Inclusion Flow:

$$Re_i = \frac{v_i d_i}{\nu} \quad (2.5)$$

$$Fr_i = \frac{v_i}{\sqrt{g d_i \Delta\rho/\rho}} \quad (2.6)$$

where v_i and d_i are the velocity and mean diameter of the inclusions (particles), respectively, ρ and ν are the density and kinematic viscosity of the fluid (water or steel), respectively, and $\Delta\rho$ is the density difference between the fluid and the inclusions. Since the viscosities of steel and water are approximately the same, the inclusion Reynolds number, Re_i , can be matched if the particle velocity and diameter are the same in the water and steel systems. Even if particles of the same size and shape as the reoxidation products are chosen for the water model, the velocities will only be the same if the

inclusion Froude number, Fr_i , can be matched. This requires the density ratio $\sqrt{\Delta\rho/\rho}$ to be the same in the steel and water systems. Table 1 summarizes relevant densities for the steel system and a water model with various simulated inclusions. It can be seen that the density ratios and, hence, the Froude numbers can be matched if, for example, moist cork or hollow silica microspheres are utilized as the simulated inclusions in the water model. Again, these simulated inclusions should be of the same size and shape as the actual reoxidation products in steel pouring. Uncertainties exist due to the variable nature of the reoxidation products (chemical composition, phase); nonetheless, the examples in Table 1 illustrate that satisfactory simulated inclusions for the water model can be found.

Since the flow behaviors of the melt and the particles through the system and filter can be well simulated using an one-to-one water model and simulated inclusions, it can be expected that the entrapment process is also similar. This would not be the case for particles smaller than $30\ \mu\text{m}$ where surface forces are responsible for the retention of the inclusions. The modeling of filtration of such small particles would require close matching of the surface tension and contact angle. As already mentioned, for the large reoxidation products (relative to the pore size) the attachment forces are purely mechanical and the wetting behavior of the inclusions is believed to be unimportant.

Little information is presently available on the filtration of inclusions that are in the liquid state. Their flow behavior will be very similar to that of solid inclusions, and the above similarity considerations will also apply. However, the entrapment process in the filter may be somewhat different for liquid inclusions, and it is not clear whether solid particles can be used in the model. Differences are expected in the attachment to the filter surface, since liquid readily deforms under the influence of (mechanical) shear forces.

Table 1: Densities for Inclusion Flow [5, 6, 7, 12].

System	Liquid		Inclusions		$\sqrt{\frac{\Delta\rho}{\rho}}$
	Nature	Density [g/cm ³]	Nature	Density [g/cm ³]	
Steel Casting	steel	7.0	FeO MnO SiO ₂	5.7 5.2 2.2	0.43 0.51 0.83
Water Model	water	0.998	moist cork	0.25 to 0.35	0.8 to 0.87
			hollow silica microspheres	0.35	0.8

3. Summary and Conclusions

Reoxidation products larger than $100\ \mu\text{m}$ are filtered by mechanical entrapment. Due to the fact that the inclusions are of a similar size as the mean pore diameter of a typical ceramic filter (both smaller and larger), the filter can act in both the surface and depth filtration mode.

Using an one-to-one, full scale water model and certain simulated inclusions of the same size and shape as the reoxidation products, it is possible to match the relevant dimensionless parameters and

model the flows in the casting and filter as well as of the inclusions in steel pouring. Because surface forces are not important, the filtration (or inclusion removal) efficiency in the water model is expected to be in good agreement with that of the actual steel filtration system. The good similarity in the flows also permits evaluation of the effectiveness of the filter in laminarizing the flow.

Limitations and uncertainties in water modeling of filtration of reoxidation inclusions in steel exist in the following areas: (i) the variable nature of the reoxidation products in terms of their chemical composition and phase as well as their size and shape; careful examination and analysis of filters used in steel filtration is recommended, (ii) priming of filters cannot be studied due to differences in the wetting behaviors of steel and water, and the fact that water will not solidify; small-scale experiments using metals are recommended, and (iii) the attachment mechanics of inclusions that are in the liquid state; nonetheless, their flow is well simulated using solid particles; considerable additional research is required in this area. The use of filters and inclusions of a different size as in the actual steel system is not recommended, due to difficulties in matching of the various Reynolds and Froude numbers.

III. References

- [1] H. Kobus, "Introduction to Air-Water Flows", in Air Entrainment in Free-Surface Flows, I. R. Wood, ed., A.A. Balkema, Rotterdam, 1991.
- [2] Southern Research Institute and SFSA, "Clean Cast Steel Technology", SRI Proposal Number 8910109-002, Aug. 1991.
- [3] H. Kobus and H. P. Koschitzky, "Local Surface Aeration at Hydraulic Structures", in Air Entrainment in Free-Surface Flows, I.R. Wood, ed., A.A. Balkema, Rotterdam, 1991.
- [4] D. A. Ervine, "Behaviour of Turbulent Water Jets in the Atmosphere and in Plunge Pools", Proc. Inst. Civ. Engrs., Vol 83, pp. 295-314, 1987.
- [5] J. F. Elliot, M. Gleiser and V. Ramakrishna, Thermochemistry for Steelmaking, Vol. II, Sec. 9, Addison-Wesley, 1963.
- [6] F. D. Richardson, Physical Chemistry of Melts in Metallurgy, Vol. 1, Academic Press, London, 1974.
- [7] Landolt and Bornstein, Zahlenwerte der Physik und Chemie, Teil 5, Bandteil a, Springer Verlag, Berlin, 1969.
- [8] S. Ali, R. Mutharasan and D. Apelian, "Physical Refining of Steel Melts by Filtration", Met.Trans. B, Vol. 16, pp. 725-742, 1985.
- [9] L. A. Spielman, "Particle Capture from Low-Speed Laminar Flows", Ann. Rev. Fluid Mech., Vol. 9, pp. 297-319, 1977.
- [10] S. Ali, D. Apelian and R. Mutharasan, "Refining of Aluminum and Steel Melts by the Use of Multi-Cellular Extruded Ceramic Filters", Can. Metall. Quarterly, Vol. 24, pp. 311-318, 1985b.
- [11] D. Apelian, R. Mutharasan and S. Ali, "Removal of Inclusions from Steel Melts by Filtration", J. Mat. Science, Vol. 20, pp. 3501-3514, 1985.
- [12] G. V. Samsonov, The Oxide Handbook, IFI/Plenum, New York, 1973.