REVIEW ARTICLE ON PHYSICAL AND NUMERICAL MODELLING OF SEN AND MOULD FOR CONTINUOUS SLAB CASTING

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Abstract
Over the years, considerable efforts have been made to study the performance of Submerged Entry Nozzle (SEN) and mould of continuous slab caster. Numerous physical and numerical modelling studies have already been carried out and reported in the literature to study the fluid flow behaviour inside the mould. Based on the extensive literature search, a summary of these is presented here. For the sake of convenience, the studies have been categorized into two major groups, e.g., physical modelling and numerical modelling. In each of these categories, a large number of publications on various aspects have been reported. Sufficiently reliable numerical models are also currently available and these also allow one to carry out full scale predictions and useful engineering design calculations.

KeyWords: Submerged Entry Nozzles (SEN); Physical modelling; Numerical modelling; Fluid flow; Computational Fluid Dynamics (CFD).

1. Introduction

Steel is still the most reliable, appropriate and inexpensive material for different industrial appliances. Even in a time where alternative materials are increasingly utilized, steel still seems to be irreplaceable owing to its availability, strength and price advantage above others.

Submerged Entry Nozzles (SEN) are used in the steelmaking process to prevent reoxidation of the molten steel directly from stream contact with the surrounding environment and from air entrainment and splashing when the molten stream strikes the liquid surface in the mould. SEN design plays a vital role in a continuous casting mould. It governs the fluid flow pattern inside the mould, which in turn, dictates the quality and productivity of the process. Phenomena which are influenced by fluid dynamics in the SEN and mould includes nozzle clogging, shell growth, superheat dissipation, inclusion flotation, flux entrapment, argon entrapment, flux distribution, meniscus freezing and surface turbulence. Table 1 shows the connections between metal delivery phenomena and caster quality and productivity. In the context of metal delivery, SEN design is essentially a question of internal diameter and port geometry. Operating practices which affect metal delivery include the depth of nozzle submergence, off-centre SEN location in the mould, electromagnetic stirring and injection of inert gas. Table 2 shows the variable which are seen to have an effect on the range of metal delivery influenced phenomena. Table 3 shows the techniques and capabilities of water modelling relevant to caster metal delivery. Table 4 shows the design variations in slab caster SENs producing wide range of steel. As shown in Table 4, the above design parameters on the SEN are widely varied all over the world. It is believed that in the inner bore of SEN an oval cross section has advantage over the circular one while casting a narrow section. On similar lines, it may be explained that a rectangular outlet port would distribute liquid steel more evenly without touching the wide faces while casting a narrow section. A downward angled port impinges liquid steel deep into the mould. This would cause least disturbances to the meniscus. On the other hand, an upward angled port enhances inclusion floatation, but increases the meniscus turbulence as well. It has been observed that in case of circular port SENs there is a pressure drop across the port, with a lowest pressure region at the top of the port. This may produce stagnant conditions and even flow back into the SEN.

Table1. Metal delivery connections to quality and productivity [Herbertson et al., (1991)]

Surface quality	**Internal quality**	**Cleanness**	**Productivity**
Surface Turbulence Flux Distribution Meniscus Freezing Shell Growth Flux Entrapment Argon Entrapment Inclusion Entrapment	Superheat Dissipation Argon Entrapment	Nozzle Clogging Inclusion Flotation Flux Entrapment Surface Turbulence Vortexing	Nozzle Clogging Shell Thinning Flux Distribution Speed Restriction

Table 2. Design and operating variables which effect metal delivery [Herbertson et al., (1991)]

SEN Design	**Operating Practices**	**Process Variables and Constraints**
Internal bore diameter Port geometry/design Port location Number of ports Internal base design Well depth	SEN submergence depth SEN position Argon injection rate Electromagnetic stirring Tundish flow control	Mould geometry Superheat Casting speed

Over the years, a lot of water modeling and numerical modeling work has already been done to study the fluid flow behaviour in the mould region of the continuous casting process. Thomas et al. [Thomas et al., (1990)] investigated fluid flow and heat transfer in the mould region of slab caster using a finite element based numerical model. Influence of SEN port angle, casting speed and mould width variation on flow field in the mould has been reported by them. Najjar et al. [Najjar et al., (1995)] studied the effect of nozzle geometry and operating parameters on the flow behaviour of the SEN.

During the same period Flint [Flint, (1990)] developed a 3D model using a commercial CFD codes to describe fluid flow in the mould of continuous casters. Recently, Harvey et al. [Harvey et al., (1998)] carried out physical and numerical modelling, both to optimize liquid steel flow through the SEN and in the mould. Wang [Wang, (1990)] investigated experimentally, in a cold model, the vortex formation in the mould due to shearing of two surface flows from the mould narrow faces meeting adjacent to the SEN. Gupta and Lahiri [Gupta and Lahiri, (1992), (1994), (1996)] observed the vortex formation in a water model beyond a critical flow rate, which depends upon the nozzle configuration, immersion depth and aspect ratio of the section being cast. They reported the effect of operating parameters on amplitude of standing waves generated at the free surface of the liquid.

Consequently, the purpose of the present work has been to bring together the results of a large number of investigations in this area and to present a comprehensive review. In the subsequent sections therefore, laboratory, pilot scale modelling and numerical modelling studies of continuous casting SEN and mould systems have been reported. For the sake of convenience these investigations have been categorized into two major groups, e.g., physical modelling and numerical modelling.

Table 3. Summary of water modelling and capabilities [Herbertson et al., (1991)]

Phenomena	Water Modelling
Internal SEN and port flow	Flow visualization, transparent SENs , pressure and velocity distribution at port exits
Nozzle clogging	Hydrogen bubbles to simulate inclusions, velocity measurement by Laser Doppler Velocimetry
Mould fluid flow and recirculation	Flow visualization using dye injection, saw dust, polystyrene beads, flow rate measurements by hot wire anemometer, by tracking movement of polystyrene beads poured through SEN, ultrasonic doppler speedometer.
Temperature distribution and solidification	The effect of stream impingement on narrow face can be inferred by impact pressure measurements at narrow face using pressure transducers; velocity measurement. Solidification simulation requires freezing model
Inclusion flotation and gas bubble distribution	Inference from observed flows. Measurement of gas residence time with electrical void probe .Simultaneous using low-density micro-spheres, Stokes velocity similarity.
Electromagnetic stirring or braking	Difficult to achieve more than qualitative approximation.
Flux entrapment	Simulated using ground cork, plastic chips.
Vortexing	Readily visualized in water models
Meniscus freezing	Inferences from velocity measurements in the vicinity of meniscus
Flux distribution	Surface distribution of solid and liquid flux simulated with oils, cork particles etc.
Surface movement and turbulence	Surface movement measurements with ultrasonic sensors
Calibration and validation	Validation against plant or pilot plant data

Table 4. Some SEN designs used worldwide

Location	Bore dia. (mm)	Shape	Outlet Port Angle	Direction	Slag Line	Product
Europe	75	70	25	Downward	Duplex	Strip,Plate,Electricl
Europe	85	80	25	Downward	Duplex	Strip, Plate
Europe	67	70	25	Downward	Thru wall	Strip
Europe	80	75X130	0	Horizontal	Duplex	Strip, Plate
Europe	75	70	20	Down	Duplex	Plate
Europe	55	55	15	Upward	Duplex	Stainless
Europe	60	60X50	25	Upward	Duplex	Stainless
Europe	75	70	20	Downward	Duplex	Strip ,Plate
Europe	90	85X85	15	Downward	Thru wall	Strip, Plate
Europe	75	80X65	0	Horizontal(Sump)	Duplex	Strip,Plate,Electricl
Europe	75	70	25	Downward	Duplex	Strip, Plate
Europe	75	70	20	Downward	Duplex	Strip, Plate
N. America	93	90X60	15	Downward(Sump)	Thru wall	Strip
N. America	93	60X90	5	Upward(Sump)	Duplex	Strip
N. America	75	70X85	0	Horizontal(Sump)	Duplex	Strip
N. America	50	50	0	Horizontal(Sump)	Thru wall	Stainless
N. America	55	55	15	Upward	Duplex	Stainless, Electrical
China	80	80X65	15	Downward	Duplex	Strip
South Africa	80	70	25	Downward	Duplex	Strip
Australia	68	80X60	15	Downward(Sump)	Duplex	Strip, Plate
New Zealand	60	60X60	15	Downward	Duplex	Strip
Japan	40	60	20	Downward(Sump)	None	Stainless

2. Physical Modelling

Fig.1 shows a schematic physical modelling of the SEN and mould arrangement of relevance to the continuous casting of steel. The molten steel which comes from tundish is fed into SEN and from which it comes to mould of the continuous caster.

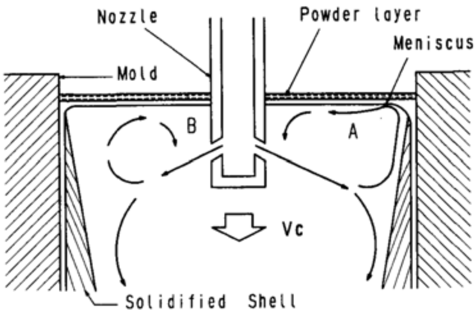

Fig.1.Schematic diagram of SEN and mould flow

Over two to three decades a number of investigators have studied various aspects of the continuous casting mould. It is now well established that there are four recirculating domains inside the mould, two above the nozzle port and two below. The lower two recirculating domains are comparatively bigger in size than the upper ones. The first study was done for straight bore nozzle by Afanaseva et al. [Afanaseva and Iventsov , (1958)], Heaslip et al. studied about the fluid flow behaviour in submerged entry nozzles with stopper rod and slide gate control system.[Heaslip et al., (1987)],[Heaslip and Schade , (1999)].

A number of researchers reported that the fluid flow inside the mould is symmetrical along the central plane. Gupta et al. [Gupta et al., (1991), (1996)] have observed that the flow pattern inside the continuous slab caster mould is not symmetrical about its central plane. Moreover there is a frequent oscillation in the fluid flow pattern. He also investigated the residence time distribution [Gupta et al., (1991)], and slag entrapment [Gupta and Lahiri, (1996)]. Tanaka et al. [Tanaka et al., (1992)], Teshima et al. [Teshima et al., (1993)] and Iguchi et al. [Iguchi et al., (2000)] also used water models to study slag entrainment. Wang et al studied the influence of wettability on the behavior of argon bubbles and fluid flow [Wang et al., (1999)].

Most of the modelling is done using water as the fluid representing the liquid steel. As shown in Table 5 , water at 20^0C and molten steel at 1600^0C have practically equivalent kinematic viscosities, making reduced scale aqueous models an excellent tool for investigating fluid flow process inside mould in steel making. Furthermore, using water as the representative bulk fluid gives decisive advantages as this ensures easy flow visualization in the system. In SEN and mould slag phase is simulated by oils or emulsions. Different liquid like Benzene, Toluene, oils, paraffin oils etc. have been used to simulate the slag phase but G.A. Irons noted that paraffin oil is the best liquid for simulating the slag phase in water model.

Table 5. Physical properties of water at 20^0C and steel at 1600^0 C [Wang et al., (1999)]

Property	Water (20^0C)	Steel (1600^0C)
Molecular viscosity (μ), kg/(m. s)	0.001	0.0064
Density (ρ), kg/ m^3	1000	7014
Kinematic viscosity (ν) m^2/s	10^{-6}	0.913×10^{-6}
Surface tension (σ) N/m	0.073	1.6

Thus, many physical modelling studies have been reported over the last few decades on widely varying aspects of liquid steel flow in SEN and mould. In the subsequent sections, these are discussed under two main sub-headings, namely scaling criteria for similarity consideration and innovative technology and design.

2.1 Scaling criteria for similarity consideration

Selection of an appropriate geometrical scale factor λ, defined as a ratio of the characteristic length in the model to that in the full scale system. As a thumb rule, the scale factor is to be so chosen that flow conditions in the model and full scale systems are essentially identical. Thus, if flow in full scale system is turbulent, then the chosen scale factor together with operating conditions must ensure turbulent flow in model. As a consequence, it is desirable that the scale factor should not be too small or too big. Full scale cold models on the other hand, are prohibitively expensive and their use is often not justified since all characteristics of high temperature steelmaking operations cannot be recreated in these on a one to one basis. Therefore, some element of judgment is necessary for the selection of a most appropriate scale factor for a given problem. Generally in case of SEN and mould 40% scale down water models are used by different researchers.

Physical models for a given situation are constructed by different states of similarity namely, Geometrical similarity, Mechanical similarity, Thermal similarity, Chemical similarity etc. It is based on these similarity considerations that a full scale system is scaled down or a laboratory scale model is scaled up. A full scale water model requires no velocity scaling due to the dynamic similarity between liquid steel and water, as they share approximately the same kinematic viscosity. However, the scaled model requires a velocity scaling according to Froude, Reynolds and Weber similarity.

In reduced scale model studies of isothermal, non-reacting systems, two states of similarities viz., geometrical and dynamic, are required to be satisfied between the model and the full scale. Geometric similarity simply implies that every dimension in the scale model bears a fixed ratio to a corresponding dimension in the full scale. Dynamic similarity implies that the ratio of the different forces which includes inertial, gravitational, pressure, surface tension, viscous force etc. acting on a small fluid element must be the same in the scale model and in the full scale version[Mazumdar and Guthrie, (1999)]. The dimensionless numbers used are Reynolds number (Re), Froude number (Fr), Weber number (We), Eulers number (Eu) etc. It is to be mentioned here that in aqueous modelling of steelmaking processes, geometric and dynamic similarity between model and prototype automatically ensures kinematic similarity i.e., the similarity of flow patterns.

Different similarity tests needed to be performed depending upon the flow situation. If the meniscus motion of the water model needs to be dynamically similar to that of the steel caster, Froude (Fr) similarity needs to be satisfied. The Fr-number relates inertial forces to gravitational forces and is the dominant effect in wave motion of free surface flow and is totally unimportant if there is no free surface [White, (1999)].If the SEN jet needs to be captured with water modelling tests, Reynolds (Re) similarity should be satisfied. The Re-number is always important, with or without a free surface, as it relates inertial forces to viscous forces, and can be neglected only in flow regions away from high velocity gradients as solid surfaces, jets or wakes .Another free surface parameter is the Weber (Wb) number. It relates inertia to surface tension. The Wb-number is important only if it is of order unity or less, which typically occurs when the surface curvature is comparable in size to the liquid depth, e.g., in droplets, ripples waves and very small hydraulic systems [White, (1999)].

2.2 Innovative technology and design

Physical model studies of SEN and mould of continuous casting systems have been popular in the past, not only to investigate the hydrodynamic performance of continuous casting SEN and mould, but also to develop new technology. For example, many modifications and improvements associated with SEN and mould operation in the steel industries have been the result of elaborate laboratory scale water model investigations. On the other fronts, water model trials have also been carried out to help, develop new and emerging technologies.

Water models can however not accurately predict the effect of Argon bubbles on steel flow, as the relative difference in density is quite marked. The surface tension of liquid steel also differs significantly from the full scale water model counterparts.

However, since the possibility of numerically solving similar flow situations using CFD techniques with the arrival of powerful enough computers, plant trials are not a necessity during the initial development of continuous casting components. Although complex numerical models can accurately predict the flow of liquid steel in the SEN and mould with more information available than physical plant trials, water modelling is definitely not obsolete. Water modelling is currently used to verify numerical models, to ensure that subsequent solutions of flow fields are believable and a representation of physical flow. Most previous studies utilized water models to verify CFD models before the CFD solutions are accepted as true and accurate.

3. Numerical Modelling

A numerical model is a set of equations, algebraic or differential which may be used to represent and predict certain phenomena. Numerical models for industrial processes are inherently complex and thus if classical mathematics were to be used for solving these equations, there would be little hope of predicting many phenomena of practical interest. Much work has been done regarding SEN design using numerical modelling methods [Huang et al., (1992)], [Bai and Thomas (2001)], [Najjar et al., (1995)], [Thomas, (2003)].

Earlier numerical modelling of the SEN and mould is distinguished from CFD modelling; earlier numerical modelling employed analytical differential equations with macro boundary conditions applicable to very specific SEN and mould problems. These equations are then solved using numerical computational methods developed in the 1970's [White, (1999)]. These methods were extremely tedious and the complex flows are impossible to solve using these early methods.

Little work has been reported on the mathematical modeling of the two phase flow in nozzles, although several studies have been published on two phase flow in the mold [Thomas et al., (1994)] [Bessho et al., (1991)].Works relating to two phase flows in a mould was published by Bessho et al. [Bessho et al., (1990)] who simulated mathematically the influence of argon bubbles in the jets trajectory of steel out of the SEN. Bai and Thomas [Bai and Thomas, (2001)] performed detailed mathematical simulation of two phase flow using Eularian model.

Currently commercially available CFD techniques can be applied to any geometry and any flow situation. Consequently, it is customary to use numerical methods to solve model equations. The finite volume method for incompressible viscous flows is the starting equations for the numerical modeling. The governing equations of flow have been solved numerically adapting the finite difference calculation procedure. The basic governing differential equations used for all CFD software are,

Continuity Equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho U_i) = 0 \tag{1}$$

Momentum Equations

$$\frac{D(\rho U_i)}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left\{\frac{\partial U}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right\} - \overline{\rho u_i u_j}\right] + \rho g + F_\sigma \tag{2}$$

Turbulent kinetic energy Equations

$$\frac{D(\rho k)}{Dt} = D_k + \rho P - \rho \varepsilon \tag{3}$$

Rate of dissipation of k

$$\frac{D(\rho \varepsilon)}{Dt} = D_\varepsilon + C_1 \rho P \frac{\varepsilon}{k} - C_2 \frac{\rho \varepsilon^2}{k} \tag{4}$$

In recent years, decreasing computational costs and increasing power of commercial modeling packages is making it easier to apply numerical models as an additional tool to understand the process of the continuous casting of steel. Numerical modelling has been a reasonable alternative to investigate hydrodynamics of fluid flow phenomena in SEN and mould of Continuous casting system. CFD is a numerical modelling technique that solves the Navier-Stokes equations on a discretised domain of the geometry of interest with the appropriate flow boundary conditions supplied.

The flow of an incompressible fluid is described by the well-known Navier–Stokes equations, which are expressed as follows,

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{\mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right\} \tag{5}$$

Where ρ is the fluid density, u_i is the i^{th} component of the fluid velocity u, t is time, x_j is j spatial coordinates, p is pressure, and μ_{eff} is the effective fluid viscosity.

With the advent of powerful computers and fluid flow modelling software, CFD has become an alternative tool with which to asses different Mould and SEN design. Not only can the thermal effects be incorporated, but also every detail of the flow field becomes available for extracting measure of performance.

To date, many numerical investigations have been reported in the literature on liquid steel flows in widely varying SEN and mould geometries under a wide variety of flow configurations. During casting flow of liquid steel occurs predominantly in the direction parallel to the wide face of the slab cross section [Gupta and Choudhury, (1999)]. Dash et al. [Dash et al., (2004)] first demonstrated the movement of bubble in slab caster mould through a numerical model and could show the surface disturbances matching with that of the experiments of Gupta and Lahiri [Gupta and Lahiri, (1994)]. Vikas Singh et al. [Singh Vikas et al., (2006)] did the physical and numerical modeling work for the bubble movement in the slab caster mould to understand the effect of various parameters.

Consequently, commercial software packages of CFD have been used frequently by researchers in modelling flow. Most previous flow models have used the finite difference method, owing to the availability of very fast and efficient solution methods [Markatos, (1989)]. Popular general purpose codes of this type include Fluent, CFX, Flow 3D, Magmasoft, Phoenics, Physica, Fidap, Cafe and Procast. Of all the commercial software packages Fluent however, has found the widest spread application. Using of commercial software packages for modelling fluid flows ensures considerable time savings. It is for such reasons that commercial routines have been popular and are potentially attractive in numerical modelling studies of SEN and mould system.

Many different models have been employed by different researchers for fluid flow in continuous casting, such as effective viscosity models [Choudhary and Mazumdar, (1994)] [Choudhary and Mazumdar , (1995)] , one equation turbulence models [Szekely and Yadoya ,(1973)], two-equation turbulence models [Thomas et al., (2001)] [Launder and Spalding ,(1974)], LES (Large Eddy Simulation) possibly with a SGS (sub-grid scale) model and DNS (Direction Numerical Simulation)[Szekely and Yadoya ,(1973)] .

Significant work has been done in modeling flow through the nozzle. As early as 1973, Szekely et al. [Szekely and Yadoya, (1973)] modeled the difference between fluid flow in the mold from a straight nozzle and that from a bifurcated nozzle. An extensive investigation of bifurcated nozzle flow was performed by Najjar et al. [Najjar et al., (1995)] who explored the effects of nozzle shape, angle, height, width, ports thickness, bottom geometry, inlet velocity profile, and inlet shape. Bai et al. [Bai and Thomas, (1997), (2000), (2001)] employed an Eulerian approach to investigate two phase flow in the nozzle. They also validated the swirling velocity profile exiting the nozzle by comparing with measurements from Particle Image Velocity (PIV), which has been noted by others [Hershey et al.,(1993)],[Tozaki, (1994)].Most argon gas exits the upper portion of the nozzle port, while the main downward swirling flow contains very little. Gas injection bends the jet angle upward, enhances the turbulence level, and reduces the size of the back flow zone.

The first simulations of fluid flow and heat transfer in a continuous casting mold with a straight nozzle, was carried out by Szekely and coworkers and assumed simple potential flow [Szekely and Stanek ,(1970)] and later used one equation turbulence models [Szekely and Yadoya ,(1973)] [Asai and Szekely,(1975)]. Yao et al. [Yao et al., (1984), (1985)] published the first three dimensional fluid flow simulation results for a rectangle mold and bifurcated nozzle system in 1984. Thomas and coworkers demonstrated the importance of the nozzle inlet conditions on mold flow, including K and ε inlet conditions [Thomas et al., (1990)].Wall laws and the turbulent Prandtl number were also shown to be important [Thomas and Najjar ,(1991)]. Several methods have been employed to measure the fluid flow velocity vectors in continuous casting mold system, including LDV (Laser Doppler Velocimetry) for mold [Iguchi and Kasai, (2000)] [Lan et al., (1997)] and for SEN nozzle [Yokoya et al., (1994)] [Yokoya et al.,(1994)], PIV (Particle Image Velocimetry) , hot wire anemometry [Sussman et al.,(1992)] and propeller flow meters [Andrzejewaski et al.,(1992)] [Bessho et al.,(1990),(1991)].

4. Concluding Remarks

The present review clearly indicates that useful inferences on industrial SEN and mould performance can be made from observations derived from reduced scale water models. Similarly, extensive numerical modeling of fluid flow and validation of numerical model predictions against laboratory, as well as plant scale experimental data, indicate that a reasonably accurate numerical frame work now exists to effectively carry out design and process analysis calculations in continuous casting SEN and mould system. Necessary background on numerical modelling and CFD modelling illustrated the basic principles of using computers to model real engineering flow problems. Furthermore, the importance of engineering insight into any CFD modelling exercise was highlighted.

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