Study of Transient Flow Structures in the Continuous Casting of Steel

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Abstract

Continuous casting is the predominant way by which steel is produced in the world. Continued viability of the high-volume-low-profit-margin steel industry depends upon improved efficiency and consistent quality of the steel production.[1] Plant observations have found that many serious quality problems are directly associated with the flow pattern in the mold [1]. Defects caused by non-optimal fluid flow are even more important to the nearer-net-shape thin-slab casting processes, which are starting to transform the industry [2]. In some previous studies, a limited amount of understanding of this flow region was obtained through numerical simulations in which time-averaged turbulence models were used to represent the effects of turbulence. Such numerical studies have been very valuable, but this approach of modeling turbulence has reached its limits of accuracy. The next step to obtain more reliable predictions of this transient turbulence process is to directly compute the evolution and dynamics of the large-scale turbulence structures. The proposed research is concerned with such computations, using accurate numerical schemes and parallel computers to solve the governing fluid flow equations. We believe the results of this study will be of significant benefit to the steel industry by leading to improvements in design and operating conditions in continuous casting that avoid costly defects.

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[1] Today, US produces around 80 million tons of steel per year. The net cost per ton of scrapping is about $100 per ton. Even if a fraction of one percent of scrap is avoided due to improving the process, the savings is still significant.

1. Introduction:

A schematic of part of the continuous casting process is depicted in Figure 1. Steel flows through the “tundish,” and then it exits down through a ceramic Submerged Entry Nozzle (SEN) and into the mold. Here, the steel freezes against the water-cooled copper walls to form a solid shell, which is continuously withdrawn from the bottom of the mold at a “casting speed” that matches the flow of the incoming metal. The primary reason for submerging the nozzle is to protect the molten steel from re-oxidation as the steel is delivered from the tundish to the mold. Argon gas is injected into the nozzle to help prevent clogging with alumina inclusion deposits. The submerged nozzle also has an important influence on steel quality through its effect on the flow pattern in the mold. The nozzle should deliver steel uniformly into the mold while preventing problems such as surface waves, meniscus freezing, and crack formation.

Unsteady flow features play an important role in the continuous casting of steel, yet have received relatively little attention. Accurate resolution of these flow structures is a must for improved predictions of the physical processes and processing conditions which create defects due to flow maldistribution. Such knowledge can lead to reductions in defects in cast steel, and thus to increased profits to the steel industry. In recent years, with the development of fast computers, it has become possible to significantly improve turbulent flow predictions by resolving the large scales of transient and turbulent flows [3-4]. These simulations, known as Large-Eddy Simulations (LES) lie in-between the approaches of Direct Numerical Simulations (DNS) and the Reynolds-averaged approach. In LES, the dominant, energy containing scales of motion are accurately resolved and the small scales are modeled. The premise of LES is that the small scales of turbulent motion are nearly isotropic and universal across different flows. Therefore, the effects of the small scales can be modeled relatively more accurately compared to modeling all the scales by a single model. In recent years, LES has been successfully applied to several flows and the results have been superior to those obtained from a Reynolds-averaged approach.

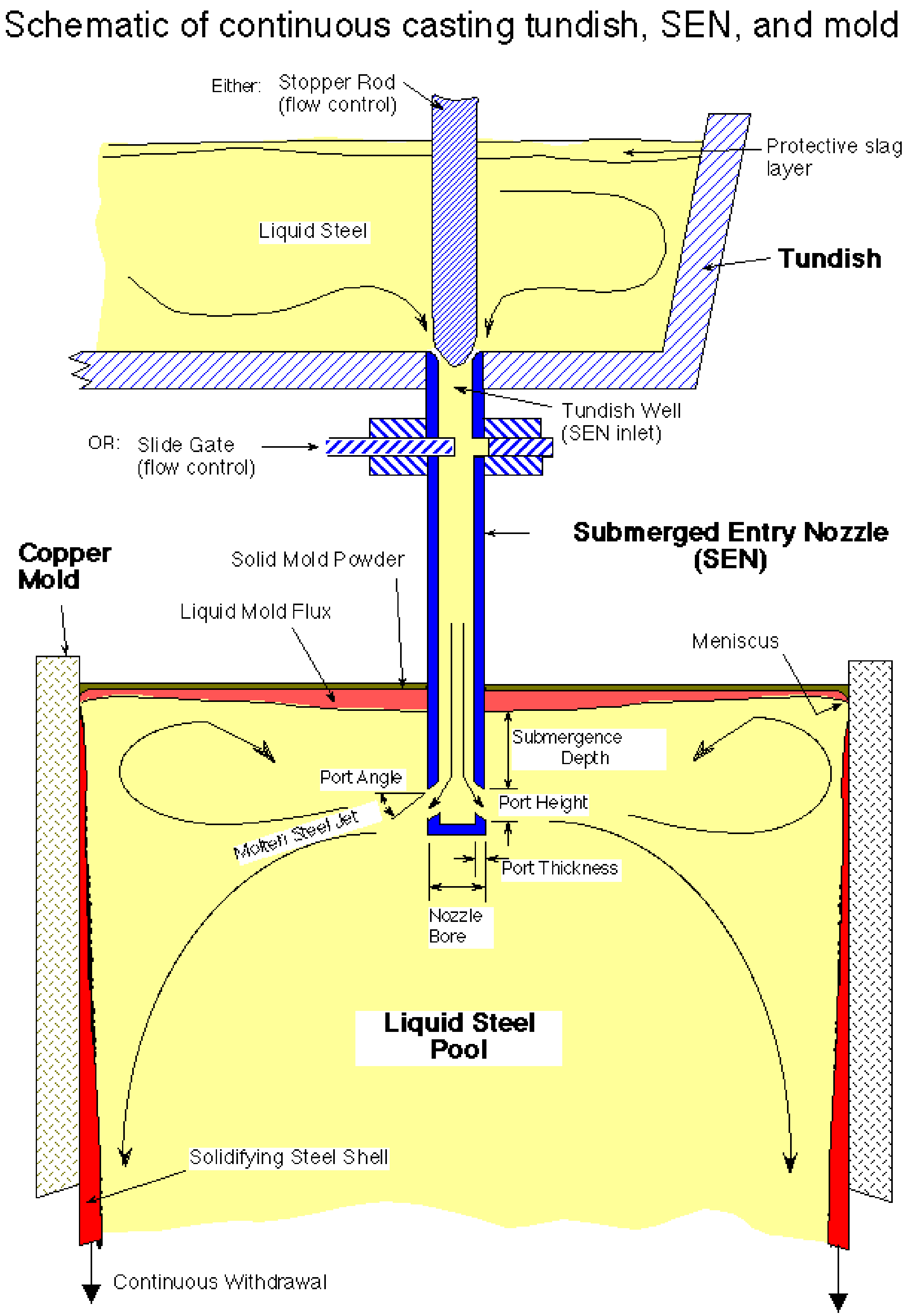

Figure 1. Schematic of tundish and mold region of continuous casting process

2. Technical Approach:

An exact numerical solution of the governing equations with resolution of all appropriate temporal and spatial scales is called a Direct Numerical Simulation (DNS). However, such a simulation requires very large computational resources, and is currently not feasible at the Reynolds numbers encountered in continuous casting of steel. Therefore, in the proposed research, we shall first filter out the small scale turbulent motions and solve the governing equations for the large scale flow field. The effects of the filtered small scales are represented by a sub-grid model which relates the sub-grid scale stresses to the resolved flow field.

A computer program has been developed which integrates the three-dimensional unsteady incompressible Navier-Stokes equations using an explicit fractional step algorithm. Further, in order to take full advantage of parallel computers, the algorithm has been implemented with a general domain decomposition strategy. Each sub-domain of the flow can be calculated separately on an individual processor with data interfacing at the sub-domain boundaries. Advantage is taken of the Message Passing Interface (MPI) standards to ensure portability across a variety of parallel computers, including shared and distributed memory machines.

In conjunction with the proposed modeling work, experiments will be performed to measure the flow fields in water models, as well as in an operating steel caster. In addition to providing additional insight into the flow phenomena, these experiments are even more important to validate the mathematical models, so that subsequent parametric studies can be calculated with confidence. Measurements on physical water models will be obtained at the companies in the continuous casting consortium, which have full-scale water models of their continuous casters. Companies with these facilities include Armco, Inc., LTV Steel, and Inland Steel. Flow will be measured using standard hot-wire anemometry and /or particle image velocimetry (PIV). Although expensive, measurement of time-evolving flow patterns is feasible in a water model.

3. Goals:

Calculations will be performed to study various fluid flow issues relating to the continuous casting process. In particular:

a) Random surface defects arising due to the fluctuations of the surface level will be studied.
b) Entrainment of the liquid mold flux as inclusions will be related to the transverse surface velocity, through empirical relations based on experiments.
c) Parametric studies will be performed to find optimized nozzle geometry and casting conditions that minimize these defects. Particular attention will be paid to transient conditions, such as sudden changes in casting speed, SEN gate position, argon flow, non-uniform flow due to clogging, and other parameters.

4. Results:

This project has just gotten underway. In preliminary work [5-6], a 3-D finite-difference model has been developed of multiphase flow of molten steel in the mold region of a continuous slab caster using the Reynold's averaged approach. Initial calculations revealed the importance of transient phenomena and suggested correlations between the time-averaged model results and quality indicators such as surface level fluctuations and height of the standing wave [5]. Recent steady computations have utilized the commercial CFD program, CFX [6-8]. The predicted flow patterns match quite well with experimental measurements on a full-scale water model, found in the literature [9], as shown in Figures 2-3. The casting conditions for the comparisons are given in Table I, and model inlet conditions have been estimated from previous calculations of nozzles [10-12]. The calculations in Figures 2a) and 3a) show contours of gas fraction in addition to the velocity vectors.

These comparisons demonstrate that different amounts of gas injection can make significant qualitative changes in the flow pattern that can be reproduced by the model. Figure 2 shows that the jet traverses completely across the mold cavity and impinges on the narrow face, before flowing upward and downward. Figure 3 shows that increasing the gas percentage (by slowing down the casting speed for the same gas flow rate), makes the jet bend upward to impinge first on the top surface. This increases the average level of surface turbulence, so may be detrimental. A critical amount of gas appears to be able to make the flow pattern "flip" between the strong surface-directed jet (with high turbulence levels) and the submerged jet (with lower surface turbulence levels).

The corresponding heat transfer model appears unable to match experimental measurements unless a special user-subroutine is written that changes the heat extraction function along the wall. This will be the subject of further study.

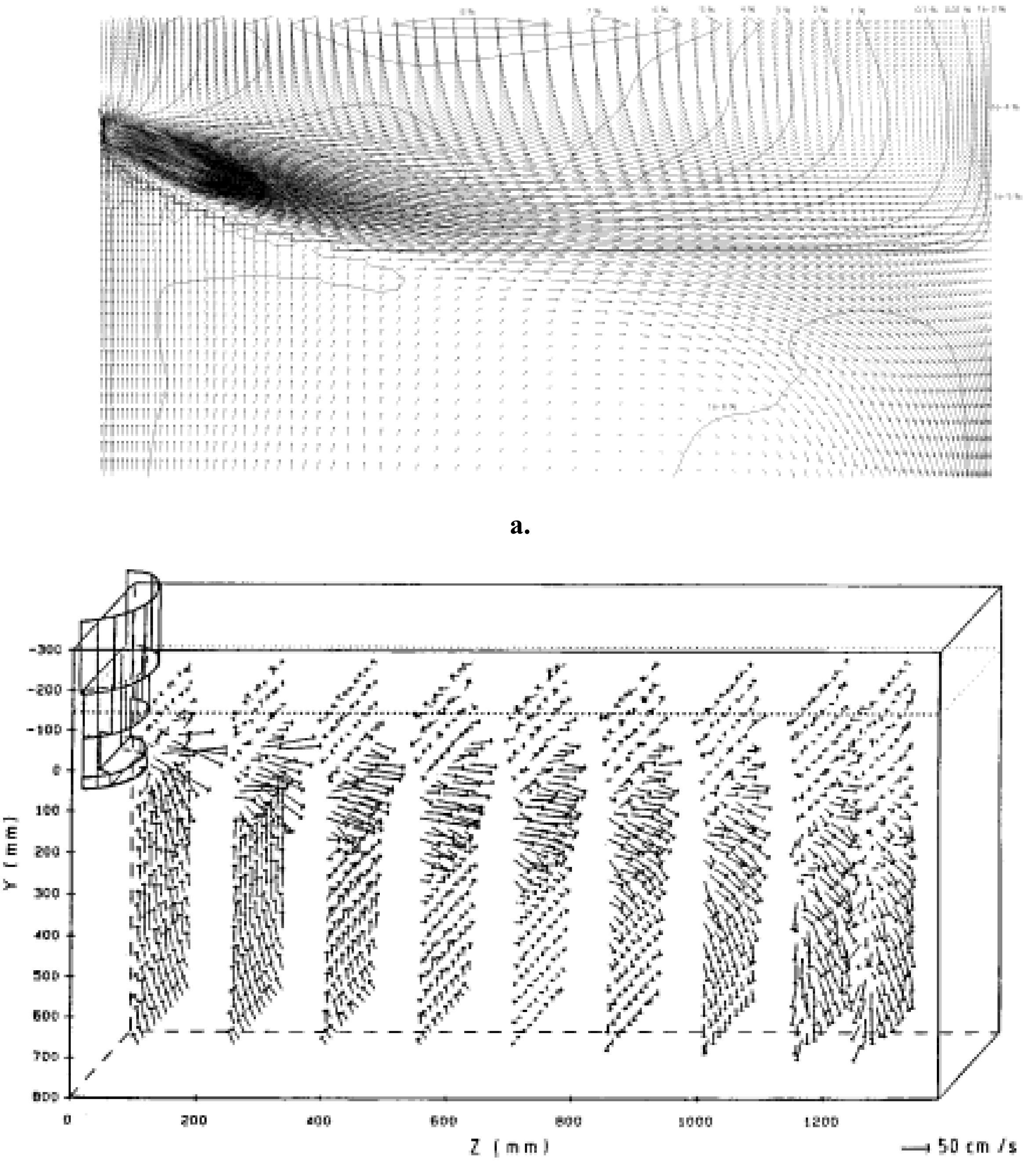

Fig. 2. Comparison of velocity profiles in continuous casting mold wideface for Case 1 conditions, a) predicted by current CFX model, and
b) measured in a water model [Fig. 6 in Ref. 9]

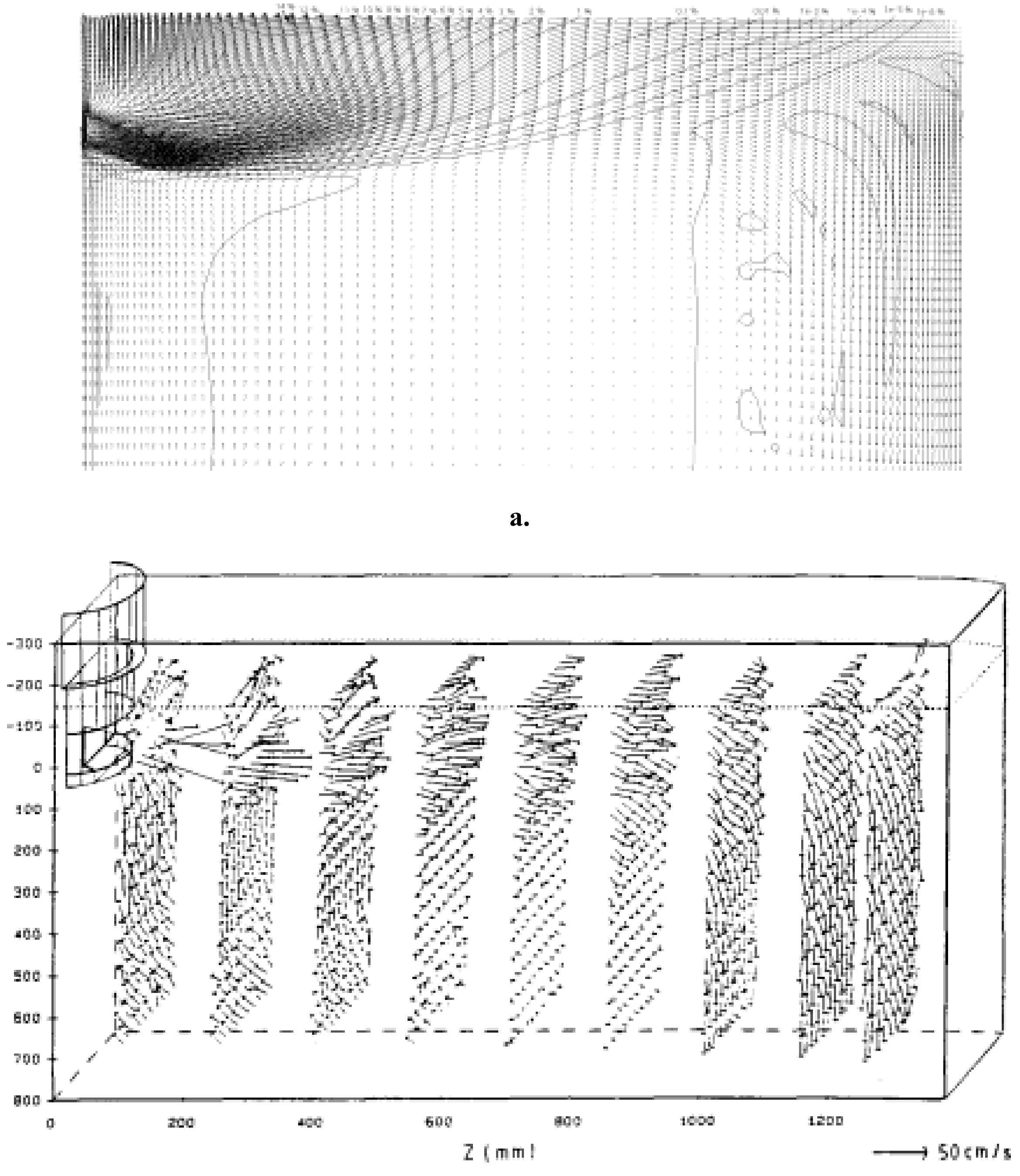

Fig. 3. Comparison of velocity profiles in continuous casting mold wideface for Case 2 conditions, a) predicted by current CFX model, and
b) measured in a water model [Fig. 7 in Ref. 9]

Table I Casting Conditions

Parameters	Case 1	Case 2†
Mold thickness	220 mm	
Mold width	2765 mm	
SEN submergence depth (top surface to top of port)	100 mm	
Nozzle bore inner diameter	85 mm	
Port wall thickness	27 mm	
Nozzle port height	95 mm	
Nozzle port width	75 mm	
Inlet jet height	38 mm	
Inlet jet width	75 mm	
Nominal vertical angle of port edges	15 ° down	
Inlet jet vertical angle	25 ° down	
Inlet jet spread angle	0°	
Gas bubble size	1 mm	
Inlet gas volume flow rate, Q_g	5.0x10^{-4} m^{3}/s (30 SLM)	
Inlet volume fraction of gas bubbles	4.0%	7.7%
Volumetric steel flow rate	110 x10^{-4} m^{3}/s	60 x10^{-4} m^{3}/s
Casting speed	18.1 mm/s (1.1 m/min)	9.9 mm/s (0.6 m/min)
Inlet turbulent kinetic energy	0.0502 m^{2}/s^{2}	
Inlet turbulence dissipation rate	0.457 m^{2}/s^{3}	
Liquid steel laminar viscosity	0.0055 kg/s-m	
Liquid steel density	7020 kg/m^{3}	
Top surface flux coverage	none	

† Unlisted values are the same as Case 1.

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