

## Study of Transient Flow Structures in the Continuous Casting of Steel

S.P. Vanka and B.G. Thomas

University of Illinois at Urbana-Champaign  
Mechanical and Industrial Engineering.  
1206 West Green Street, Urbana, IL 61801  
Ph: 217-244-8388, 217-333-6919; Fax: 217-244-6534;  
Email: s-vanka@uiuc.edu, bgthomas@uiuc.edu

### Abstract:

In continuous casting of steel, plant observations have found that many serious quality problems are directly associated with the flow pattern in the mold. Previous studies have generated understanding mainly through numerical simulations using time-averaged turbulence models. However, many problems are intermittent and the essential transient nature of the flow may be important to their formation. To obtain further understanding of these important transient turbulence processes, this project aims to directly compute the evolution and dynamics of the large scale turbulence structures. Accurate numerical schemes and parallel computers are being applied to solve the governing fluid flow equations using a Large-Eddy Simulation (LES) approach. Computations are also performed using traditional  $k-\epsilon$  models in order to evaluate their accuracy and to examine more cases. The ultimate goal is to generate deeper understanding of how costly defects form and to find improvements in design and operating conditions that can avoid them.

### Introduction:

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. Steel scrapped due

to defects is both costly and wasteful of energy.<sup>1</sup> Plant observations have found that many serious quality problems are directly associated with the flow pattern in the mold<sup>[1]</sup>. 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<sup>[2]</sup>. Some understanding of this flow region can be obtained through numerical simulations which use time-averaged turbulence models. The next step to obtain deeper insight into the transient turbulent aspects of this process is to directly compute the evolution and dynamics of the large-scale turbulence structures. The current research is concerned with such computations, using accurate numerical schemes and parallel computers to solve the governing fluid flow equations.

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-

---

<sup>1</sup> 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.

# Schematic of continuous casting tundish, SEN, and mold

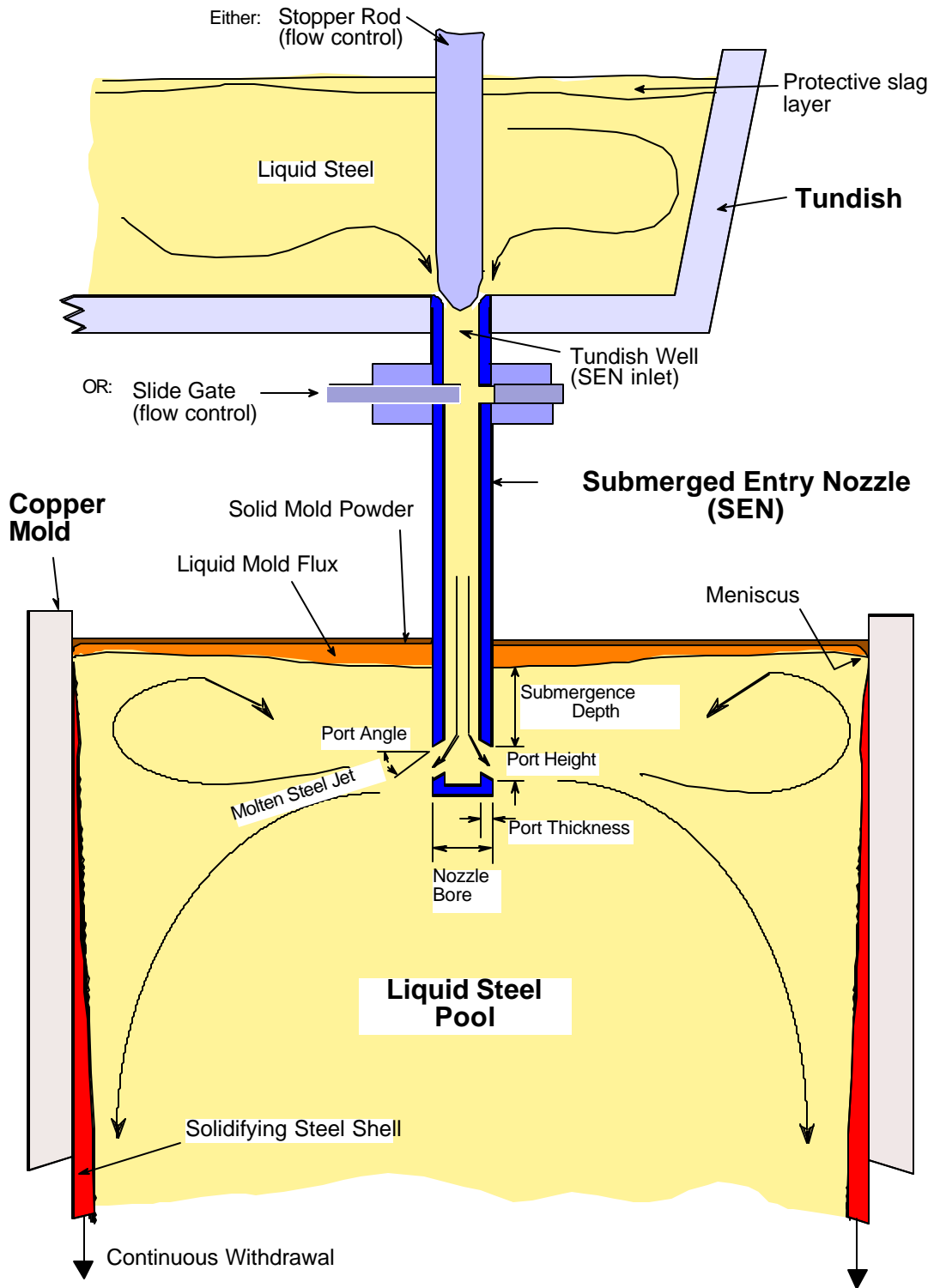


Figure 1. Schematic of tundish and mold region of continuous casting process.

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. Mold powder is added to the top of the liquid steel, which melts to form an insulating liquid slag layer that encourages uniform solidification at the meniscus.

Unsteady flow features play an important role in the continuous casting of steel, yet have received relatively little attention. 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<sup>[3, 4]</sup>.

The present paper presents recent results of flow and heat transfer for five different parts of this project:

- 1) Two-phase flow in tundish nozzles
- 2) Effect of argon gas bubble distribution on flow in the mold
- 3) Flow and transfer in liquid slag layers
- 4) Transient flow in a 0.4 scale water model
- 5) Transient flow in a full scale water model
- 6) Particle transport in a full scale water model

### **Technical Approach:**

Three different computational models of fluid flow are used in this work.

Firstly, the Reynolds-averaged approach was used to simulate the three-dimensional time-averaged two-phase flow and heat transfer fields in both the nozzle and mold regions. These models were developed using the k- $\epsilon$  turbulence model in the commercial package CFX for turbulent flows.

Secondly, Large-Eddy Simulation models of transient flow in the nozzle and mold have been developed. 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.

The computer program, LES3D, 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.

Thirdly, the coupled laminar Navier-Stokes and heat transport equations are solved in the viscous liquid slag layers using the commercial finite element code, FIDAP.

In conjunction with the modeling work, experiments are being 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 both physical water models and in operating continuous casting in the plant have been obtained at several of the co-sponsoring steel companies, including AK Steel, and LTV Steel.

### **Results:**

The rest of this paper presents a brief overview of six parts of the project, focussing on recent results with the LES flow model to simulate three different transient flow phenomena in water models.

### **Two-Phase Flow in Tundish Nozzles:**

The tundish nozzle has an important influence on steel quality through its effect on the flow pattern in the mold. Argon is commonly injected into the tundish nozzle to avoid nozzle clogging. It also affects casting operation and product quality by changing the flow pattern in the nozzle and mold. In this part of the project, a three-dimensional finite difference model has been applied to model the multi-phase, steady-state turbulent flow in continuous casting tundish nozzles under a wide range of geometries and conditions.

The model has been validated through comparison with PIV experiments in water models and flow rate measurements in operating casters [5, 6]. Extensive parametric studies using the validated model have been

performed to investigate the effects of many different variables on the flow pattern. This work is reported in two pending publications [7, 8].

Finally, the nozzle model was used to predict the occurrence of negative pressure in the nozzle, which may lead to air aspiration and reoxidation, which causes nozzle clogging and detrimental large inclusions in the final product. Clogging can be detected by comparing the measured flow rate in the plant with the flow rate predicted by the model. The minimum argon levels required to avoid this problem are summarized and operating conditions to minimize the negative pressure phenomenon are presented [6, 9, 10].

### **Effect of argon gas bubble distribution on flow in the mold:**

Argon gas, which is commonly injected into the tundish nozzle, has a great effect on flow in the mold and associated defects. To investigate the effect of argon gas flow on flow in the mold, a parametric study was first conducted with air in a water model to measure the initial size of the bubbles that form when gas is injected through the nozzle walls [6, 11]. A simple mathematical model was developed to predict the measured results and was then applied to predict the size of argon gas bubbles in steel [6]. The bubble size distributions are also measured. Using the results of this study, argon gas bubbles with multiple sizes are injected mathematically into a multiphase 3-D model of flow in the mold, using the multiphase, multifluid model in CFX. The results are compared with measurements both in water models and in operating casters [12].

### **Flow and heat transfer in liquid slag layers:**

The thickness of the molten slag layer which floats on top of the liquid pool is very influential on steel quality. As a first step towards

predicting this important quantity under transient flow conditions which cause defects, a steady-state model was developed of flow and heat transfer within the slag layer. The flow is driven by transverse flow of molten steel across the bottom of the long, thin domain and by natural convection. After validating the model, it is applied in a parametric study to present the heat transfer across the layer (which governs the layer thickness) as a function of steel surface velocity and slag properties <sup>[13]</sup>. These results will be extended and incorporated into future applications of the other models.

### **Transient Flow in a 0.4 Scale Model:**

Transient fluctuations in the flow in the mold can cause defects in several ways. As a first step to the prediction of these complex phenomena for this project, computations of the unsteady flow in a 0.4 scale water model were conducted <sup>[14]</sup>, and the results were compared with the PIV data taken at LTV Steel <sup>[15]</sup>. Two simulations with different inlet conditions were performed in this study. In the first computation, the inlet flow was steady and uniform over the nozzle cross-section. In the other, the inlet velocities were prescribed from an unsteady computation of flow in a turbulent square duct. The second inlet condition was more realistic of the two, but when compared with the actual PIV flow exiting the nozzle in the water model, several features were missing. First, the distribution at the exit of the nozzle was non-uniform because of the several upstream effects starting at the gate valve in the pipe feeding the submerged nozzle. Second, the exit flow had a swirl, again due to the upstream effects. Neglect of both of these features in the two computations mentioned above led to several discrepancies in the flow field in the mold region. Specifically, the point of impingement of the jet was different in PIV and the LES computations. This led to

several differences in the measured and computed velocities at various locations.

Consequently, a new computation was performed with a more realistic inlet flow field. In this computation, the inlet velocities were generated in three different steps. First, a turbulent pipe flow calculation with a partially blocked inlet was performed for a length of 0.437 meters, to incorporate the effect of the slide gate. This was then truncated at 0.312 meters, and the exit flow was fed to a rectangular duct of 0.031m x 0.027m cross-section, representing the bottom of the nozzle. The velocities developed in this duct were also truncated at a location 0.011m from the inlet (corresponding to the thickness of the nozzle) and rotated to provide a mean inclination of 30 degrees with the horizontal. The unsteady velocity field so constructed was then supplied as inlet to the mold region. Figures 2 - 5 show a comparison of the PIV velocity field exiting the nozzle, and the presently prescribed flow field. Computations were then performed for a grid exactly as in <sup>[14]</sup>, and the results were compared with the PIV measurements in <sup>[15]</sup>. Figure 6 first shows an instantaneous vector plot of the flow field at the center plane, and compares it with the PIV data. Compared with the results obtained with a turbulent duct flow, the comparisons are better, with the jet deflected more as in the PIV experiments. Figure 7 shows a time-averaged flow field, and compares it with the PIV time-averaged flow field. Compared with previous computations, the present results are in better agreement with experiments. Figure 8 provides a comparison of velocities along the top surface. The agreement is better than before, illustrating the importance of the inlet conditions to both the steady and transient flow phenomena and the related formation of defects.

### **Transient Flow in a Full Scale Model:**

The next computation performed in the current year is of the flow in a full-scale water model for which experiments were performed at AK Steel in 1992 <sup>[16]</sup>. In this experiment, solid spheres lighter than water were used to study transport of particles in the mold region. The spherical particles were sized and selected to mimic the motion of alumina inclusions that exit the nozzle in a real caster. Details of the geometry, and the particle sizes are given in Figure 9 and Table 1. The outlets to the domain were represented as rectangular ports, as shown in Figure 9. The inlet conditions to this flow were still prescribed from a fully developed pipe flow and the more sophisticated construction of inlet conditions described above has not yet been attempted.

The present simulations have been performed with a considerably fine grid consisting of 128 x 169 x 64 nodes in the x, y and z directions shown in the Figure 9. These resolutions were dictated by what could be achieved in a reasonable overall computation time. Finer resolutions are necessary in the thermal boundary layer for heat transfer calculations. The Smagorinsky model is used to represent the effects of the unresolved scales. The time-dependent equations are integrated for 62,500 time steps (47.5 seconds of real time). After a stationary state of turbulence is achieved, mean and fluctuation statistics have been collected for comparison with experimental data.

Figure 10(a) shows one representative instantaneous plot of the velocity field. The flow field is similar to that observed in the 0.4 scale model, although some minor differences exist because of the different flow rates and the geometrical dimensions. Comparisons of selected time-averaged velocity profiles with experimental data are given in Figure 11. The agreement is satisfactory.

### **Particle Transport:**

The inclusions exiting the submerged nozzle may either float to the top surface and get entrained into the slag layer, or may be trapped in the solidifying front, leading to defects such as internal cracks and slivers in the final rolled product. Determining where these inclusions will finally end up is therefore quite important. AK Steel Company previously conducted experiments of particle transport in a water model. The particle density and size were selected to scale with alumina inclusions in an actual steel cater. The density of the particles was 988 kg/m<sup>3</sup>, with the water density being 1000 kg/m<sup>3</sup>. Their size was 3.8mm diameter, which has the same drag as a 300-micron spherical alumina inclusion in steel. A total of fifteen thousand particles were injected and the percentage of particles reaching the top surface was determined by capturing them with a screen placed close to the surface. Measurements after 10, 100 and 300 seconds were made.

In the LES calculations, particles were injected at the inlet after the turbulent flow reached a stationary state. The fifteen thousand particles were injected over a time interval of 1.6 seconds. Currently, the simulations are done only for 30 seconds. Hence comparisons of particle distributions could be made only for the first ten seconds. Figure 10 (b) shows the particle distribution after 10 seconds. The experiments indicate that 22.3 percent of particles are trapped by a screen which is placed close to the upper surface. Similar estimates from the simulations give a value of 26.96 percent. Considering the approximate nature of the experiments, and uncertainties in the computations, this agreement appears to be quite good.

### **Future work:**

There are still many unresolved issues to be studied in this project. It is observed in the water model that the flow in the mold region is

not symmetric about the center plane. To simulate such an asymmetry, it is necessary to simulate the nozzle walls. Our current computer program, which uses a fast direct solver for the pressure equation, cannot handle such obstructions. To implement the nozzle wall, it is necessary to use a different, slower, approach to solve the pressure equation. We will in future consider this feature. Also, we are in a position to simulate the actual steel plant conditions and study the flow structures that may be a better representative of the structures in the actual manufacturing process. Finally, it is necessary to include the geometry upstream of the nozzle so that we can get more realistic inlet conditions as an integral part of the simulations. This will require further extensions to the computer program currently used.

their validation with water model experiments. This work is just part of this NSF project to gain insight and solve problems of relevance to improving the continuous casting process. Other work on this project in the past year has studied multiphase flow through the nozzle, <sup>[6]</sup> fluid flow and heat transfer across the molten flux layer <sup>[13]</sup>, and the effect of realistic argon bubble size distributions on the flow pattern and the associated defects <sup>[12]</sup>. When combined with other related ongoing projects to investigate interface heat transfer, <sup>[12, 17]</sup> shell solidification <sup>[18]</sup> and strength for breakout prediction, <sup>[19]</sup> micro-segregation modeling for crack prediction, <sup>[12]</sup> and bulging analysis for strand width control, <sup>[20]</sup> this work is making a significant impact on improving continuous casting technology.

**Summary:**

The present paper focuses on recent results using 3-D transient fluid flow models and

Table 1. Conditions for the full-scale water model simulation.

Symbol	Parameter	Value
<b>L</b>	Domain Length	2.152m
<b>W</b>	Domain Width	0.965m
<b>N</b>	Domain Thickness	0.238m
<b>L<sub>n</sub></b>	SEN Submerged Depth	0.15m
<b>a</b>	Averaged Jet Angle	25° down
<b>V<sub>inlet</sub></b>	Averaged Inlet Velocity	1.69m/s
<b>V<sub>casting</sub></b>	Simulated Casting Speed	0.0152m/s
<b>n</b>	Laminar Kinematic Viscosity	1.0×10 <sup>-6</sup> m <sup>2</sup> /s
<b>r</b>	Liquid Density	1000kg/m <sup>3</sup>
<b>r<sub>p</sub></b>	Particle Material Density	988kg/m <sup>3</sup>
<b>d<sub>p</sub></b>	Particle's Diameter	3.8mm

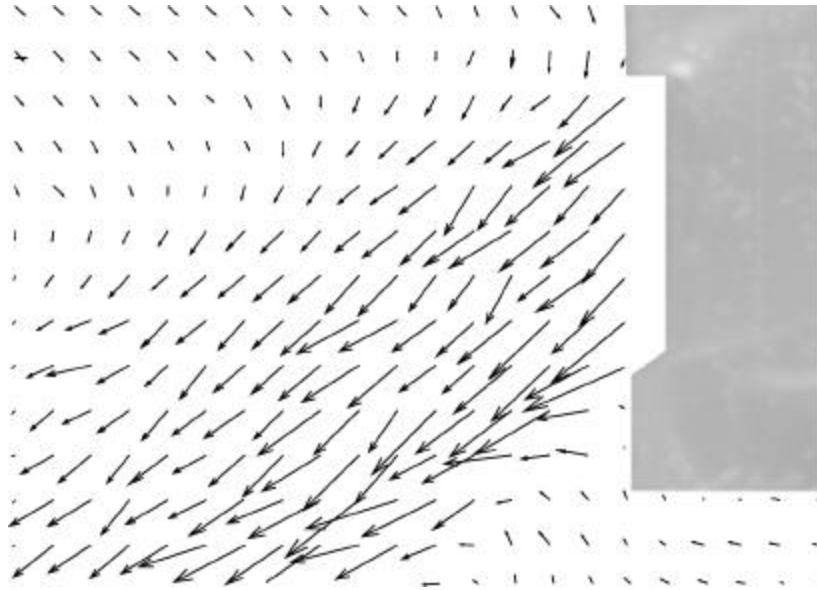


Figure 2. PIV measured fluid velocity near the nozzle port.

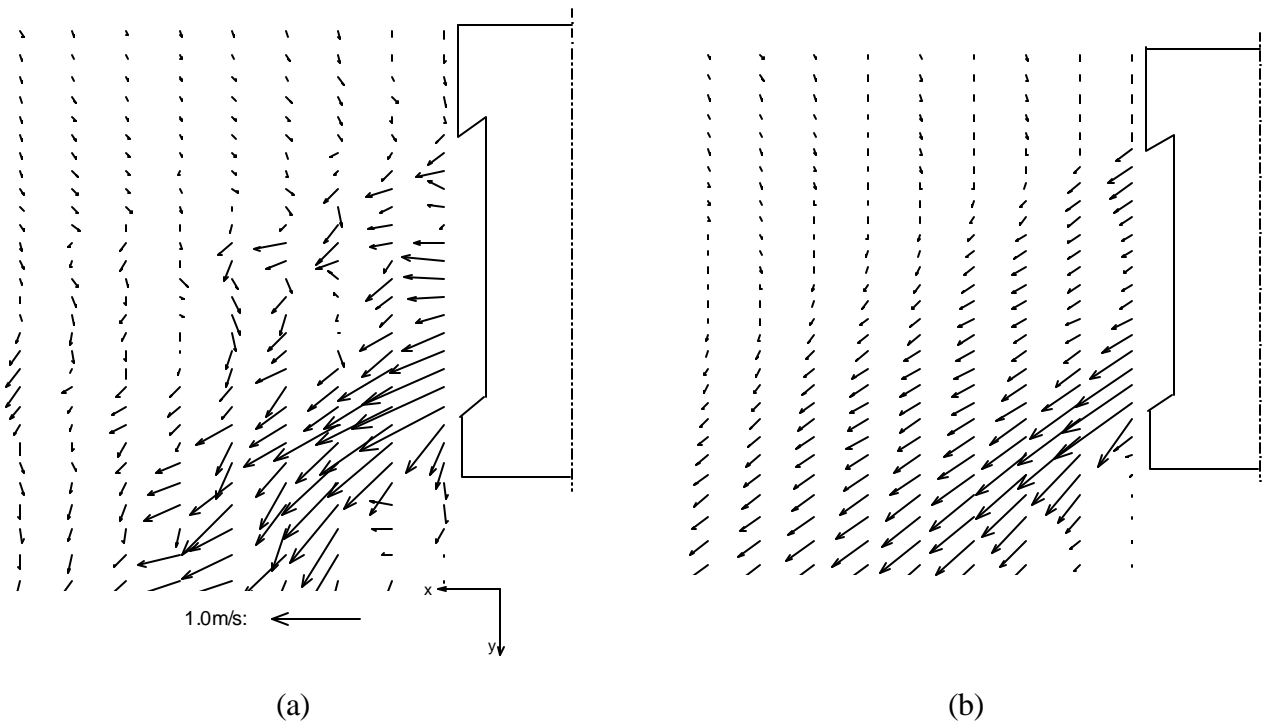


Figure 3. Fluid flow near the inlet port in LES simulation: (a) instantaneous and (b) time averaged vector plot.



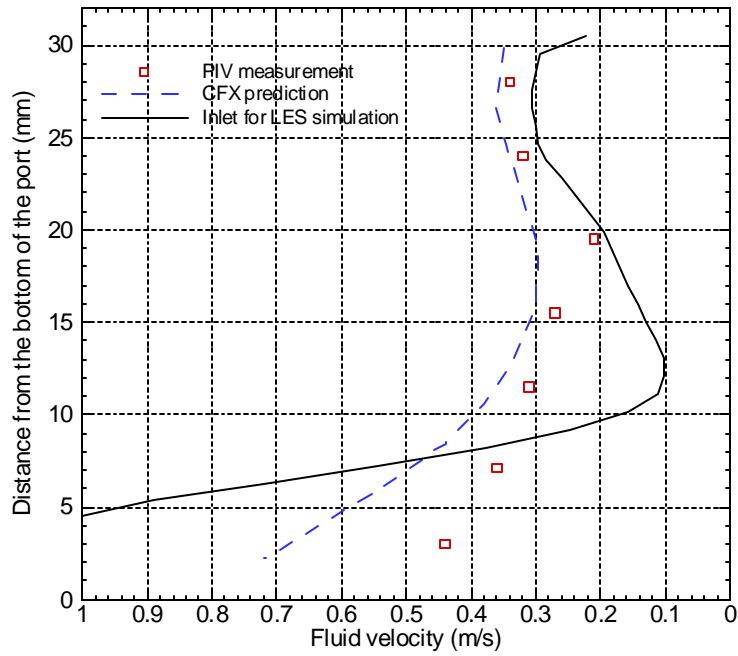


Figure 4. Comparison of inlet velocity  $(u^2+v^2)^{1/2}$  along the centerline of the inlet port.

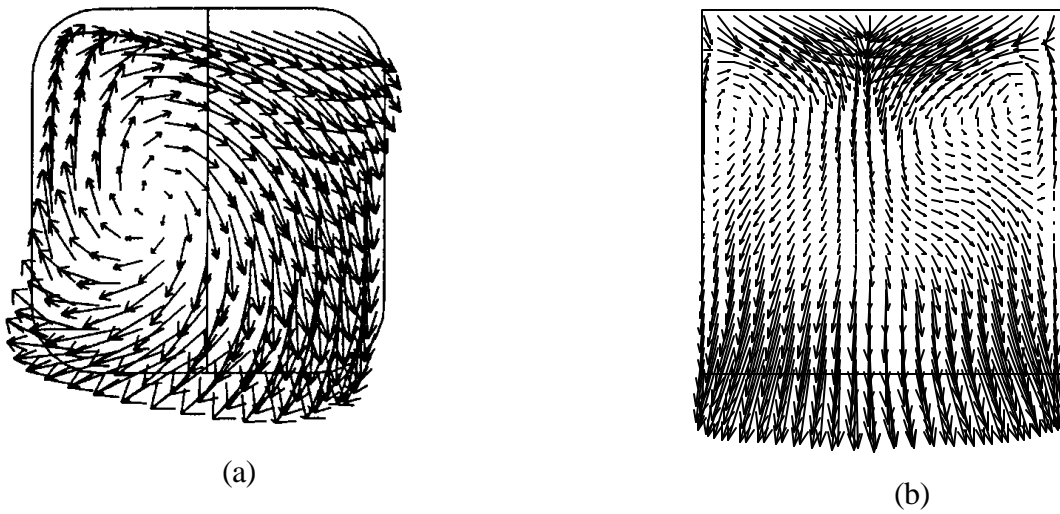


Figure 5. Comparison of inlet flow pattern of 0.4 water model: (a) CFX prediction; (b) inlet used in the LES simulation.

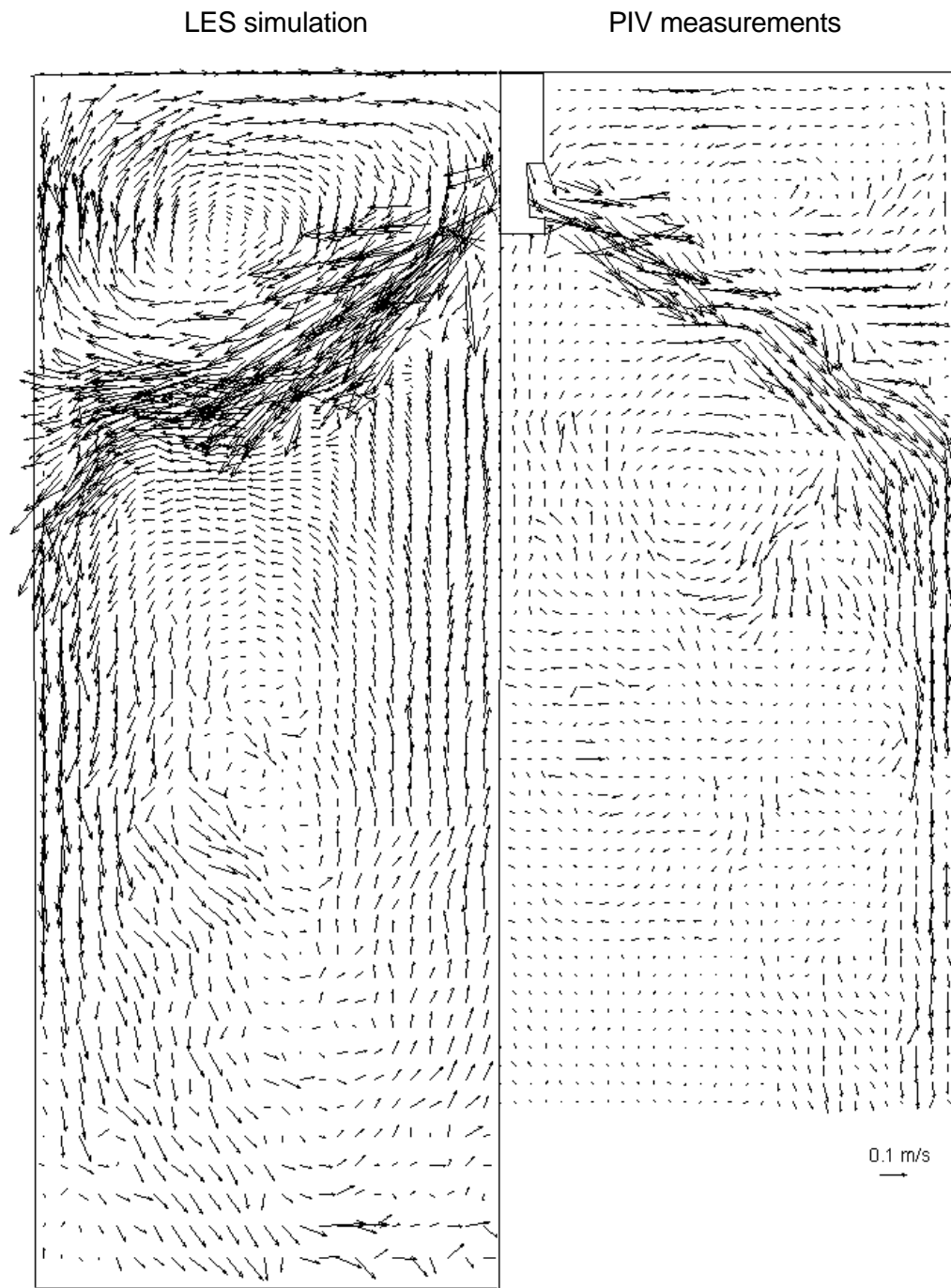


Figure 6. Comparison of instantaneous velocity between LES simulation and PIV measurements.

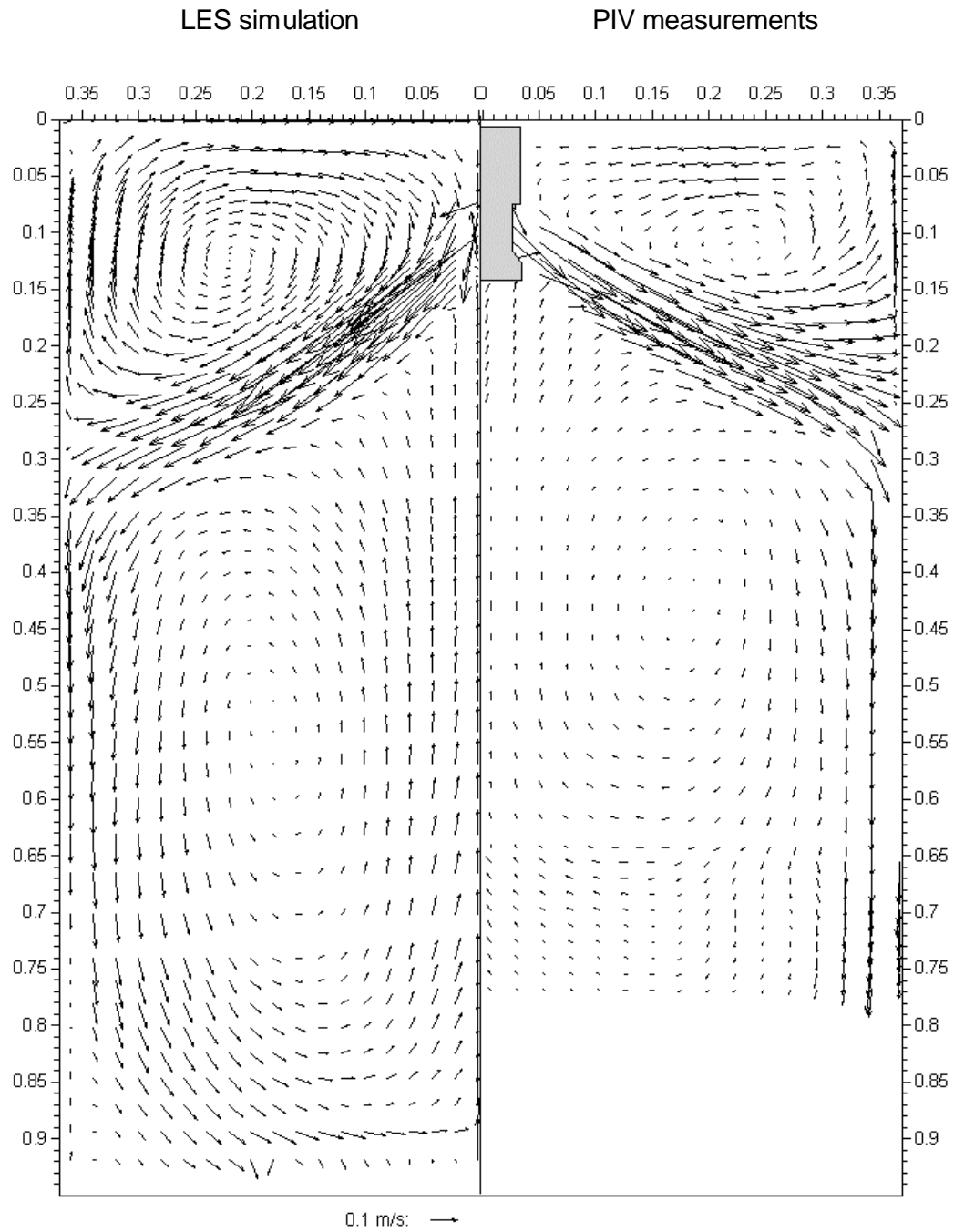


Figure 7. Comparison of time averaged velocity between LES simulation and PIV measurements.

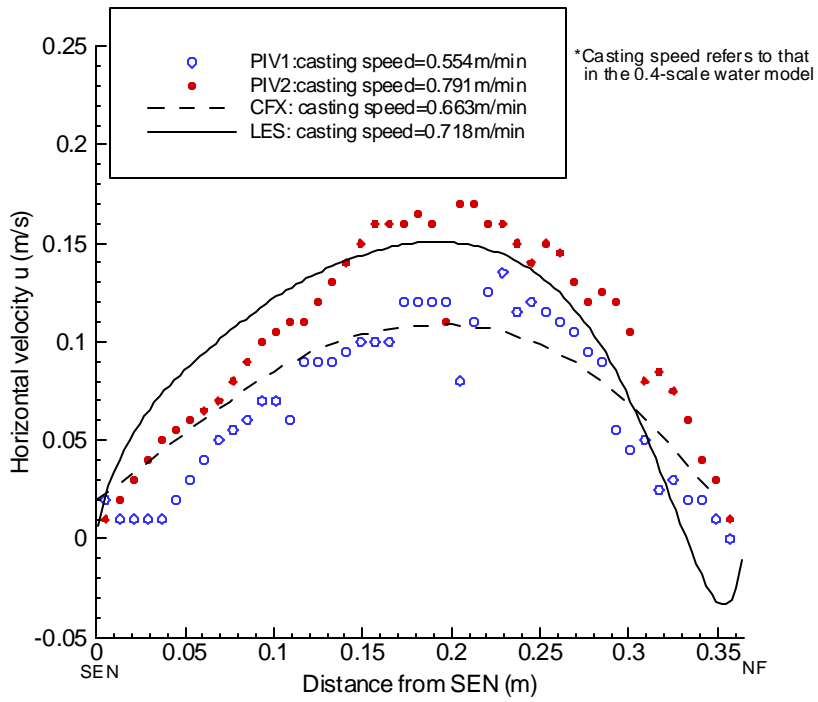


Figure 8. Horizontal fluid velocity variation along the top surface at the center plane.

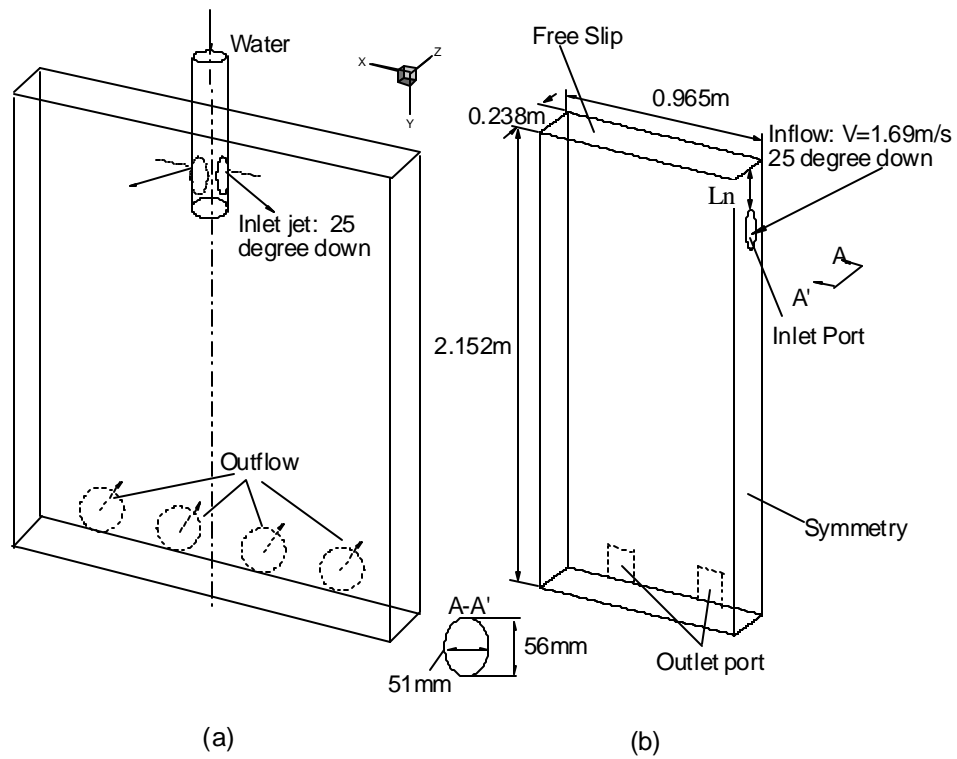


Figure 9. Sketch of the full-scale water model and numerical simulation domain.

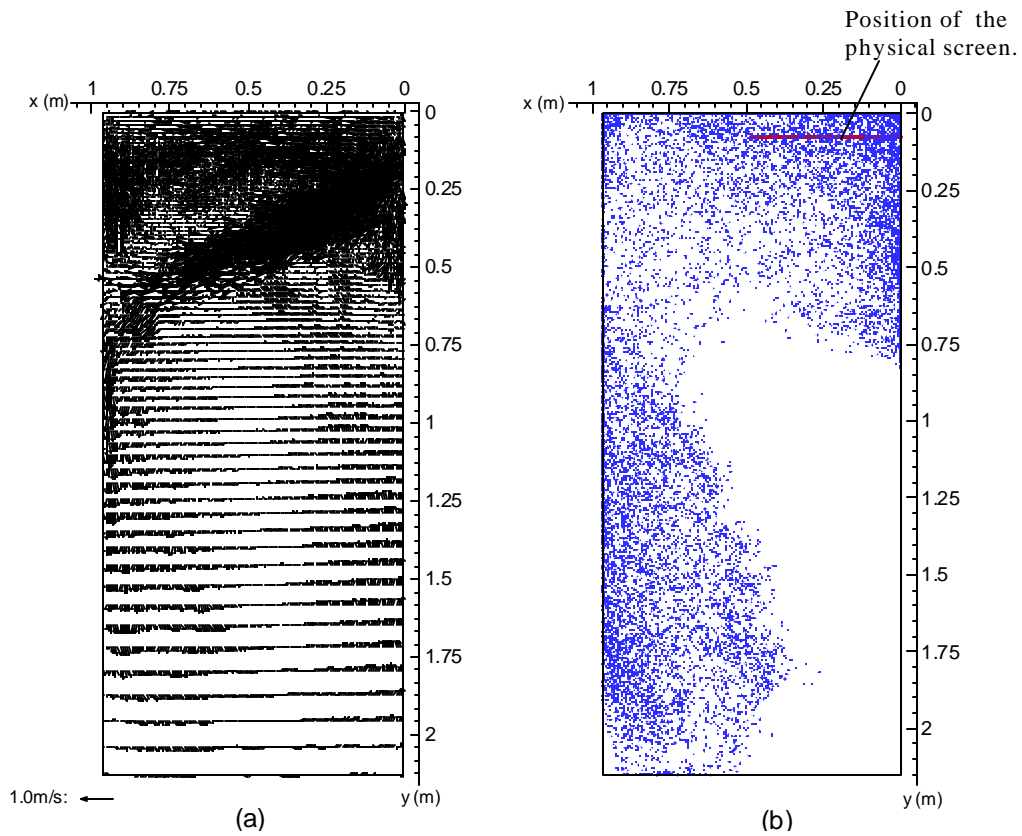


Figure 10. LES prediction of (a) instantaneous fluid velocity and (b) particle distribution at 10s.

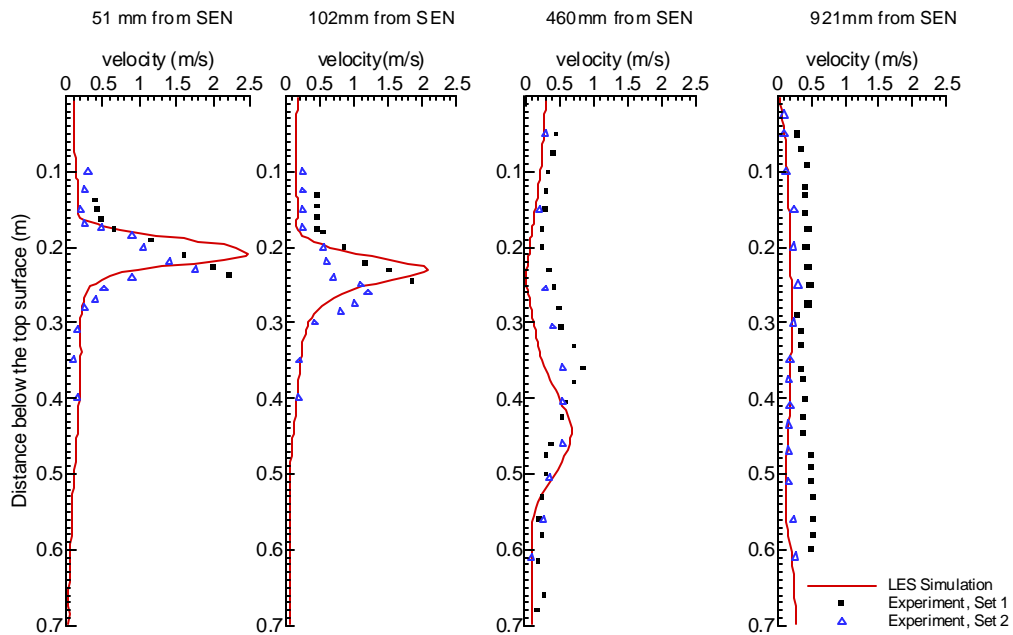


Figure 11. Comparison of fluid velocity variation along the center plane below the top surface.

## References:

1. J. Herbertson, Q.L. He, P.J. Flint, R.B. Mahapatra, "Modelling of Metal Delivery to Continuous Casting Moulds," in Steelmaking Conf. Proceedings, 74, (ISS, Warrendale, PA, 1991), 171-185.
2. T. Honeyands and J. Herbertson, "Flow Dynamics in Thin Slab Caster Moulds," Steel Research, 66 (7) (1995), 287-293.
3. R. Rogallo and P. Moin, "Numerical Simulation of Turbulent Flows," Ann. Rev. Fluid Mechanics, 16 (1984), 99.
4. X. Huang and B.G. Thomas, "Modeling of Transient Flow Phenomena in Continuous Casting of Steel," Candian Metallurgical Quarterly, 37 (304) (1998), 197-212.
5. H. Bai and B.G. Thomas, "Two-Phase Flow in Tundish Nozzles During Continuous Casting of Steel," in Materials Processing in the Computer Age, 3, V. Voller and H. Heinein, eds., (TMS, Warrendale, PA, 2000), 85-99.
6. H. Bai, "Argon Bubble Behavior in Slide-Gate Tundish Nozzles During Continuous Casting of Steel Slabs" (PhD Thesis, University of Illinois, 2000).
7. H. Bai and B.G. Thomas, "Turbulent Flow of Liquid Steel and Argon Bubbles in Slide-Gate Tundish Nozzles, Part I, Model Development and Validation," Metal. & Material Trans. B. (2000), under review.
8. H. Bai and B.G. Thomas, "Turbulent Flow of Liquid Steel and Argon Bubbles in Slide-Gate Tundish Nozzles, Part II, Effect of Operation Conditions and Nozzle Design," Metal. & Material Trans. B. (2000), under review.
9. H. Bai and B.G. Thomas, "Effect of Clogging, Argon Injection, and Casting Conditions on Flow Rate and Air Aspiration in Submerged Entry Nozzles Steel," in 83rd Steelmaking Conference Proceedings, 83, (Pittsburgh, PA, March 2-29, 2000: ISS, Warrendale, PA, 2000), 183-197.
10. H. Bai and B.G. Thomas, "Effects of Clogging, Argon Injection and Continuous Casting Conditions on Flow and Air Aspiration in Submerged Entry Nozzles," Metal. & Material Trans. B. (2000), under review.
11. H. Bai and B.G. Thomas, "Bubble Formation during Horizontal Gas Injection into Downward Flowing Liquid," Metal. & Material Trans. B. (2000), under review.
12. B.G. Thomas, "Mathematical Models of Continuous Casting of Steel Slabs" (Report, Continuous Casting Consortium, University of Illinois at Urbana-Champaign, 2000).
13. S. Sivaramakrishnan, "Transient Fluid Flow in the Mold and Heat Transfer Through the Molten Slag Layer in Continuous Casting of Steel" (M.S. Thesis, University of Illinois, 2000).
14. S. Sivaramakrishnan, B.G. Thomas and P. Vanka, "Transient Flow Structures in Continuous Cast Steel," in Materials Processing in the Computer Age, V. Voller and H. Heinein, eds., (Nashville, TN: TMS, Warrendale, PA, 2000), 189-198.
15. S. Sivaramakrishnan, H. Bai, B.G. Thomas, P. Vanka, P. Dauby, M. Assar, "Transient Flow Structures in Continuous Cast Steel," in Ironmaking Conference Proceedings, 59, (Pittsburgh, PA: ISS, Warrendale, PA, 2000), 541-557.
16. R.C. Sussman, M. Burns, X. Huang, B.G. Thomas, "Inclusion Particle Behavior in a Continuous Slab Casting Mold" (Paper presented at 10th Process Technology Conference, Toronto, Canada, Iron and Steel Society), 10, 1992, 291-304.
17. D. Stone, "Mathematical Modeling of Interfacial Heat Transfer in the Continuous Slab Casting Process" (M.S. Thesis, University of Illinois, 2000).
18. B.G. Thomas, R. O'Malley, T. Shi, Y. Meng, D. Creech, D. Stone, "Validation of Fluid Flow and Solidification Simulation of a Continuous Thin Slab Caster," in Modeling of Casting, Welding, and Advanced Solidification Processes, IX, (Aachen, Germany, August 20-25, 2000: Shaker Verlag GmbH, Aachen, Germany, 2000), 769-776.
19. C. Li and B.G. Thomas, "Analysis of the Potential Productivity of Continuous Cast Molds" (Paper presented at Brimacombe Memorial Symposium, Vancouver, Canada, Canadian Inst. Min. Metall., Montreal, Canada), 2000, 17p.
20. L. Yu, "Bulging in Continuous Cast Steel Slabs" (M.S. Thesis, University of Illinois, 2000).

**Acknowledgments:** The authors wish to thank students Quan Yuan and Sivaramakrishnan for results referred to in this paper and for help with preparation of figures. Funding from the National Science Foundation (Grant # DMI9800274) and the Continuous Casting Consortium (Allegheny Ludlum Steel, Brackenridge, PA; Armco, Inc., Middletown, OH; Columbus Stainless Steel, Middelburg, South Africa; Inland Steel Co., East Chicago, IN; LTV Steel Co., Cleveland, OH; and Stollberg Inc., Niagara Falls, New York) is gratefully acknowledged. Finally, thanks are extended to the National Center for Supercomputing Applications at the University of Illinois for computing time and use of the CFX code.