Yuan, Quan, S.P. Vanka and Brian G. Thomas, 3rd International Symposium on Turbulence and Shear Flow Phenomena, Sendai, Japan, 25-27 June, 2003, Conference Proceedings, Vol. 2, pp.681-686, 2003.

Large Eddy Simulations of Transient Turbulent Flow During Continuous Slab Casting of Steel

Quan Yuan, S.P. Vanka and B.G. Thomas
Department of Mechanical Engineering, University of Illinois at Urbana-Champaign
1206 W. Green St., Urbana, IL, USA, 61801
Email: quanyuan@uiuc.edu; s-vanka@uiuc.edu; bgthomas@uiuc.edu

The quality of continuous cast steel is greatly affected by the turbulent flow in the mold region, especially for transient operation and transport of inclusion particles. During the continuous casting process, shown in Figure 1, the superheated molten steel flows into the mold region from the tundish through the nozzle ports. The molten steel freezes against the water-cooled mold walls to form solidified slab shells, which are continuously withdrawn from the bottom at the casting speed. The jets entering the mold region carry inclusion particles (e.g. alumina) and argon bubbles, which will either be safely transported to the top surface and removed by the slag layer or get entrapped in the final product, resulting in costly defects (e.g. internal cracks, blisters etc.). The flow in the mold is turbulent with Reynolds numbers in excess of 10^5 (based on the nozzle port hydraulic diameter). Plant observations found that the transient nature of this turbulent flow greatly influences the transport of the inclusions and bubbles, causing intermittent defects. This study is part of a larger ongoing research project to investigate the transient structures of this mold flow with an objective of minimizing the defects.

Several previous studies have used Reynolds averaged turbulence models (mainly k-ε model) [1] to understand this flow. However, the k-ε model only predicts the time-averaged velocities and cannot predict the detailed turbulent dynamics. Large Eddy Simulation (LES) is a more realistic and accurate method for resolving the evolution and dynamics of the large-scale turbulence structures, which are crucial to estimating heat, mass and momentum transport, and transport of inclusions. LES has been applied in many previous studies to simulate model turbulent flows [2, 3]. The application of LES to the present turbulent flow, however, leads to many challenges, including the prescription of inlet conditions, resolution of velocity and thermal boundary layers, the moving solidifying front and the long term transients. Thus the simulations require large computer memory and CPU time.

Because of nearly equal kinematic viscosities of the molten steel and water, flow in the steel casting mold region has been studied using scaled water models, which are easier to operate and allow flow visualization. Recently, we applied Particle Image Velocimetry (PIV), to study the flow in a 0.4 scaled water model [4]. This study provides data to validate the numerical code. The water model differs from the real caster. First the side walls, which represent the moving solidifying shell, are non-porous and stationary. Further, the water model has a flat bottom with outlet ports to represent the tapering molten pool.

This study presents results from three simulations. First, the LES approach is validated by comparing its results with the PIV data on the 0.4-scale water model. LES was then employed to simulate the flow in a full-scale water model including the nozzle and the mold. Finally, a simulation of the turbulent flow and inclusion transport in the full-scale steel caster is performed. First, the flow in the complex shaped nozzle is computed using LES (with approx. 630,000 cells), and the exit velocities were stored every 0.025 seconds for a period of 9.45 seconds. These were then used as inlet values to the mold flow simulations, and recycled periodically.

The time-dependent three-dimensional Navier-Stokes equations were solved using the Harlow-Welch fraction step procedure. Second order central differencing is used for the convection terms and the Crank-Nicolson scheme is used for the diffusion terms. The Adams-Bashforth scheme is used to descretize in time with second order accuracy. The pressure Poisson equation is solved using a direct Fast Fourier Transform solver for the first simulation and an Algebraic Multi-grid solver for the last two simulations. In the first two simulations, no sub-grid model was used while the third simulation incorporates a dynamic model for the sub-grid scale kinetic energy [5]. Computational grids consisting of 1.5 million, 0.7 million and 1.3 million cells are used for the three mold computations of this work.

Figures 2 and 3 compare the LES and PIV results of time-averaged horizontal velocity along the top surface centerline and the *rms* of the vertical velocity along a horizontal line 0.6m below the top surface. The LES statistics are averaged over 45 seconds of integration time. Reasonable agreement between LES and PIV is seen. Figure 4 and 5 present a typical instantaneous and the time-averaged (over 48.5 seconds) velocity vector plots at the centerplane of the full-scale water model. This particular nozzle geometry consists of an additional central jet entering the mold. The turbulent structures in the mold and a slight asymmetry between the two side jets can be seen in this instantaneous plot. The time-averaged plot shows a double-roll flow pattern on each side. One of the objectives of this study is to investigate the effects of this central jet on the mold flow pattern.

The complete paper will describe in detail the results of these three simulations, including comparisons between the results of the water model and the real caster with a moving solidifying shell boundary.

References:

1. Thomas, B.G. and L. Zhang, *Mathematical Modeling of Fluid Flow in Continuous Casting*. ISIJ International, 2001. **41**(10): p. 1181-1193.
2. Kaltenbach, H.-J., M. Fatica, R. Mittal, T.S. Lund, and P. Moin, *Study of Flow in a Planar Asymmetric Diffuser using Large-Eddy Simulation.* Journal of Fluid Mechanics, 1999. **390**: p. 151-185.
3. Hughes, T.J.R., A.A. Oberai, and L. Mazzei, *Large Eddy Simulation of Turbulent Channel Flows by the Variational Multiscale Method.* Physics of Fluids, 2001. **13**(6): p. 1784-1799.
4. Sivaramakrishnan, S., H. Bai, B.G. Thomas, P. Vanka, P. Dauby, and M. Assar, *Transient Flow Structures in Continuous Cast Steel*, in *Ironmaking Conference Proceedings*. 2000, ISS, Warrendale, PA: Pittsburgh, PA. p. 541-557.
5. Kim, W.W. and S. Menon, *Application of the Localized Dynamic Subgrid-Scale Model to Turbulent Wall-Boundary Flows.* AIAA 97-0210, 1997.

Yuan, Quan, S.P. Vanka and Brian G. Thomas, 3rd International Symposium on Turbulence and Shear Flow Phenomena, Sendai, Japan, 25-27 June, 2003, Conference Proceedings, Vol. 2, pp.681-686, 2003.

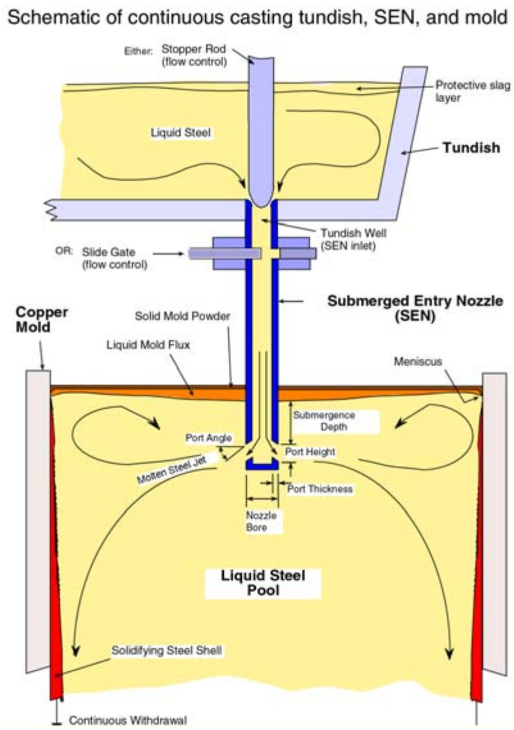

Figure 1. Schematic of the continuous casting process.

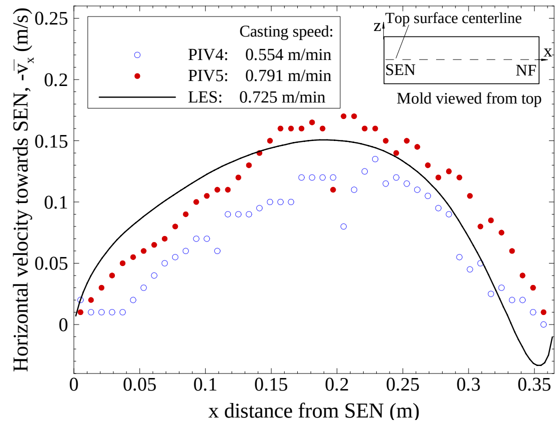

Figure 2. Comparison of time-averaged velocity along top surface centerline between LES and PIV (0.4-scale water model).

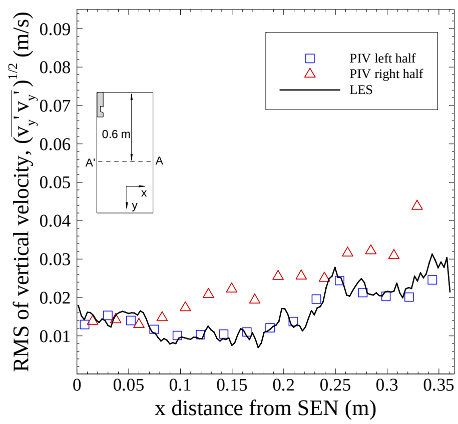

Figure 3.Comparison of RMS between LES and PIV (0.4-scale water model).

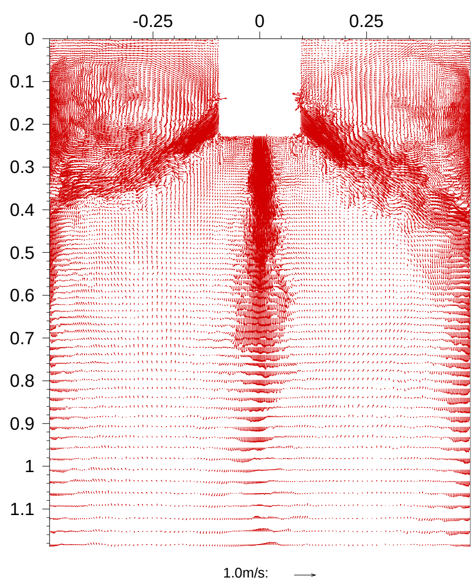

Figure 4. A typical instantaneous velocity field at the center plane of a full-scale water model.

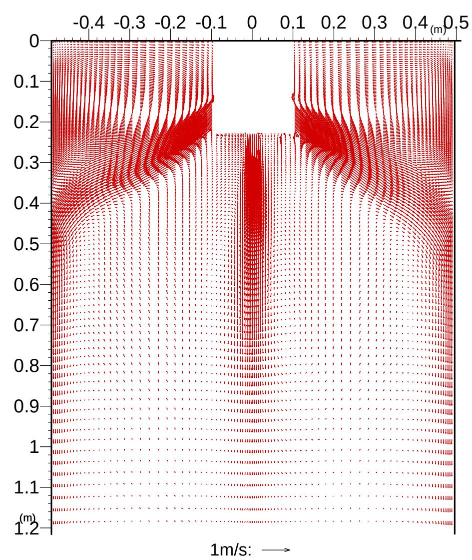

Figure 5. Time-averaged velocity field at the center plane of the full-scale water model.