Agenda

**University of Illinois Continuous Casting Consortium Meeting – October 18, 2001**

*Mathematical Models of Continuous Casting of Steel Slabs*

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| **Tentative Attendees**: | AK Steel | Ron O'Malley | |
| | Allegheny Ludlum | Mark Quigley | |
| | Columbus Stainless | Johann Ackermann | |
| | LTV Steel | Pierre Dauby and Mohammed Assar | |
| | Stollberg | Darrell Sturgill | |
| | Hatch | Chino Srinivasan | |
| | Accumold | Don Lorento | |
| | Carpenter Tech. | M. Collur | |
| | University of Illinois | Brian G. Thomas | Pratap Vanka |
| | | Lifeng Zhang | Chunsheng Li |
| | | Meng Ya | ~~Tiebiao Shi~~ |
| | | Quan Yuan | Bin Zhao |
| | | Seid Koric | |

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| 8:00 am | Introductions | Coffee in conference room: 143 Mech. Eng. Bldg. |
| 8:15 | B.G. Thomas: | "Overview of projects: past, present, and future" |
| 8:30 | Quan Yuan | "Transient fluid flow using LES models" |
| 9:00 | Lifeng Zhang | "Inclusion entrapment – literature review and modeling" |
| 10:15 | Bin Zhao | "Heat transfer from impinging jets using LES models" |
| 10:45 | B.G. Thomas (Tiebiao Shi) | "Effect of argon gas distribution on fluid flow in the mold using time-averaged K-ε models" |
| 11:30 | Discussion of flow projects | |
| 12:00 pm | Lunch | 143 Mech. Eng. Bldg |
| 12:30 | Ya Meng | "Modeling interfacial flux layer phenomena in the shell / mold gap using CON1D" |
| 1:15 | Chunsheng Li: | "Application of thermal-stress models to bulging below the mold and maximum casting speed to avoid cracks" |
| 2:00 | B.G. Thomas; J.K. Park | "Effect of corner radius on billet casting cracks" |
| | B.G. Thomas, L. Yu, K. Lin: | "Bulging between rolls, roll contact, spray zone and roll heat extraction, and implications in CC slabs" |
| | B. G. Thomas, T. Morthland | "Application of 3-D models of mold temperature to level prediction – a Case Study at Columbus Stainless" |
| 3:00 | Discussion of future projects and directions | |
| 4:00 | Adjourn | |

# Mathematical Models of Continuous Casting of Steel Slabs

**Brian G. Thomas, University of Illinois at Urbana-Champaign**

**October 18, 2001 Research Projects**

***Sponsors***:

| | |
|---|---|
| Accumold | AK Steel |
| Allegheny Ludlum | Columbus Stainless |
| Hatch Associates | LTV Steel |
| Stollberg, Inc. | |
| National Science Foundation | NCSA (supercomputing) |


## *Large Eddy Simulation of turbulent flows*, - Q. Yuan, B. Zhao, P. Vanka

Transient events are important to the generation of quality problems in continuous cast steel. Large eddy simulation models are being developed to directly simulate three-dimensional transient flow in the nozzle and mold regions. Results are being compared with conventional K-e model results in addition to experiments on water models (PIV and hot wire anemometry) and in commercial casting machines (MFC sensor data). The turbulent inlet flow pattern has an important influence which is recently being more accurately starting with a k-ε nozzle simulation from FLUENT. Next, the transient velocity field in the LTV 0.4-scale water model is simulated using both K-ε and Large Eddy Simulation in FLUENT 5.5.14. The flow in a symmetric half mold region and whole mold region are compared with an open-bottom LES simulation of flow in both sides. The simulated results reasonably agree with previous PIV measurements. The models will be used to investigate multiphase flow effects, dissipation of superheat, and the movement of argon gas bubbles and solid inclusion particles. The results will help us understand and prevent flow-related quality problems.

## *Inclusion Transport and Entrapment – Literature Review and Modeling* – L. Zhang

Inclusions are detrimental to steel quality, and efforts to minimize them have intensified in recent years. Due to the difficulty in direct evaluating inclusion amount (size distribution), some indirect ways, such as total oxygen level, nitrogen pickup, and aluminum loss (for low-carbon Al-killed steel), are employed to evaluate inclusions in steel. This work is surveyed for steel plants around the world.

The continuous casting mold is the last opportunity to remove inclusions from the steel. Modeling of inclusion behavior coupled fluid flow in mold can provide useful information. Initial modeling efforts are focusing on comparison with water model measurements. The effect of turbulence models, including k-ε model, LES (Large Eddy Simulation) model, RSM (Reynolds Stress Model), on fluid flow and inclusion movement are investigated. The choice of turbulence model and discretization scheme greatly affects the results. Secondly fluid flow and inclusion movement in liquid steel casters are modeled, including both "random walk" stochastic motion in K-ε simulations and the effect of the open bottom. Inclusion removal from the steel is different from the water system, despite the similar flow pattern. The extent of top surface shape contour and level fluctuation is being investigated using the indirect method of pressure distribution analysis at the top surface.

### *Effect of argon gas distribution on fluid flow in the mold using time-averaged K-ε models* – L. Zhang and T. Shi

Three dimensional finite difference models are being applied to predict turbulent multiphase flow in the liquid pool using CFX. The model includes the effect of argon bubble size distribution and evolution and is being applied to quantify flow pattern and flow-related quality problems. The bubble size distributions are extrapolated from water model measurements. Water model flow patterns are found to differ significantly from steel caster flow pattern for the same conditions (using MFC sensors), but the CFX model is able to roughly match both. The transition between single roll and double roll and the penetration depth of argon gas bubbles is being investigated for different casting conditions. These results have implications for flow-related quality problems, including surface defects, due to meniscus freezing, level fluctuation, and entrained inclusions, due to free-surface motion, and internal defects, such as pencil-pipe defects, due to entrained argon bubbles.

### *Modeling interfacial flux layer phenomena in the shell / mold gap using CON1D* - Y. Meng

Heat transfer in continuous casting molds is controlled primarily by heat conduction across the interface between the solidifying steel shell and the water-cooled copper mold. A comprehensive model, CON1D, has been developed to predict this heat transfer, including mass and momentum balances on the interfacial powder layers, superheat delivery from the turbulent liquid pool, and gap formation between the shell and the mold walls. The model has recently been extended to predict shear stress due to friction between the mold walls and within the flux layers. The shear stress model in liquid and solid flux layers has been validated by separate transient numerical models in the liquid flux (FDM in MATLAB) and in the solid (ANSYS). The model gives detailed analysis of the flux layers, including slip and fracture of the solid flux layer. A parametric study is being performed to investigate the effects of the flux properties including fracture strength, friction coefficient, and low-temperature viscosity. The results are compared with plant measurements of mold friction and shed light on lubrication phenomena, gap behavior, and even transverse crack formation.

The results show that when friction on mold side cannot compensate the shear stress on flux solid/liquid interface, axial stress builds up in solid flux layer. The likelihood of fracture depends on the critical basic consumption rate. Among the parameters studied, the flux viscosity is most important and affects both critical consumption rate and the possible fracture position.

### *Application of 2D thermal-stress models to predict casing speed limit restricted by billet submold bulging* – C. Li

A finite element model, CON2D, has been developed to simulate thermal and mechanical behavior of the solidifying shell during continuous casting of steel both in and below the mold. It features an elastic-viscoplastic creep constitutive equation that accounts for the different responses of the semi-solid, delta-ferrite, and austenite phases. The model is applied to predict temperature, stress, strain and deformation in a 2D L-Shape billet section under conditions that lead to varying degrees of shell growth and surface cooling. The model includes ferrostatic pressure and intermittent contact between the mold wall and billet surface within the mold. A parametric study predicts the maximum casting speed before excessive bulging causes subsurface strain to exceed a criterion for generating longitudinal cracks. The results show how the critical casting speed depends on section size, mold length, grade, and other parameters.

*Billet Casting Modeling* - J-K Park and Y. Meng

Thermal stress analysis of solidifying steel billets is being performed at UBC under the direction of BG Thomas and IV Samarasekera. Experimental measurements from Posco have been obtained to validate the models. The models are recently being applied to simulate the effect of varying corner radius on temperature and stress both in and below the mold. The results indicate that corner surface reheating, leading to a thinner corner and greater submold bulging, and causing off-corner cracks to initiate beneath the surface are more likely with larger corner radius.

*Bulging Between Rolls in Continuous Casting* - L. Yu, Kuan-Ju Lin

Beneath the mold in the spray zone of a continuous caster, internal pressure causes plastic creep bulging of the solidifying steel between the support rolls. This leads to cracks, segregation, and permanent shape changes. To understand these phenomena, finite element thermal stress models have been developed using ABAQUS. The models are first applied to quantify bulging and internal strains for a range of conditions and steel grades. The effects of roll misalignment and sudden changes in roll pitch have also been studied. The contact length against the rolls is quantified for different roll radius, pitch, and bulging. Heat transfer prediction in the spray zones is validated using embedded thermocouple measurements. Eventually, the results will be implemented into a model to predict and control the final width of slabs, which is known to vary with casting conditions, and is likely affected by bulging.

*3-D Heat Conduction in the Mold* – T. Morthland

A new 3-D mold heat conduction model to predict the temperature distribution accurately near water slots and thermocouples anywhere in the mold. The model features detailed treatement of the geometry variations near the end of the slots. It is applied to predict heat flux curves for a typical slab caster (Columbus Stainless). It can be used to find offset positions, which are input to CON1D. The results indicate how thermocouple signals might be interpreted to determine the location of the meniscus, based on local differences. The maximum safe position for the liquid level is also predicted.

# Future Projects

## *Slab Width Variations - ??*

Having determined how to quantify below-mold bulging and heat transfer beneath rolls, further progress should be possible on the prediction of slab width variations.

## *Inclusion experiments for model validation* - Lifeng Zhang

1) Obtain simultaneous liquid steel composition (including total oxygen, nitrogen, etc.) in the tundish and mold, mold flux samples, (including alumina and other oxides), slab samples, and / or coil samples (to measure inclusion content).

2) Conduct fundamental tests to determine particle flotation and drag properties, (for gas bubbles, both spherical and dendritic solid inclusions, and liquid inclusions) and criteria for their entrapment in either the top powder flux layers or the solidifying shell.

## *Flux Viscosity and Friction Measurement* - Ya Meng

1) Use UIUC tribology apparatus to measure flux friction against the mold wall.

2) Obtain mold friction data from casters in service (together with accompanying heat transfer data) in order to validate the models and to understand, predict, and improve interfacial behavior and defect formation in the mold.

## *Limits to casting speed to avoid narrow face breakouts due to excessive superheat – ??*

Use results from con2d simulations together with con1d simulations (based on heat flux data from jet impingement study) to predict limits to casting to avoid breakouts.

## *Transient Heat Conduction in the Mold –* T. Morthland

Adopt new 3-D mold heat conduction model to transient temperature evolution. Apply model to interpret mold level fluctuations for different thermocouple positions.