Agenda

**University of Illinois Continuous Casting Consortium Meeting – September 25, 2000**

*Mathematical Models of Continuous Casting of Steel Slabs*

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| **Attendees**: | Inland Steel | Rich Gass and Honbin Yin | |
| | AK Steel | Ron O'Malley | |
| | Allegheny Ludlum | Mark Quigley | |
| | Columbus Stainless | Johann Ackermann | |
| | LTV Steel | Pierre Dauby and Mohammed Assar | |
| | Stollberg | Darrell Sturgill | |
| | University of Illinois | Brian G. Thomas | Pratap Vanka |
| | | Chunsheng Li | Lan Yu |
| | | Meng Ya | Tiebiao Shi |
| | | Young-Mok Won | Quan Yuan |
| | | Melody Langeneckert | Bin Zhao |
| | | Kuan-Ju Lin | Lifeng Zhang |

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| 8:15 am | Introductions | Coffee in conference room:<br>235 Commons, Grainger Library. |
| 8:30 | B.G. Thomas: | "Overview of projects: past, present, and future" |
| 8:45 | Quan Yuan | "Transient fluid flow and inclusion motion using LES models |
| 9:45 | Tiebiao Shi | "Effect of argon gas distribution on fluid flow in the mold using time-averaged K-ε models" |
| 10:30 | Discussion of flow projects | |
| 11:00 | Melody Langeneckert | "Influence of 3-D mold geometry on mold heat transfer and thermocouple temperatures" |
| 11:30 | Ya Meng | "Modeling interfacial flux layer phenomena in the shell / mold gap using CON1D" |
| 12:30 pm | Lunch | 235 Commons, Grainger Library |
| 1:15 | Lan Yu: | "Bulging between rolls in continuously-cast slabs" |
| 1:45 | Chunsheng Li: | "Application of thermal-stress models to ideal taper, maximum casting speed to avoid breakouts, and the prediction of strand width variations" |
| 2:30 | B.G. Thomas & Y.M. Won | "Segregation and microstructure in continuous cast shell" |
| 3:00 | Brian G. Thomas | "Validation of Fluid Flow and Solidification Models – a Case Study at AK Steel" |
| 3:30 | 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**

**September, 2000 Research Projects**

***Sponsors***:

| | |
|---|---|
| Armco, Inc. | Allegheny Ludlum |
| Columbus Stainless | Ispat Inland Inc. |
| 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 simulte 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). Recent predictions of both flow and particle motion show the importance of inlet conditions on both steady and transient behavior in the mold and show reasonable agreement with the 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.

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

Three dimensional finite difference models are being applied to predict turbulent multiphase flow in the liquid pool using CFX. The model is used to investigate the effect of argon bubble size distribution and evolution on parameters to quantify flow-related quality problems. The bubble size distributions are extrapolated from water model measurements. The sensitivity of the flow pattern to bubble size is found to vary greatly with both bubble size and distribution. The transition between single roll and double roll observed in the plant might be caused by these gas bubble effects. 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.

*Influence of 3-D mold geometry on mold heat transfer and thermocouple temperatures* – M. Langeneckert

Three-dimensional ANSYS finite-element models are being used to study the relationship between mold geometry and heat transfer. Three-dimensional calculations to relate thermocouple measurements to heat flux are being distilled into simple analytical relationships. Simple relationships are also being developed to predict corner temperature, where slot distribution is uneven. The results will be incorporated into an existing heat transfer model, CON1D, and applied together with a statistical evaluation of plant measurements to understand, predict and prevent a variety of quality problems related to heat transfer phenomena in the continuous casting mold.

### *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 results are compared with plant measurements of mold friction and shed light on lubrication phenomena, gap behavior, and even transverse crack formation.

### *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 are being 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 results are being used to understand the mechanisms of strand width change. 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.

### *Application of thermal-stress models to ideal taper, maximum casting speed to avoid breakouts, and the prediction of strand width variations* – 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, and strain in a section through the steel shell cast under conditions that lead to varying degrees of shell growth and surface cooling. At mold exit, ferrostatic pressure is applied and the mechanical response is predicted. The results suggest critical conditions that lead to excessive strain and failure of the shell for different steel grades. The model is extended to quantify possible mechanisms for strand width variations.

### *Segregation and microstructure in continuous casting shell* - Y-Mok Won

A simple analytical model of microsegregation in solidifying steel has been developed based on the Clyne-Kurz model, and includes the effects of multiple components, columnar dendrites, coarsening and the $\delta/\gamma$ transformation. A new empirical equation for the secondary dendrite arm spacing has been developed, which varies with cooling rate and carbon content, based on measurements by several different researchers. Predictions with this microsegregation model agree with both experimental measurements and calculations with a detailed finite difference model. The model is being implemented into CON1D, to extend its capabilities and accuracy. Calculations for a typical continuous cast shell reveal that the effects of increasing arm spacing and decreasing cooling rate almost cancel, so the solidus temperature does not change with position or time for low carbon steels. In high carbon steels, however, the interior has a higher solidus temperature and nonequilibrium effects are much more important.

*Validation of Fluid Flow and Solidification Models – a Case Study at AK Steel* – Brian G. Thomas, Ron O'Malley, Tiebiao Shi, Ya Meng, David Creech, David Stone, and M. Langeneckert

The CCC models are tested by comparing their predictions with extensive experimental measurements on the AK Steel - Mansfield stainless-steel caster. Three-dimensional calculations of steady turbulent flow through the nozzle into the mold using CFX 4.2, agree with flow measurements in a full-scale water model. The corresponding predictions of steady superheat distribution of superheat in the molten pool compare well with measurements conducted by inserting a thermocouple probe downward through the top surface at several locations in the operating thin slab caster. The heat flux profiles calculated using CON1D match with both the cooling water heat balance and thermocouple measurements in the mold, calculated using the new adjustments based on 3-D ANSYS mold simulations. The predicted shell thickness profiles predicted by CON1D under transient conditions compare well with many shell thickness profiles measured around the perimeter of a breakout shell. This work demonstrates the quantitative ability of this modeling approach to simulate coupled fluid flow and solidification heat conduction in a real steel continuous casting process.

## Future Projects

*Inclusion motion in the mold and "pencil pipe" defect*s - Lifeng Zhang

Large inclusion clusters, containing alumina and / or mold flux components and associated with argon bubbles, lead to occasional but severe surface defects, including "pencil pipe" defects in ultra-low carbon steel. Models are being used to investigate the mechanisms causing this problem, focusing on the formation and transport of the large inclusion particles to the solidifying steel shell.

1) Apply CFX mold and nozzle models to perform complete parametric study of fluid flow, heat transfer, and particle paths / entrapment locations and residence times with varying casting conditions: (steel throughput, argon injection rate, mold curvature, mold width, submergence depth, nozzle inlet angle, etc.)

2) Validate models through comparison with 3-D LES models and plant measurements.

3) Focus on most likely particle size / shape responsible for defects and develop entrapment criterion at solidifying steel shell interface.

4) Understand mechanism for pencil pipe formation and evaluate means to counter the problem.