

# ANNUAL REPORT 2006

Meeting date: June 15, 2006

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## ***Continuous Casting Consortium Annual Meeting***

**Brian G. Thomas, Director**



*Department of Mechanical & Industrial Engineering  
University of Illinois at Urbana-Champaign*

## OBJECTIVES

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- To develop computational models of continuous casting of steel and related processes
- To apply these models to problems of practical interest to the steel industry

# Tentative Attendees

Nucor Steel, Decatur, AL:	Ron O'Malley & Jay Watson
Accumold:	Don Lorento
Algoma Steel:	Murray, Kamal Ughadpaga & Erminio Cerilli
LWB Refractories:	Don Griffin, & Paul Bridgett
Mittal Riverdale:	Gary Norgren
LaBein:	Claudio Ojeda & Jon Barco
Corus:	-
Postech:	Gogi Lee
Steel Dynamics Inc.:	Clayton Spangler + 2
Boasteel:	Ruan Xiaoming

Fluent Inc.:	Ashwini Kumar
Dofasco	Joydeep Sengupta & Stanley Sun
Delavan / Goodrich:	Stephen Swoope
IIT Madras, India:	Prasanna Kumar
U Helsinki, Finland	Seppo Louhenkilpi
U Norway, Trondheim	Lifeng Zhang

University of Illinois:	Brian G. Thomas, Joseph Bentsman, Seid Koric, Kai Zheng, Bryan Petrus, Kun Xu, Sami Vapalahti, Sana Mahmood, Aravind Sundararajan, Amar Behera, Kevin Cukierski, Michael Okelman, Gogi Lee, Claudio Ojeda, Zaher Hashisho, Ruan Xiaoming
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## Day 1: Morning Session

8:00am Breakfast & Introductions 2005 Mech. Eng. Lab. (Deere Pavilion)

8:10	B.G. Thomas:	"Overview of projects"
8:20	Sana Mahmood	"Asymmetric Fluid Flow and Particle Entrapment in the Nozzle and Mold"
9:10	Lifeng Zhang	"Steel Cleanliness Control and Fluid Flow in Continuous Casting Strands"
9:35	Gogi Lee	"Hook formation near slab corners, and prediction of argon gas bubble size in the slab casting mold"

10:00 Break

10:15	Kevin Cukierski	"Electromagnetic Control of Fluid flow in the Mold - Introduction"
10:40	C. Ojeda	"Modeling Meniscus Thermal and Fluid Flow Behavior during Oscillation"
11:30	HJ Shin / BG Thomas	"Mold Flux Consumption Model for high-speed casting"

11:50 Discussion of flow projects

12:15pm Lunch

2005 Mech. Eng. Lab.

# Day 1: Afternoon Session

12:45	K. Zheng / B. Petrus	"Online control of spray cooling using CONONLINE"
1:35	Amar Behera	"Temperature evolution in the spray zones: plant measurements and CON1D prediction"
2:00	Sami Vapalahti	"Modeling Of CC Secondary Cooling: An Experimental Study"
2:25	Kun Xu	"Modeling of precipitate formation during secondary spray cooling"
2:45	<i>Break</i>	
3:00	Kun Xu	"Heat transfer in a Beam-Blank Mold: plant measurements and model computations"
3:20	Seid Koric	"Thermal-mechanical behavior of the solidifying shell and ideal taper in a Beam-Blank Mold"
3:45		"Thermal-mechanical behavior of the solidifying steel shell in a thin slab caster with a funnel-mold"
4:10	<i>Break</i>	
4:20	M. Okelman	"Design & Installation of Novel Thermal Sensors into the Continuous Casting Mold"
4:40	A. Sundararajan:	"Heat transfer analysis of a refractory nozzle wall" "Thermal analysis of depression formation in Al strip casting"
5:00	Discussion of future projects and directions	
5:30	Adjourn meeting	
6:00	<i>Dinner</i>	Colonial Room, Illini Union Building

# Day 2

8:00 am-?	<i>B.G. Thomas: 356 Mech. Eng. Bldg.</i> Informal discussions on future projects
8:00 am-?	<i>Research group: 345 Mech. Eng. Bldg.</i> Informal discussions Further details on current projects and software CON1D and CON2D operation Questions

# Research Summaries

## Flow Dynamics and Electromagnetic Effects in Continuous Casting of Steel (starting)

B.G. Thomas,\* Kevin Cukierski

*Continuous Casting Consortium\*\**

Computational models of transient, multiphase fluid flow are being developed, validated, and applied to improve understanding of transient flow, inclusion transport and defect formation in the mold region during the continuous casting of steel slabs. The important effect of electromagnetic forces to slow down and control the flow pattern are being incorporated. Process parameters, such as nozzle geometry and gas injection rate, which are easy to change and yet profoundly influence both flow and product quality, are being optimized. Models to compute the transport and entrapment of inclusion particles are being tested through water model experiments, steel plant trials, and metallographic measurements at several steel companies who are cosponsoring this research.

## Entrapment of Bubbles and Inclusions during Flow in the Mold

B.G. Thomas,\* S.H. Kim, S. Mahmood, G. Lee

*Continuous Casting Consortium\*\**, POSTECH, Korea

Inclusion particles and bubbles carried by the turbulent flow of molten steel through the continuous casting nozzle and mold pool lead to serious surface and internal defects in the final product. Three-dimensional turbulent fluid-flow models are being applied to understand and quantify inclusion transport and entrapment for different casting conditions. The models incorporate the effects of nozzle clogging, and inclusion entrapment by the solidifying dendritic interface. Experimental and water model studies are being conducted and analyzed to determine the argon bubble size. The computations are validated and augmented with measurements, metallographic analysis, and plant trials conducted at POSCO and elsewhere.

# Research Summaries

## GOALI: Online Dynamic Control of Cooling in Continuous Casting of Thin Steel Slabs (ongoing)

B.G. Thomas,\* J. Bentsman\*, Vapalahti, S., K. Zheng, B. Petrus, and A. Behera

*Continuous Casting Consortium\*\* and National Science Foundation GOALI DMI 05-00453*

Temperature variations during cooling cause quality problems such as cracks, especially under transient conditions such as caused by changes in casting speed. Setting the spray water flow rates to maintain optimal temperature profiles during process changes becomes increasingly difficult when the casting speeds are high and response times must be fast. This project aims to develop a fundamentally-based online system to dynamically control the water flow rates in order to continuously optimize and stabilize cooling conditions in the thin slab casting process. The system will use model-based predictive control, incorporating both online measurements of mold heat removal and on a high-speed finite-difference model of heat conduction and solidification during the process.

## Thermal Stress and Surface Crack Formation in Continuous Casting (ongoing)

B.G. Thomas,\* Kun Xu

*Continuous Casting Consortium\*\**

Thermal stress in the steel shell as it moves down through the mold and below between the rolls in the secondary cooling zones contributes to many different problems, including transverse cracks, slab shape problems, and support roll wear. Mathematical heat flow and stress models are being developed to predict the temperature, and the associated distortion, stresses and strains, both in and below the mold. In addition, criteria for crack formation will be developed, based on steel ductility measurements and a model of grain size and nitride, oxide, and sulfide precipitation to track the susceptibility of different steel grades to ductility problems. Results will be compared with experience prior to establishing cracking criteria and applying the models to understand and explore ways of preventing cracking problems.

# Research Summaries

## Initial Solidification and Meniscus Hook Formation in Continuous Slab Casting (ongoing)

B.G. Thomas\*, C. Ojeda.

*Continuous Casting Consortium\*\**, POSTECH, Korea, and Labein, Spain.

The first few seconds of solidification at the meniscus create the final cast product surface, and may include defects such as deep oscillation marks, surface depressions, and subsurface hooks in the microstructure, if conditions are not optimal. Computational fluid flow, heat flow and stress models of the meniscus region are being developed and applied to simulate these phenomena. Plant measurements such as mold temperature, liquid surface shape, and metallographic examination of oscillation marks and hooks are being conducted on slabs cast at POSCO. Together, ways to optimize casting conditions such as speed, level control, superheat, mold oscillation practice, and mold powder composition are being investigated to minimize meniscus hook depth.

## Thermal Stress Analysis of Solidifying Steel Shells (ongoing)

B.G. Thomas\*, S. Koric, K. Xu, C. Ojeda, L. Hibbeler

*Continuous Casting Consortium\*\**

A coupled, two-dimensional, transient finite-element model has been developed to predict temperature, shrinkage, and stress development in both horizontal and vertical sections through the solidifying shell as it moves down through the caster. The model includes the effects of the volume change during phase transformation, ferrostatic pressure, the generalized plane strain stress state, the constraining influence of the mold, creep plasticity, and the dynamic effect of solidification shrinkage on heat transfer across the interfacial gap between the mold and the shell. The model is being applied to simulate the early stages of solidification, ideal taper for different steel grades, maximum casting speed to avoid excessive bulging, and understanding crack formation. Finally, the model is being extended to simulate behavior in complex shapes including ideal taper of beam blank molds, and crack formation in thin slabs cast in funnel molds, using full three dimensional simulations.

# Research Summaries

## Contacting and Solidification in Casting-by-Design

B.G. Thomas\*, Aravind Sundararajan

*National Science Foundation, Collaborative Research: NSF DMI 04-23794*

The continuous casting of thin aluminum strip with a single-wheel melt spinning process offers great potential for low-cost production of finished products with unique surface textures. To perfect this process requires fundamental understanding of the phenomena which control solidification shape, including flow oscillations in the melt pool, meniscus interaction with the wheel surface, intermittent solidification against the moving wheel, and thermal distortion. Aided by measurements by collaborators at Cornell, advanced computational models are being applied at UIUC to achieve this new understanding. Recent simulations match the contoured shape of the strip surface, based on the initial shape of the solidified meniscus, which is also the subject of model investigation.

## SIRG/Collaborative Research: Distributed Subwavelength Photonic Sensors for In-situ High Spatial and Temporal Resolution Monitoring in Manufacturing Environments

B.G. Thomas\*, M. Okelman

*National Science Foundation SIRG DMI #05-28668 and Continuous Casting Consortium\*\**

Monitoring of mold level and meniscus behavior is important for controlling quality during the continuous casting process. This project aims to develop new sensors to measure temperature in the mold very near to the meniscus, initially to use as a new research tool to investigate meniscus behavior to better understand defect formation. The ultimate goal is to revolutionize online thermal monitoring of industrial continuous casting molds. A process will be developed to insert sensors manufactured at UW Madison into the mold coating layer. Tests of sensor integrity will be conducted, data collected, and the signals analyzed using computational models. The meniscus region will further be modeled computationally to predict events during an oscillation cycle – including modeling of the sensor itself. This will determine the relationship between the sensor signal and the actual meniscus events. Insights gained will enable optimization of the size and location of the new sensors and interpretation of their signals to gain maximum benefit from their installation into operating molds.

# Research Summaries

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## Fluid flow, Heat transfer and Interfacial Phenomena in Nozzle Refractories (starting)

B.G. Thomas,\*

*Continuous Casting Consortium\*\*, LWB Refractories*

Dolomite nozzles differ from conventional nozzles in having higher resistance to alumina clogging but are more easily eroded. Fundamental modeling studies are being performed to understand and characterize the behavior of these nozzles, to compare them with conventional nozzles, and to optimize their use in service. Specific studies include an analysis of the flow of argon gas within the porous refractory walls to learn the gas distribution upon entering the molten steel. Heat transfer through the refractory walls is being modeled for a variety of realistic conditions, to understand the role of steel skulling on clogging for different refractory properties. Finally, the interfacial behaviors which govern the clogging attachment, the dissolution of the refractory, and the thermodynamic reactions are being studied.

## Modeling of Clogging and Erosion of Nozzle Refractories in Steel Casting

B.G. Thomas,\*

*Continuous Casting Consortium, LWB Refractories*

Depending on their composition relative to the inclusions in the steel, the walls of nozzle refractories can clog or erode, leading to severe quality problems in cast products. These phenomena have rarely been subjected to fundamental modeling, and never to computational modeling involving the several coupled phenomena that govern it: the turbulent flow of molten steel through the nozzle, contacting of solid inclusions in the steel with the nozzle wall, heat transfer in the wall and steel, the diffusion of compounds such as  $Al_2O_3$  and  $CaO$  through the nozzle wall, and the thermodynamics of the chemical reactions that form solid precipitates, or liquefy the inclusions, allowing them erode from the walls. With the support of numerous experimental measurements that have been made for this project, computational models will be developed to increase understanding of this important, yet complex problem.