Sensors, Sampling, and Simulation for Process Control
Edited by: Brian G. Thomas, James A. Yurko, and Lifeng Zhang
TMS (The Minerals, Metals & Materials Society), 2011

IMPLEMENTATION OF A REAL-TIME MODEL-BASED SPRAY-COOLING CONTROL SYSTEM FOR STEEL CONTINUOUS CASTING

Bryan Petrus[1], Kai Zheng[1], Xiaoxu Zhou[1],
Brian G. Thomas[1], Joseph Bentsman[1], Ron O'Malley[2]

[1]University of Illinois, Mechanical Science and Engineering;
1206 West Green Street; Urbana, IL 61801, USA
[2]Nucor Steel Decatur
4301 Iversion Boulevard; Trinity, AL, 35673, USA

Keywords: Heat Transfer, Solidification Model, Thin Slabs, Secondary Cooling, Real-Time Simulation, Proportional-Integral Control

Abstract

In continuous casting of steel, maintaining the shell surface temperature profile under transient conditions is important to minimize surface cracks. For this purpose a spray-cooling control system, CONONLINE, has been implemented on a commercial caster. The system includes a software sensor of shell surface temperature, control algorithm, and a monitor allowing operator input and displaying the predicted shell surface temperature profiles and other important operating data. Simulation results demonstrate that the new control system achieves better temperature control performance than conventional systems during a change in casting speed. Plant trials have shown that the performance can be improved by modifying the classical anti-windup method, and modifying the control algorithm during unusual casting conditions.

Introduction

Since its development in the mid 1980's, an increasing amount of the steel produced in the world has been made through thin-slab continuous casting. Thin-slab casting, defined here as slabs less than 100 mm thick, has faster casting speeds and is usually based on scrap. In this process, molten steel is poured into a water-cooled mold at the top of the caster, where a solid shell is formed around the liquid core. This partially solidified "strand" is then driven through the "secondary cooling" region, which has a series of rolls alternating with water or water-mist sprays that contain and cool the strand until it is fully solidified into slabs. If the steel is not fully solidified when it leaves this containment region, the ferrostatic pressure causes the strand to bulge. This costly and possibly dangerous event is called a "whale."

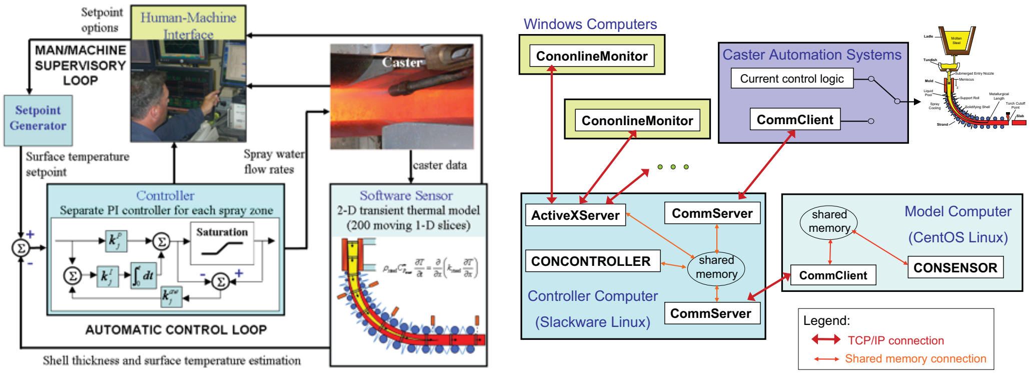
Robust and accurate control of secondary cooling is vital to the production of high quality slabs[1]. Defects such as transverse surface cracks form unless the temperature profile down the caster is optimized to avoid excessive stress and strain, such as caused by unbending, during temperature regions of low ductility[2]. This is especially important in thin-slab casters, because high casting speed and a tight machine radius exacerbate cracking problems. Thus, there is great incentive to implement control systems to optimize spray cooling to maintain desired temperature profiles.

However, conventional feedback control systems based on hardware sensors have not been successful because emissivity variations from intermittent surface scale and the harsh, steamfilled environment make optical pyrometers unreliable. Most casters control spray-water flow rates using a simple look-up table based on casting speed, but this produces undesirable temperature transients during process changes. Recent dynamic control systems have been developed based on real-time computational models.

Early systems[3-6] updated slowly or had relatively crude models, due to limited computing speed. More recently, significant achievements have been made in open-loop model-based control systems for conventional thick-slab casters[7-9], although none of the models are robust enough for general use, and none has been applied to a thin-slab caster.

A new online control system was briefly introduced in [10, 11] and is described in more detail in [12]. This system, called CONONLINE, has been implemented at the Nucor Steel casters in Decatur, Alabama. The system features a real-time solidification and heat-transfer model, CONSENSOR, of a longitudinal slice through the strand as a "software sensor" of surface temperature. A control algorithm, CONCONTROLLER, featuring a bank of proportional-integral (PI) controllers, uses this prediction to maintain the shell surface temperature profile at desired setpoints in each of the spray cooling zones through changes in casting conditions. Finally, a monitor interface provides real-time visualization of the shell surface temperature and thickness predictions, along with other information important to the operator, as well as to allow operator input through the choice of temperature setpoints.

Simulation results, described here, demonstrate that significantly better shell surface temperature control is achieved. Also, the useful lessons learned during implementation of this system at Nucor Decatur are discussed.



a) general overview b) system overview

Figure 1. Schematics of CONONLINE system

Model and Control System Design

An overview of the real-time control system is pictured in Fig. 1a. It features a "software sensor" CONSENSOR, which estimates strand temperature in real time from available casting conditions for CONTROLLER, which evaluates the error compared to operator-chosen setpoints and sends spray water flow rate "commands" to both the plant and CONSENSOR. Fig. 1b shows the computing setup, as implemented at Nucor Decatur. The software sensor and controller run on separate servers for stability and speed reasons. The monitor program runs on Windows PCs to display the programs' outputs. The programs communicate using shared memory on each server and TCP/IP connections between the computers. Further details are given in [10] and [12].

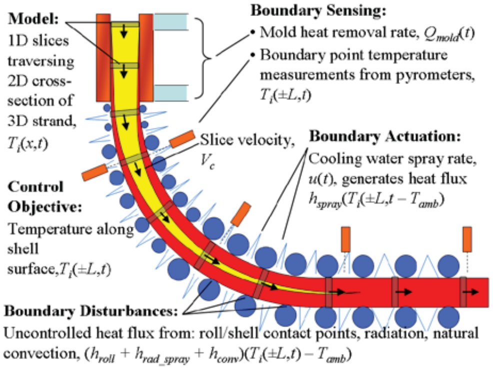


Figure 2. CONSENSOR slice diagram

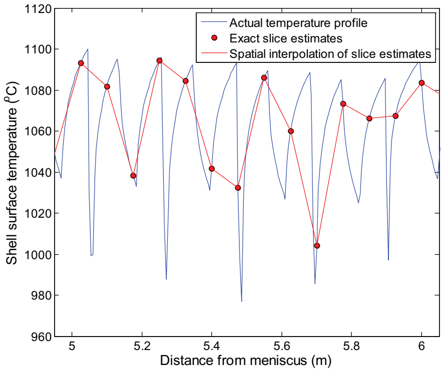


Figure 3. Slice interpolation

Software Sensor – CONSENSOR

At typical casting speeds, the continuously-cast strand has a high Peclet number, rendering axial heat conduction negligible. Hence, the temperature and solidification of the steel at any point in the strand can be predicted by modeling a "slice" of the material as it moves down through the caster at the casting speed. The temperature in each slice is described by the 1-D transient heat conduction equation[13]:

$$\rho_{steel} Cp^*_{steel} \frac{\partial T(x,t)}{\partial t} = k_{steel} \frac{\partial^2 T(x,t)}{\partial x^2} + \frac{dk_{steel}}{dT}\left(\frac{\partial T(x,t)}{\partial x}\right)^2 \quad (1)$$

where k_{steel} is thermal conductivity, ρ_{steel} is density, and Cp^*_{steel} is the effective specific heat of the steel, which includes the latent heat based on liquid fraction via a modified Clyne-Kurz microsegregation model[13, 14]. The spatial dimension x extends through the entire thickness of the strand, perpendicular to the casting direction to allow nonsymmetrical heat extraction. The initial condition is the pour temperature, measured by a thermocouple in the tundish. Heat flux boundary conditions are applied based on plant measurements of cooling water flow rates and temperature rise for the mold, and heat transfer coefficients according to spray water flow rates for the secondary cooling region.

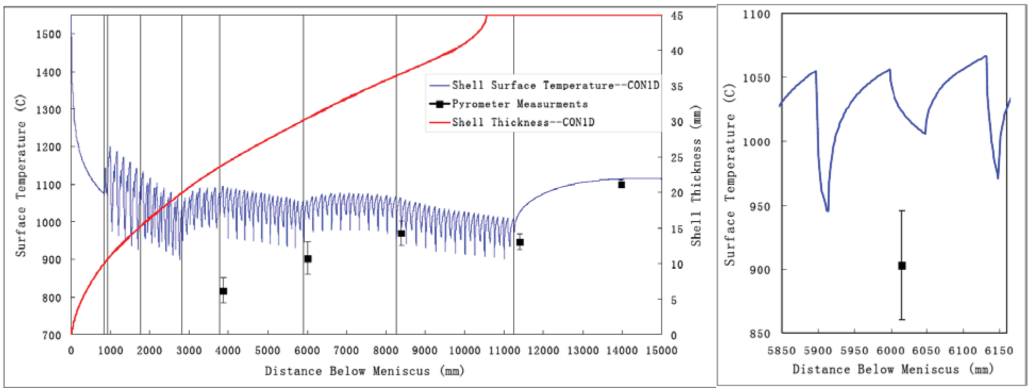
Focusing on the centerline of the strand, these model equations describing temperature in the one-dimensional slices can be computed quickly using an explicit finite-difference scheme[13]. By simulating and interpolating between multiple slices, as illustrated in Fig. 2, the temperature of the strand is estimated in real-time. More detail on this model is provided elsewhere [12, 13].

An offline computational model with these features was previously developed as the program CON1D. The accuracy of this model has been demonstrated through comparison with analytical solutions of plate solidification and plant measurements[13, 15]. Because of its accuracy, CON1D has been used in many previous studies to predict successfully the effects of casting conditions on solidification and to develop practices to prevent problems such as whale formation[16].

The software sensor, CONSENSOR, uses CON1D as a subroutine to simulate individual slices, starting each slice simulation at the meniscus at different times to achieve a fixed spacing between the slices. This is illustrated in Fig. 2 using $N = 10$ slices for simplicity. To assemble the complete temperature profile requires careful interpolation of the slice results. As illustrated in Fig. 3, the span between slices can pass over the temperature dips and peaks caused by the roll and spray spacing, resulting in errors of 100 °C or more. This problem is overcome by "delay interpolation," estimating the temperature at each point in the caster at time t from the latest temperature available from the CON1D slice histories. This process is described in detail in [12].

The model was calibrated to match the average surface temperatures measured under steady-state conditions using five pyrometers installed in the south caster at Nucor Steel Decatur in January, 2006. An example comparison of the measurements and temperature predictions is shown in Fig 4. The predicted temperatures generally exceed those measured by the pyrometers, except for the last pyrometer, which is outside the spray chamber and expected to be most reliable. The difference is believed to be due to the pyrometers reading lower than the real temperature, owing to steam-layer absorption and surface emissivity problems. Further work is needed to improve the accuracy of the pyrometer measurements, the spray heat-transfer coefficients, the spray-zone lengths, and the predicted variations in surface heat transfer and temperature, in order to improve the agreement.

The shell thickness prediction has also been calibrated to match recorded whale events at the Nucor Decatur casters, as well as high casting speed conditions where containment was not lost.



a) along entire domain b) close-up near one roll spacing

Figure 4. Comparison of CON1D surface temperature predictions and measurements

Control Algorithm – CONCONTROLLER

In a continuous caster, rows of individual spray nozzles are grouped into "spray zones" based on how they are connected via headers and pipes to control valves. All rows of nozzles in a zone have the same spray-water flow rate and spray density profile. The spray rate for zone j is denoted below as u_j. CONCONTROLLER controls each zone with an independent PI controller, tuned separately to meet the desired control performance. CONSENSOR, as described above, only predicts the temperature along the center of the strand. Hence, CONCONTROLLER only applies PI control to zones covering the center. The spray flow rates for other zones across the strand width are prescribed as a function of slab width using separate logic.

At each time step t, the shell surface temperature profile estimate, $\hat{T}(z,t)$ where z denotes the casting direction, is obtained by CONSENSOR and the desired temperature profile $T^s(z,t)$, or setpoint, is determined as discussed below. The difference between the two is averaged over each zone j, giving the zone errors $\Delta T_j(t)$. Then the spray-water flow rate command for the next time interval is calculated via the classic PI control law:

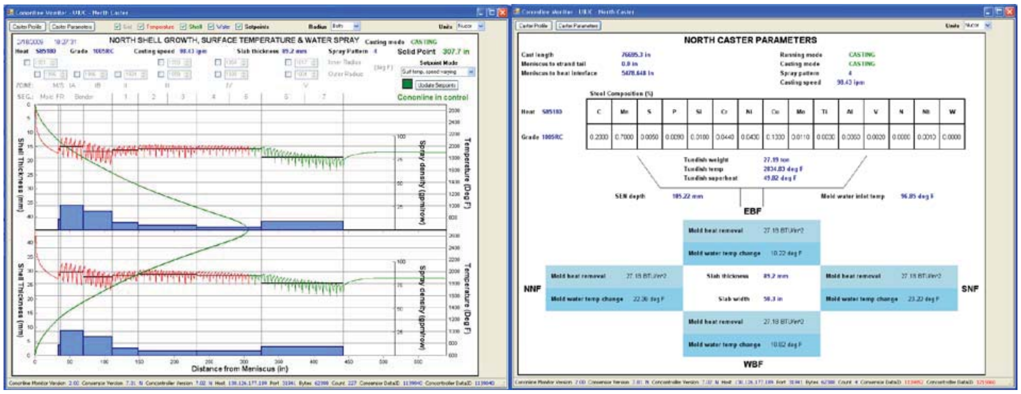
$$u_j(t+\Delta t) = u_j^P(t+\Delta t) + u_j^I(t+\Delta t), \quad j = 1,\dots,n_{zone}, \tag{2}$$

where the proportional and integral components are calculated as:

$$u_j^P(t+\Delta t) = k_j^P \Delta T_j(t), \quad j = 1,\dots,n_{zone}, \tag{3}$$

$$u_j^I(t+\Delta t) = u_j^I(t) + k_j^I \Delta T_j(t)\Delta t + \frac{1}{N_{aw}} \sum_{n=0}^{N_{aw}-1} \left[u_j^{measured}(t-n\Delta t) - u_j(t-n\Delta t) \right], j = 1,\dots,n_{zone}. \tag{4}$$

The first part of (4) is a discrete-time integral over the time interval Δt. The summation term is an anti-windup[17] adjustment, adopted to avoid integrator windup when the control flow-rate commands are outside the limits on the possible flow rates through the valves. This tends to cause controller instability, known as "windup". This problem is prevented by subtracting the difference between the measured spray rates and the controller-suggested spray rates from the integral in Eq. (4). This difference is averaged over N_{aw} time steps to filter out oscillations caused by chattering in the valves, as discussed below.



NORTH SHELL GROWTH, SURFACE TEMPERATURE & WATER SPRAY

Casting mode CASTING

Heat 585180 Grade 1005RC Casting speed 98.43 ipm Slab thickness 89.2 mm Spray Pattern 4 Solid Point 307.7 in

Conoline in control

NORTH CASTER PARAMETERS

Cast length 76695.3 in
Meniscus to strand tail 0.0 in
Meniscus to heat interface 5478.648 in
Running mode CASTING
Casting mode CASTING
Spray pattern 4
Casting speed 98.43 ipm

Steel Composition (%)

	C	Mn	S	P	Si	Cr	Ni	Cu	Mo	Ti	Al	V	N	Nb	W
Heat 585180															
Grade 1005RC	0.2000	0.7000	0.0050	0.0090	0.0100	0.0440	0.0430	0.1300	0.0110	0.0030	0.0360	0.0020	0.0000	0.0010	0.0000

Tundish weight 27.19 ton
Tundish temp 2834.83 deg F
Tundish superheat 49.82 deg F
SEN depth 185.22 mm
Mold water inlet temp 96.85 deg F

EBF
Mold heat removal 27.18 BTU/in^2
Mold water temp change 10.22 deg F

NNF
Mold heat removal 27.18 BTU/in^2
Mold water temp change 22.36 deg F

Slab thickness 89.2 mm
Slab width 58.3 in

SNF
Mold heat removal 27.18 BTU/in^2
Mold water temp change 23.22 deg F

WBF
Mold heat removal 27.18 BTU/in^2
Mold water temp change 10.02 deg F

a) Profile screen b) Parameter screen

Figure 5. CONONLINE Monitor interface screens

Visualization – CONONLINE Monitor

The monitor, as illustrated in Fig. 1, is an important part of the system that provides real-time display of many variables, setpoints, and predictions, permitting operators and plant metallurgists to monitor the caster and the control system performance, and to make adjustments as needed. Fig. 5 shows typical screen shots of the two interface screens that the monitor can display.

Fig. 5a shows the "profile screen," which serves two purposes. The first purpose is to relay key simulation outputs to the operators and plant engineers. It is also an interface for operator input to the controller, via controls for changing the temperature setpoint in any zone manually. Fig. 5b shows the "parameter screen," which displays the most important caster measurements input to the model. This allows for easy checking of the casting conditions, and program statuses.

Setpoint Generation

Choosing a good setpoint profile $T^s(z,t)$ is as challenging and important as the control task itself. Traditional spray practice is based on "spray-table control." Spray flow rates for each zone that produce good quality steel in a specific caster are determined from plant trial and error and previous experience. Higher casting speeds require higher water flow rates to maintain the same cooling conditions, so a different spray profile is tabulated for several casting speeds in a database spanning the range of normal operation. This array of spray rates, or "spray pattern," is organized by zone and casting speed and may be different for differing grades of steel. During casting, spray setpoints are interpolated from the database, called a "spray table," for the chosen pattern and casting speed. This method does not accommodate transient behavior very well.

To take advantage of this available knowledge base, the spray table was converted to a table of surface temperature profile setpoints. For each pattern, CON1D was run at a typical casting speed (3.5 m/min for Nucor Decatur) using the water spray rates in the spray table. Therefore, each pattern has a corresponding temperature profile as the setpoint for the PI controller, $T^s(z,t)$.

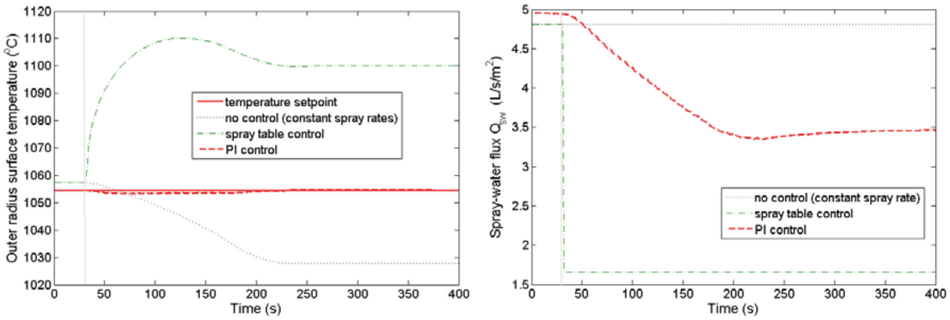
The automatic setpoints can also be over-ridden in any zone(s) using the monitor interface.

Simulation Results

The model and controller programs can be also used to simulate the caster response to changing casting conditions, and the monitor can be used to view the results graphically in real-time. For example, Fig. 6a compares the zone-average surface-temperature histories extracted from the software sensor predictions in the fifth (next to last) spray zones below the meniscus during a sudden drop in casting speed from 3.0 m/min to 2.5 m/min at t = 30s. Fig. 6b shows the respective spray rates assigned to each zone using 3 different control methods. Additional results from these simulations are available in [12].

If no change is made to the spray-water flow rates, the surface temperature eventually drops. With a controller that changes spray water flow rates in proportion to casting speed, during the sudden speed drop, all of the spray rates drop immediately. However, with the recently higher casting speed, the upstream steel is hotter than expected, so the temperature overshoots the steady-state value. The steady-state temperatures are higher at the lower speed because the spray rates assigned in the spray table are predicted by the model to drop even more than the drop in speed requires. Finally, with PI control, the surface temperature is kept remarkably constant through the speed change. The spray flow rates decrease more gradually after the casting speed change. Furthermore, the flow rates lower in the caster drop more gradually than those nearer to mold exit (not shown). Steady state is not reached until steel starting at the meniscus at the transition time finally reaches the given point in the caster, after being cast entirely under the new conditions.

This case study demonstrates that all of the controllers perform as expected. The PI controller produces the best response for steel quality, as detrimental surface temperature fluctuations are lessened. The quality of the control system now depends on the accuracy of the software sensor calibration to match the real caster. Work is proceeding to measure heat transfer, both with fundamental laboratory experiments, and with optical pyrometers and other experiments in the commercial steel thin-slab caster.



a) Zone-average outer radius surface temperature b) Spray water flow rates

Figure 6. Results of offline simulation of slowdown, comparing control methodologies

Implementation at Nucor Steel Decatur

The real-time CONSENSOR model has been running on servers at the Nucor Decatur sheet steel mill since 2006. Since 2008, dedicated workstations have been set up in the caster pulpit to run monitors for each of the two casters, which are called North and South caster at the mill. The system was run in “shadow mode,” in which temperature and shell predictions are supplied to operators through the monitor, but the system does not control the water sprays. At first, the system was only installed on the North Caster. During this time, a whale event occurred on the South caster, while on the North caster operators used the visual prediction of the liquid core to reduce casting speed as needed to prevent loss of containment. The operators immediately requested the system also be installed on the South caster.

Several successful tests with CONONLINE in control of the water sprays have been performed, up to several hours in length. In addition to model calibration, changes have been made to the control algorithm to resolve issues noticed during the tests. In particular, the controller gains were made less aggressive when it was found that the spray valve system had a longer time constant than was anticipated. Also, the valves had some chattering that lead to sinusoidal noise in the spray rates. The classical anti-windup method, equivalent to Eq. (4) with $N_{aw} = 1$, transmitted these oscillations to the control signal. To prevent this, the oscillations were filtered out by averaging the anti-windup signal over time. The controller also sometimes called for sharp changes in spray rate in the first few spray zones, due to significant variations in strand surface temperature at mold exit caused by changes in mold heat flux, casting speed, and steel grade. To avoid this problem, the temperature setpoint for the first spray zone is now half-way between the surface temperature at mold exit and the setpoint for the second zone.

Finally, it has been found that additional logic is needed to deal with unusual casting conditions. In particular, Nucor Decatur has a breakout prevention system that sometimes slows down the casting speed to 0.25 m/min when thermocouple readings in the mold indicate a thin spot. However, since CONSENSOR uses average mold heat removal, it does not predict the highly localized thin spot. As discussed in the previous section, PI control would lower the spray rates during sudden slowdowns, which could cause the thin spot to break out. Instead, during these so-called “sticker slowdowns,” CONCONTROLLER has been adjusted to override PI control in the first three spray zones with default minimum sprays based on the spray table. Similar efforts are continuing to help with casting startups and tailouts. Once resolved, the plan is for CONONLINE to take over permanent control of the casters.

Acknowledgments

Matthew Smith, Rob Oldroyd, Terri Morris, Kris Sledge and the caster operation crews at Nucor Steel Decatur are gratefully acknowledged for their unwavering support and help with this work. We are grateful for work on CON1D calibration by former UIUC students Sami Vahpalahti and Huan Li. This work is supported by National Science Foundation Grants DMI 05-00453 and CMMI-0900138, and the Continuous Casting Consortium at UIUC.

References

1. J.K. Brimacombe, P.K. Agarwal, S. Hibbins, B. Prabhaker and L.A. Baptista: "Spray Cooling in Continuous Casting," in *Continuous Casting*, vol. 2, J. K. Brimacombe, ed., 1984, pp. 105-123.
2. M. M. Wolf: *Continuous Casting: Initial Solidification and Strand Surface Quality of Peritectic Steels*, vol. 9, Iron and Steel Society, Warrendale, PA, 1997, pp. 1-111.
3. K. Okuno, H. Naruwa, T. Kuribayashi and T. Takamoto: *Iron Steel Eng.,* 1987, vol. 12 (4), pp. 34-38.
4. K.-H. Spitzer, K. Harste, B. Weber, P. Monheim and K. Schwerdtfeger: *Iron Steel Inst. Jpn,* 1992, vol. 32 (7), pp. 848-856.
5. S. Barozzi, P. Fontana and P. Pragliola: *Iron Steel Eng,* 1986, vol. 11, pp. 21-26.
6. B. Lally, L. Biegler and H. Henein: *Met. Trans. B,* 1990, vol. 21B, pp. 761-770.
7. K. Dittenberger, K. Morwald, G. Hohenbichler and U. Feischl: "DYNACS Cooling Model - Features and Operational Results," *Proc. VAI 7th International Continuous Casting Conference*, (Linz, Austria), 1996, pp. 44.1-44.6.
8. R.A. Hardin, K. Liu, A. Kapoor and C. Beckermann: "A Transient Simulation and Dynamic Spray Cooling Control Model for Continuous Steel Casting," *Metal. & Material Trans.,* 2003, vol. 34B (June), pp. 297-306.
9. Seppo Louhenkilpi, Jukka Laine, Tuomo Raisanen and Tenho Hatonen: "On-Line Simulation of Heat Transfer in Continuous Casting of Steel," in *2nd Int. Conference on New Developments in Metallurgical Process Technology*, (Riva del Garda, Italy, 19-21 Sept, 2004), 2004.
10. K. Zheng, B. Petrus, B.G. Thomas and J. Bentsman: "Design and Implementation of a Real-time Spray Cooling Control System for Continuous Casting of Thin Steel Slabs,," in *AISTech 2007, Steelmaking Conference Proceedings,* , (Indianapolis, IN), 2007.
11. B.G. Thomas, J. Bentsman, B. Petrus, H. Li, A.H. Castillejos and F.A. Acosta: "GOALI: Online Dynamic Control of Cooling in Continuous Casting of Thin Steel Slabs," in *Proceedings of 2009 NSF CMMI Engineering Research and Innovation Conference*,Honolulu, Hawaii, June 22-25, 2009., 2009, p. 16p.
12. Bryan Petrus, Kai Zheng, Xiaoxu Zhou, Brian G. Thomas and Joseph Bentsman: "Real-Time Model-Based Spray-Cooling Control System for Steel Continuous Casting," *Metals and Materials Transactions B,* to appear.
13. Y. Meng and B.G. Thomas: "Heat Transfer and Solidification Model of Continuous Slab Casting: CON1D," *Metal. & Material Trans.,* 2003, vol. 34B (5), pp. 685-705.
14. Y.M. Won and B.G. Thomas: "Simple Model of Microsegregation during Solidification of Steels," *Metallurgical and Materials Transactions A (USA),* 2001, vol. 32A (7), pp. 1755-1767, 179.
15. B. Santillana, L.C. Hibbeler, B.G. Thomas, A. Hamoen, A. Kamperman, W. van der Knoop: "Investigating Heat Transfer In Funnel-Mould Casting With CON1D: Effect of Plate Thickness," *ISIJ Internat.,* 2008, vol. 48 (10), pp. 1380-1388.
16. Joydeep Sengupta, Manh-Kha Trinh, David Currey and Brian G. Thomas: "Utilization of CON1D at ArcelorMittal Dofasco's No. 2 Continuous Caster for Crater End Determination," *Proc. AISTech 2009 Steelmaking Conference Proc.*, (St. Louis, MO, May 4-7, 2009), 2009, vol. 1.
17. C. Edwards and I. Postlethwaitex: "Anti-windup and Bumpless Transfer Schemes," *Proc. UKACC International Conference on CONTROL*, 1996, pp. 394-399.