NSF GRANT #DMI- 0500453
NSF PRORAM NAME: Materials Processing & Manufacturing

Online Dynamic Control of Cooling in Continuous Casting of Thin Steel Slabs

B.G. Thomas
W. Grafton & Lillian B. Wilkins Professor
University of Illinois at Urbana-Champaign
Department of Mechanical and Industrial Engineering
1206 West Green Street, Urbana, IL 61801
Ph: 217-333-6919, 217-244-4656; Fax: 217-244-6534;
Email: bgthomas@uiuc.edu

J. Bentsman (Professor), **K. Zheng, S. Vapalahti, B. Petrus, J. Kim, A.K. Behera**
University of Illinois at Urbana-Champaign

A.H. Castillejos and **F.A. Acosta**
Cinvestav, Saltillo, Mexico

Abstract: This research aims to accurately predict and control temperature in real time during the continuous casting of large, semi-finished steel shapes. The approach is to create a fast, accurate transient computer model of heat transfer during the solidification process that serves as a "software sensor", calibrated in real time through online temperature measurements to provide feedback to a control system, based on algorithms which will be designed specifically for this class of problem. The new software system will continuously read in operating conditions and mold temperatures and continuously adjust the spray-water flow rates in the secondary cooling zone of the caster, in order to maintain the desired temperature profile throughout the steel. This profile will be set by steel plant engineers, in order to minimize the formation of cracks and other defects. The system will be calibrated using thermocouple and optical temperature sensors, tested and implemented at an operating U.S. thin slab caster.

This project is important because 96% of the 100 million tons of steel produced in the U.S. each year is continuously cast, and the fraction produced by the new high-speed thin-slab casting process grows every year. This process experiences many defects caused by undesired temperature variations during spray cooling, which are unavoidable using current control systems. Conventional feedback control cannot be used because temperature sensors are too inaccurate and expensive. The model-based predictive control system proposed here must overcome many challenges, including the high speed of the process and increased relative importance of mold solidification.

In the first year of this large project, progress has been on several different subprojects. A finite difference model, CON1D, has been optimized to run in an online environment under fully transient conditions. It has been integrated into a control system and found to outperform the existing control system used at the steel plant. It is currently being tested. Spray cooling experiments have begun, new control algorithms have been developed, and new insights into defect formation have been found. Future improvements to this novel model-based control system should revolutionize the control of continuous casting spray systems, with improved steel quality, and will have beneficial impact on related scientific fields and commercial processes.

1. Introduction: For the high-volume low-profit-margin steel industry to compete in the world market, it must improve efficiency and consistency of steel quality. Implementing better control systems for the continuous casting process is one way to achieve this. Continuous casting produces 96% of steel in the U.S. and the fraction of the new high-speed thin-slab casting process is growing every year[1]. Temperature variations during cooling in this process cause quality problems such as cracks, especially under transient conditions. Due to the high casting speeds and short response times, setting the spray water flow rates to maintain optimal temperature profiles during process changes becomes for operators increasingly difficult. Conventional feedback control systems cannot, however, be used for this purpose due to the insufficient reliability of temperature sensors. Recent model-based predictive control systems face special problems in thin slab casting, owing to the higher speed and the increased relative importance of solidification in the mold, which is not easy to predict accurately.

Previous studies, including those of the principal investigators, have developed comprehensive and efficient computational models of the continuous casting process based on nonlinear parabolic partial differential equations (PDEs). The accuracy of these models to predict heat transfer and solidification has been demonstrated through comparison with analytical solutions and plant measurements. This work has led to improved fundamental insights into the process. The next steps, proposed in this work, are 1) to more tightly tune these models to the thin slab casting and 2) to implement the knowledge contained in these models into a fundamentally-based system to dynamically control the water flow rates for cooling optimization. Since the thin slab casting process is in general characterized by nonlinear, spatially distributed, often time-varying, and relatively fast dynamics, a highly nontrivial control research and implementation effort is required to ensure robust optimal performance of spray cooling control systems.

Thus, the intellectual merit of the research proposed is in i) providing a refined thin slab continuous casting model using the one-time plant measurements obtained at the caster specifically instrumented for this purpose, ii) developing novel state estimation and control design tools, applicable to systems governed by a class of nonlinear parabolic PDEs of interest, and iii) through the application of the tools developed to the refined thin slab continuous casting model, addressing implementation issues by synthesizing the first online temperature profile "software sensor" calibrated in real time through reliable online measurements, and deriving the optimal spray cooling control algorithms using this sensor.

This effort combines the talents of a team of researchers, including the experience of Prof. Brian Thomas in mathematical modeling of continuous casting, Prof. Joseph Bentsman in adaptive control theory of distributed parameter systems and predictive control, experienced student researchers to carry out the work, and an industry team, led by Dr. Ron O'Malley of Nucor Steel, Decatur, Alabama, which are helping to conduct the plant measurements needed for model calibration, and are overseeing the implementation of the UIUC control algorithms into the level-2 control system of their plant. In addition, H. Castillejos is leading experimental efforts to better understand heat transfer in the spray zones. This project enhances and complements the modeling efforts at the University of Illinois Continuous Casting Consortium, created in 1989 by Prof. Thomas and currently supported by nine member companies.

Along with fundamental scientific benefits, the research proposed will have broader impacts. The direct broad impact of the effort proposed is quality improvement, cost reduction, and energy saving in continuous casting of thin steel slabs. This impact is strongly amplified by the rapid growth of thin slab casting in steel industry. In addition, improved understanding of the control issues and algorithms will broadly benefit other high-speed manufacturing processes as well. The research will educate students who will take the modeling and control tools and technologies developed into industry. Most of all, the significant improvement of this key manufacturing process will be of direct benefit to society at large.

2. The Process: A schematic of steel processing is depicted in **Fig. 1**, with a close-up of the region between two rolls in the spray zone given in **Fig. 2**.

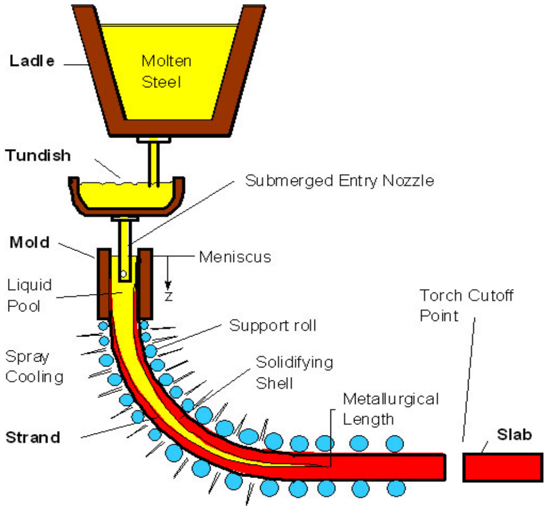


Fig. 1. Schematic of Steel Processing including ladle, tundish, and continuous casting

Steel flows from a ladle, through a “tundish,” and then exits down through a ceramic Submerged Entry Nozzle (SEN) into the mold. In the mold, the steel freezes against the water-cooled copper walls to form a thin solid shell, which is continuously withdrawn from the bottom of the mold at a “casting speed” that matches the flow rate of the incoming metal. The casting speed must be controlled to be slow enough to enable the shell to become sufficiently thick to support the liquid pool it contains, in order to avoid a catastrophic “breakout”, where molten steel penetrates the shell to drain over the bottom of the machine.

The steel strand then moves through the spray cooling zones, where water and air-mist sprays impact its surface to maintain cooling. Motor-driven drive rolls located below the mold continuously withdraw the strand downward. Many closely-spaced support rolls prevent the outward bulging of the shell due to the ferrostatic pressure arising from the liquid steel core. Water sprays emerge from high-pressure nozzles, which are interspaced between the support rolls and cool the strand during the solidification process. Other strategically placed rolls bend the shell to follow a curved path and then straighten it flat prior to torch cut-off into individual slabs. Start-up of this process is a relatively rare occurrence, and is achieved by inserting a “dummy” bar to plug the mold bottom.

The rolls support the the wide surface to prevent bulging, but greatly affect the temperature distribution. As shown in Fig. 2, sharp drops in surface temperature are experienced beneath each roll, and beneath the impacting spray jet. Reheating occurs in the adjacent regions which are protected thermally by the space under the rolls. Gravity significantly affects the water boundary layer, which causes cooling to vary above and below the jet, and between the inside and outside surfaces of the strand. The water spray rates should be continuously adjusted to maintain a desired surface temperature profile to avoid the formation of surface cracks. Cracks are caused by thermal stress combined with metallurgical embrittlement due to nonmetallic precipitates and grain growth, which depend mainly on cooling history. Spray control is difficult, because sensors such as optical pyrometers are generally unreliable due to intermittent steam and surface emissivity variations. Thus, they cannot be used for online feedback-control.

After exiting the spray cooling zones, the steel strand surface reheats, as natural convection and radiation heat extraction is small. The strand is no longer supported by rolls, so should be fully solidified. If any liquid core remains beyond the zone of roll support, the strand will bulge catastrophically, creating a thick “whale” shape, that forces costly shutdown of the process.

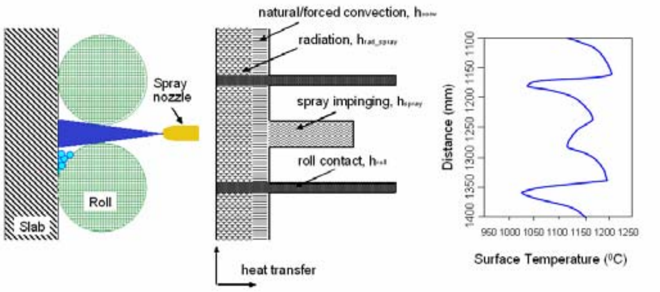


Fig. 2. Schematic of the spray region of the thin-slab steel caster, and corresponding heat transfer, and surface temperature profiles.

3. The Problem: The strand is subject to a variety of cracking problems during secondary spray cooling, such as transverse midface and corner cracks. These surface defects require expensive surface-reconditioning or even rejection of the product. These quality problems are generally caused by non-optimal cooling conditions, which arise due to unaccommodated variations in the process, such as changes in casting speed or mold powder cooling conditions. Most operations simply scale the water flow rate with casting speed. This does not provide uniform cooling, however. For example, after a temporary drop in casting speed, the colder strand near the top of the caster will need less water for a long time, while the strand near the bottom of the caster will be gone in a short time. As another example, a change in mold powder crystallization can drop the heat flux temporarily, causing a region of hotter, thinner shell at mold exit, which requires more cooling for the rest of its time in the caster. The strategy for controlling the water flow rates in spray zones should dynamically adjust for each portion of the strand, according to its entire history.

Traditional control strategies to maintain the strand surface temperature to a desired profile would utilize feedback based on temperature measurement at various places in the spray zones. However, the intermittent surface scale layer and harsh environment of the steamy spray chamber makes optical temperature sensors unreliable. Thus, heuristic-based, open-loop control with a predictive model is the only successful control strategy to date. However, the model-based predictive control systems face special problems in thin slab casting, owing to the higher casting speed and the increased relative importance of solidification in the mold, which is not easy to predict accurately. Thin slab casters are more prone to cracking problems than conventional casters, which prevents them from entering certain markets. Thus, there is great incentive to develop an improved model-based control system to optimize spray cooling, especially for the thin slab casting process.

4. Current Results: The results of this project are contained in 3 publications to date[2-4] and in our website http://ccc.me.uiuc.edu. This paper reports on six different ongoing components of the current multifaceted research project:

1) Computational model of solidification and temperature development in thin slab casting
2) Steel plant experiments for model validation
3) Online control system development
4) Laboratory measurement of water flow and heat transfer during spray cooling
5) Understanding defect formation during continuous casting
6) Optimal control algorithm development

5. Computational model of solidification and temperature development in thin slab casting: The finite-difference model, CON1D, has been developed over the past decade by the PI to compute temperature within the solidifying steel along the centerline of the strand from the meniscus, through the mold, spray zones, and reheating zone, up to torch cutoff.[5, 6] CON1D is a simple, but comprehensive model of heat transfer and solidification of the continuous casting of steel slabs, including phenomena in both the mold and spray regions. This finite-difference model solves the one-dimensional transient heat conduction equation within the solidifying steel shell:

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

The entire two-dimensional temperature distribution is computed by tracking the progression of a slice down the mold, taking advantage of the high Pe number of the process, which indicates that axial conduction is negligible.

This fundamentally-based model now predicts shell thickness on both the inside and outside radius surface of the strand, temperature distribution in the mold and shell, total heat removal, heat flux profiles down the wide and narrow faces, mold water temperature rise, ideal taper of the mold walls, and other phenomena. Mold heat flux is based on a heat balance on the measured cooling water heatup.

Below the mold, heat flux from the strand surface varies greatly between each pair of support rolls according to spray nozzle cooling (based on water flux), h_{spray}; radiation, h_{rad_spray}; natural convection, h_{conv}; and heat conduction to the rolls, h_{roll}, as shown in Fig. 2. Incorporating these phenomena enables the model to simulate heat transfer during the entire continuous casting process. The heat extraction due to water sprays is a function of water flow [7] of the following form:

$$h_{spray} = A \cdot Q_{water}^{c} \cdot \left(1 - b \cdot T_{spray}\right) \quad [1]$$

where Q_{water} (l/m^{2}s) is water flux in spray zones and T_{spray} is the temperature of the spray cooling water. In Nozaki's empirical correlation [8], A=0.3925, c=0.55, b=0.0075, which has been used successfully by other modelers.[7, 9] Very recent experimental work is being undertaken to measure these coefficients more accurately, including the effects of air mist cooling, to avoid overcooling, as described later in this paper. To avoid cracks, it is often necessary to keep the strand above a certain critical temperature, such as the AR_3 temperature, ~700°C.

Radiation is calculated by:

$$h_{rad\_spray} = \sigma \cdot \varepsilon_{steel} \left(T_{sK} + T_{ambK}\right)\left(T_{sK}^2 + T_{sprayK}^{\ 2}\right) \quad [2]$$

where T_{sK} and T_{sprayK} are T_s and T_{spray} expressed in Kelvin. Natural convection is treated as a constant input for every spray zone. For water-cooling only, it is not very important, therefore it is simplified to 8.7W/m^{2}K everywhere. Larger values can be entered for h_{conv} to reflect the stronger convection when there is air mist in the cooling zone. Heat extraction into the rolls is calculated based on the fraction of heat extraction to the rolls, f_{roll}, which is calibrated for each spray zone. A typical f_{roll} value of 0.05 produces local temperature drops beneath the rolls of about 100°C. Beyond the spray zones, heat transfer simplifies to radiation and natural convection.

The CON1D program has been optimized to run in less than 1s on a personal computer. Further details on the model equations, boundary conditions, numerical discretization, previous validation efforts and other applications are given elsewhere.[5]

In addition to successful model-based prediction and control capability, the model was used to generate setpoints for typical casting conditions. Specifically, 72 set points were generated for the Nucor caster to allow operation at 8 different spray-water patterns over a range of casting speeds (discretized as 9 different speeds over the maximum speed range). These set points are temperature profiles generated by CON1D using typical mold heat flux dependent on casting parameters which includes casting speed.[10, 11]

The model is now ready to calibrate, validate, and implement as a software sensor into a control system.

6. Steel Plant Experiments for Model Validation and Calibration: Experimental trials were carried out at Nucor Steel, Decatur, Alabama on Jan 12-17, 2006, to measure the variation of slab surface temperature under different casting conditions, varying the casting speed and spray water flow rates. These results are being used to calibrate the CON1D model. Mold heat flux is measured from the temperature rise of the cooling water, knowing the water flow rate. To measure surface temperature, two-color optical pyrometers were installed at four different locations in the spray zones. The four Modline® 5, 5R-141000, 4M5#25579 pyrometers were positioned at 3861, 6015, 8500 and 11384 mm below the meniscus.

Initial casting experiments included three different trials: i) Changing spray pattern at constant casting speed change at north caster (01/13/06 9.52 am – 10.04 am (shown in part in **Fig. 3**), south caster 01/13/06 16.12 – 16.37); ii) changing casting speed with spray water flow pattern design at south caster 01/16/06 10.10 am – 10.57 am; iii) changing casting speed at spray water flow pattern design (sprays constant except for foot roll and upper bender segments that were left dependent on casting speed) at south caster 01/16/06 20.20 – 21.04. Typical steel grade was 0.247%C and pour temperature

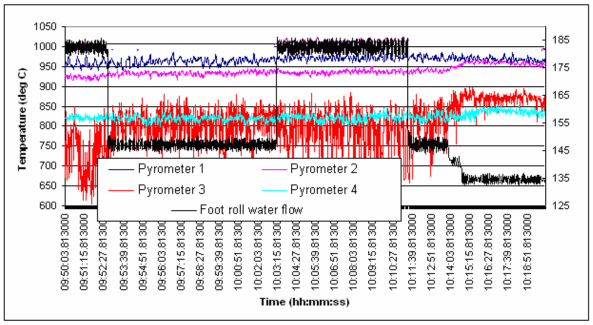


Fig. 3 Pyrometer Data during spray water change trial 1 (3.5 m/min; spray pattern 4)

The data from the caster Level II system was recored as *.dat files for analysis in ibaAnalyzer 4.3.3 and *.xls.

The pyrometer measurements varied throughout the experiments, due to the intermittent presence of steam, and possibly also due to variations in emissivity of the surface scale layer. For the sample raw data given in Fig. 3, (trial 1), pyrometers 1,2 and 4 are seen to have relatively uniform temperatures while pyrometer 3 fluctuates over several hundred degrees. Blowing the steam away with a fan was found to increase and stabilize the pyrometer temperaures, producing the mean values included as part of Fig. 4.

To compare with the pyrometer measurements, the varying surface temperatures computed by the CON1D model are averaged over 20mm of strand surface within the varying jet impingement region, which corresponds to the region that the pyrometer measures (in between rolls). This mean temperature is compared with the 4 pyrometer measurements in Fig. 4, along with the entire temperature profile. The agreement is reasonable, although further calibration is needed. Figure 4 also reveals the variations in the surface temperature, which need further work to validate.

The results from this run show that the entire processing time for this 90-mm thick strand from liquid to complete solidification takes only 1-3 minutes. Casting speed variations from 3-5m/min result in metallurgical lengths ranging from 6-13m for these typical thin slab casters. The metallurgical length for the 3.5m/min case shown is ~11m.

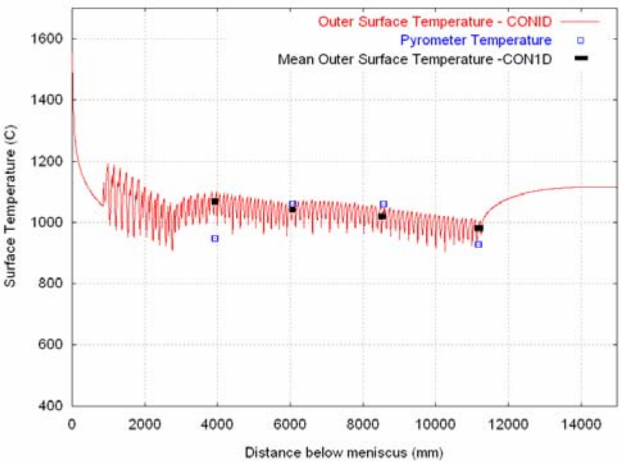
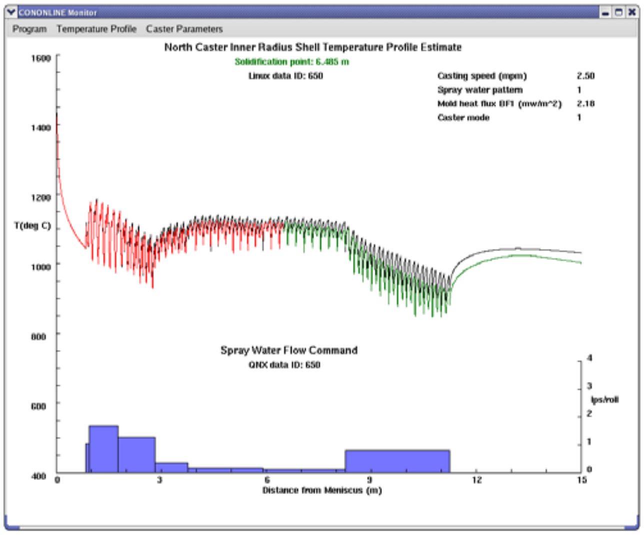


Fig. 4 Surface temperature history at steady state, comparing CON1D model predictions and steel plant measurements (3.5 m/min; spray pattern 4)

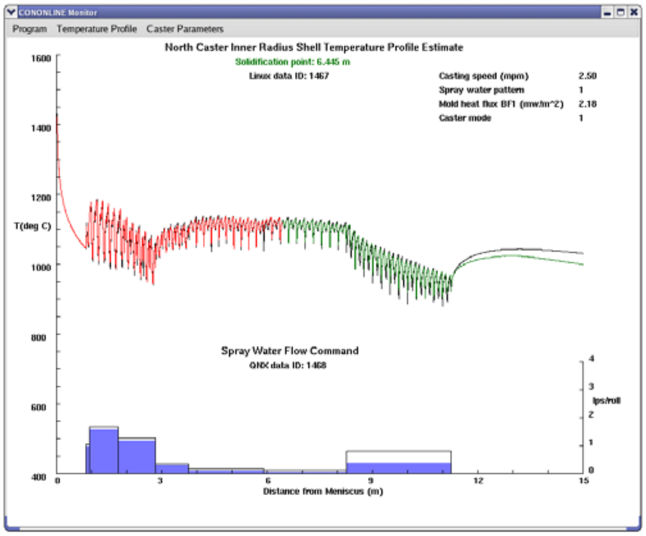
Although model validation is ongoing, the CON1D model is judged to be sufficiently accurate to implement into the control model.

7. Online Control System Development: A control system has been developed that integrates with the Level II system of a continuous caster, to control the spray water cooling flow rates in real time. The software implementation of this system, called CONCONTROLLER, includes a software sensor, called CONONLINE, which calls CON1D as a subroutine, a control algorithm to maintain desired temperature setpoints, and a monitor to display the results in real time. **Figures 5 and 6** show typical snapshots of the



Casting speed (mpm) 2.50
Spray water pattern 1
Mold heat flux BF1 (mw/m^2) 2.18
Caster mode 1

Fig. 5 Snapshot of realtime control monitor showing spray zone water flow setpoints, corresponding steady temperature profile, and predicted surface temperature history after a sudden drop in casting speed, using **conventional control algorithm**



Casting speed (mpm) 2.50
Spray water pattern 1
Mold heat flux BF1 (mw/m^2) 2.18
Caster mode 1

Fig. 6 Snapshot of realtime control monitor showing spray zone water flow setpoints, corresponding steady temperature profile, and predicted surface temperature history after a sudden drop in casting speed, using **new model-based control algorithm**

monitor, comparing the transient temperature distribution along the strand at the same instant taken 30s after a sudden change in casting speed, (from 2 m/min to 2.5 m/min at the typical rate of 0.02 m/min/s) using two different control strategies.

The conventional control scheme currently employed in the Nucor Decatur steel plant is based on interpolation between fixed setpoints. Several different sets of water flow rate setpoints that yield good performance in the steady state have been determined from past experience, for all seventeen spray zones at ten casting speeds. During transient operations, the setpoints are linearly interpolated to determine the water flow rates for the actual casting speed. Without regard to the actual dynamics of the casting process, the current control scheme increases the water flow rates proportionally to the actual casting speed under casting speed rises, causing overcooling of the casting slab.

A screen shot of the CONONLINE monitor, demonstrating the performance of the conventional control scheme in control of the CONONLINE model is shown in Fig. 5, where pronounced over-cooling is experienced in the last two spray zones. On the other hand, under casting speed drops the conventional control scheme decreases the water flow rates proportionally to the actual casting speed, resulting in under-cooling of the slab surface. Consequently, the conventional control system currently employed requires that casting speed changes are restricted to small and slow ramps, separated by constant casting speeds to minimize cracks resulting from the aforementioned over-cooling or under-cooling during transient operations. Exceptions to steady casting conditions are prone to defects.

These problems associated with a conventional controller are completely addressed by model-based PI control in CONONLINE, which exploits the shell temperature profile estimated by CONONLINE (and CON1D). Figure 6 shows the performance of the new control strategy, implemented in CONCONTROLLER in control of the CONONLINE model at the same time and conditions as used in Fig. 5.

A comparison of the estimated shell temperature profiles in these two figures clearly shows that the new CONCONTROLLER tracks the setpoint more closely. It is also observed from the instantaneous water flow rate profile at the bottom of Fig. 6, that much smaller water flow rates are needed during the transient, especially in the last two spray zones. This gives a clear explanation for the over-cooling problem indicated in Fig. 5.

To further evaluate the performance of the CONCONTROLLER with that of the current controller, the inner radius shell temperature history at the bottom of the last spray zone is plotted, shown in **Fig. 7**, for the above casting speed ramp change. It is clearly seen that the current control scheme results in prolonged undershoot with large magnitude, causing over-cooling of the casting slab, while the model-based PI control yields fast tracking of the shell temperature setpoint with a negligible undershoot. Offline testing has shown CONCONTROLLER to respond better to transient behavior during casting speed variations, especially low in the caster. The performance should improve even further when a new distributed parameter control design is implemented to replace the current PI logic (See Section 10).

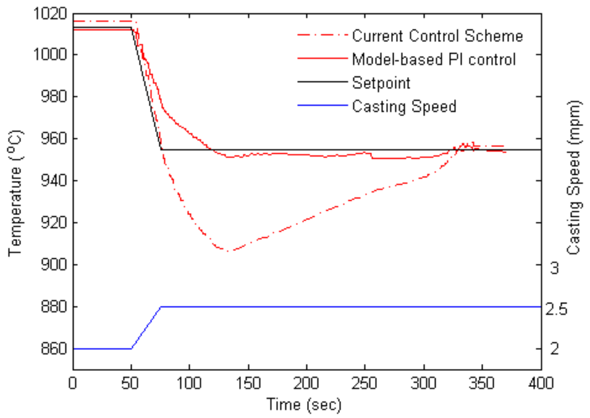


Fig. 7 Surface temperature histories predicted at 11200mm below meniscus for conventional and new model-based control systems, showing that new controller better tracks surface temperature during a change in casting speed

The new software-sensor based control system will greatly benefit steel quality at the steel plant, by maintaining temperature in the process more closely during transients. Moreover, the system, which runs in real time and accurately represents the behavior of a real caster, is a valuable research tool that enables scientific investigation of the continuous casting process. Future advances in control strategies and quality understanding can now be obtained using this system.

8. Laboratory measurement of water flow and heat transfer during spray cooling: Experiments have been initiated as part of this project to gain a more fundamental understanding of water spray cooling at high temperatures. The research focusses on the conditions found at the surface of the steel strand in the secondary spray cooling zones of steel continuous casting machine with water jet / air mist or "pneumatic" cooling. These conditions include a steel surface temperature range of 1300-700°C. Historically, hydraulic nozzles that only use water for cooling are used. Lately, pneumatic nozzles which force water out of the nozzle with pressurized air are becoming more popular because cooling severity is less. This has caused the characteristics of spray, e.g. droplet size and velocity, to play a more important role in cooling and, as literature search before starting this research showed, not enough of fundamental knowledge is available to fully understand the cooling mechanism. This understanding is very important in developing and implementing better boundary conditions for heat transfer models in continuous casting and gives more knowledge for people that design secondary cooling on capabilities of spray cooling. This research considers different air and water pressures, water impact density, time scales of the transient phenomena at the hot surface, water composition, and surface roughness. The research is being conducted in Saltillo, Mexico in co-operation with Cinvestav, a national research organization, owing to availability of specialized laboratory facilities for this type of research, and previous successful research in this field being conducted by Drs. Castillejos and Acosta.

The apparatus shown in **Fig. 8**, is for transient or unsteady state cooling conditions, where a sample steel plate is heated to the desired temperature and then quenched using different values of air and water pressures.

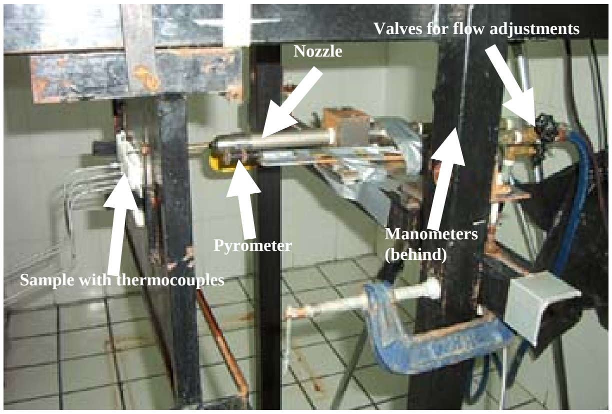


Fig. 8. Unsteady state measurement apparatus.

The first step to understand how heat transfer occurs is to measure the impact density, i.e. amount of water impacting in a unit area in unit time. The spray water exiting the nozzle is measured for a specific time using an unheated plate perforated with holes connected to tubes, called a "water collector". Impact density is calculated knowing the size of each collector hole and the spraying time. This is repeated for maximum and minimum operating conditions to see the changes caused by changes in water and air pressures. In **Fig. 9**, typical results are shown for a nozzle at both maximum and minimum operating conditions.

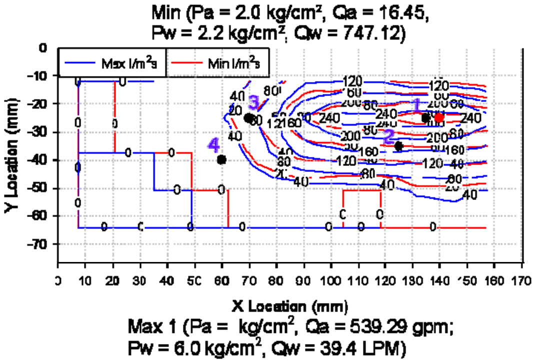


Fig. 9. Spray pattern corresponding to minimum and maximum operating conditions. Black dots thermocouple locations and the red dot is the nozzle centerline.

After the plate is instrumented with thermocouples at appropriate locations (based on the water collector results), it is heated up to between 700 and 1300°C, transported quickly to the spray station, and quenched down to room temperature. Typical measured cooling curves are shown in **Fig. 10**.

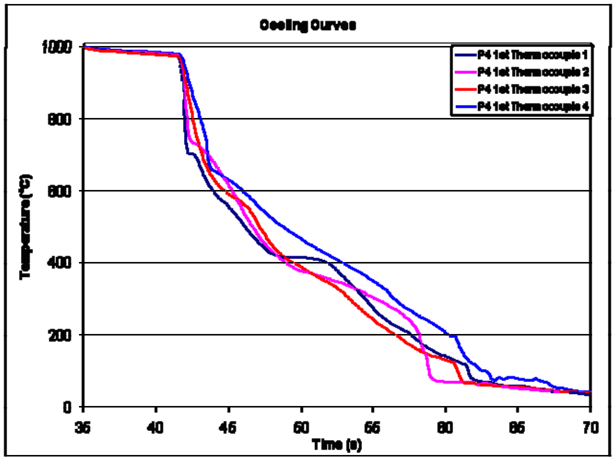


Fig. 10 Cooling curves from a transient experiment

Another approach to investigate spray cooling is to maintain the sample at a constant temperature while spraying it. An apparatus was designed for this purpose and is currently under construction. A schematic picture of the new apparatus is given in **Fig. 11**. The sample is sprayed and a thermocouple is used for monitoring its temperature. This information is sent to a controller that maintains the temperature in the sample by controlling induction heating. Both the temperature of the sample and the voltage needed for maintaining the temperature are recorded. From the recorded voltage it is possible to calculate the energy needed to maintain the temperature i.e. the energy extracted by environment and spray. With this apparatus, it is possible to measure transient heat extraction during the changes that occur during spraying at a constant temperature (due to boundary layer development, etc.) independently from the changes occurring due to changing temperature conditions.

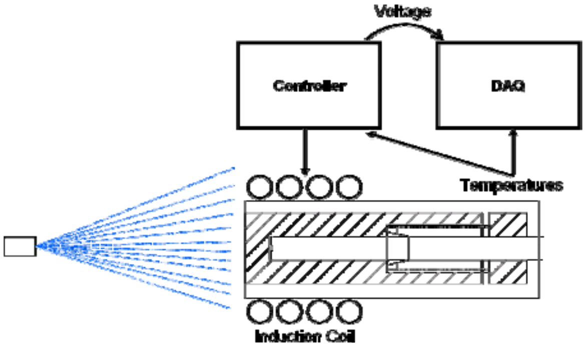


Fig. 11. New steady-state measurement apparatus.

9. Understanding Defect formation during Continuous Casting: To gain maximum benefit from a new spray-water control system, it is important to have a fundamental understanding of how defects form in the process. Parallel research is ongoing to achieve this aim. Work has been initiated to gain new insight into the mechanism of formation of defects associated with secondary spray cooling. These surface defects often initiate in the mold[6], especially at the meniscus[12], and later form surface cracks far below the mold in the secondary spray cooling zones. Cracks form at the roots of oscillation marks, which are prone to transverse crack formation during the spray cooling, depending on the temperature history. Thus, oscillation mark depth is also being studied.

10. Optimal Control Algorithm Development: Research in online control algorithms will lay the foundation for improved optimal prediction and predictive control of systems governed by the nonlinear parabolic PDEs that describe continuous casting. Recent advances have already been achieved in two such areas.

10.1 Robust Model Reference Adaptive Control of Parabolic and Hyperbolic Systems with Spatially-varying Parameters:

1. Objectives and methods

Recent developments in spatially distributed sensing and actuation and real-time computational capabilities have spurred an intensive exploration of various approaches to controller synthesis for distributed parameter systems (DPS). Both distributed and boundary partial differential equation (PDE) based sensing and control have been of interest, since for several important problems, such as, for example, solidifying shell temperature control in continuous steel casting, a single boundary control problem for a two-dimensional PDE can be well approximated by a pair of one-dimensional PDE distributed control problems - for the inner and the outer caster radii - characterized by the same disturbance with an approximately known model. In the latter application, distributed actuation is practically available, and the effort is underway in developing distributed sensing capability. The parameters of the casting process, such as heat transfer coefficients, are known to be non-smooth functions of a spatial variable due to contact of the solidifying shell with the fixed position rollers in the cooling zone of a caster. This functional dependence is known, however, only approximately, is influenced by a number of factors, such as steel grade and casting speed, and undergoes a slow time-variation caused by the solidifying shell motion. Therefore, identification and adaptive control of these systems are of interest.

The main long-standing drawback of the adaptive control laws has been the robustness deficiency that manifests itself in the possibility of a quick unpredictable algorithm blow-up, caused by setting the initial controller parameter values sufficiently far from the ideal ones, unknown a priori and/or selecting excessive reference input magnitude or adaptation gain.

2. Results and Findings.

This problem is solved in [2] for a class of DPS described by parabolic and hyperbolic PDEs with spatially-varying coefficients, removing a key obstacle in applicability of the PDE-based model reference adaptive control (MRAC) of DPS to such problems as control of continuous steel casting. This work [2] introduces the class of DPS to be considered, provides the main background definitions, and clearly brings out the robustness deficiency problem with the existing MRAC laws for these DPS. This reference introduces a novel direct MRAC structure given below that eliminates the problem both for the parabolic and the hyperbolic cases.

Plant: $u_t = (a(x)u_x)_x + b(x)u + f(x,t)$

Reference Model: $v_t = (a_1(x)v_x)_x + b_1(x)v + r(x,t)$

Adaptive control law: $f = r + \varepsilon_0 e + \eta_{a1} v_{xx} + \eta_{a2} v_x + \eta_b v$

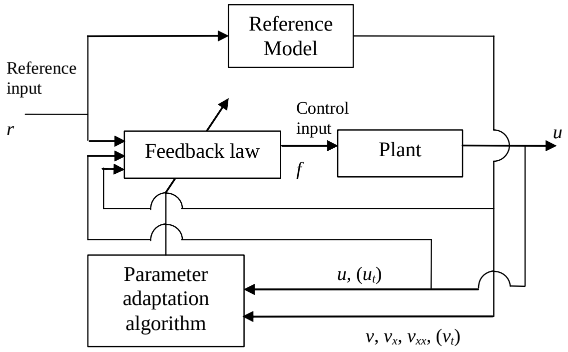


Fig. 12 Direct MRAC structure based control

The performance of this control law is shown in the following figure.

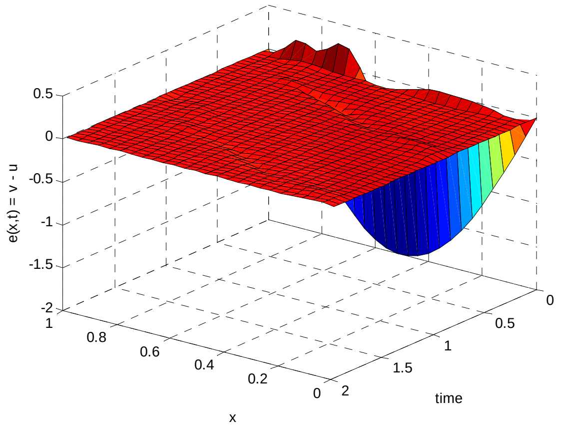


Fig. 13 Spatial and Temporal Variation of Error for Direct MRAC control law

In an effort to further enhance the performance and reduce the computational complexity of the control laws proposed when system parameters are characterized by a significant, not necessarily, smooth spatial variation, a technique for the finite-dimensionalization of the parameter adaptation laws based on multiresolution analysis is developed, as reported elsewhere. [2, 3] For this purpose, a new tool - the multiresolution Lyapunov functional is introduced. Through the wavelet-based parameter decomposition, the technique is applied to parameter adaptation laws for both parabolic and hyperbolic PDEs. The laws are shown to admit a low order high fidelity finite-dimensionalization when the wavelet basis is matched to the main plant parameter features, such as nonsmoothness, known a priori. Using the corresponding multiresolution Lyapunov functional, the stability of the closed loop system with the finite-dimensional parameter adaptation law and the infinite-dimensional plant is rigorously proven for both equation types. The advantages of the finite-dimensionalization approach proposed - reduction of computational demand and increase in the output convergence rate with no corresponding increase in the control effort are demonstrated, as well. This work[2, 3] develops inite-dimensionalization technique for the parameter adaptation laws proposed. Numerical simulations supporting the assertions made and showing attainment of good performance for the settings earlier characterized by instability are presented below.

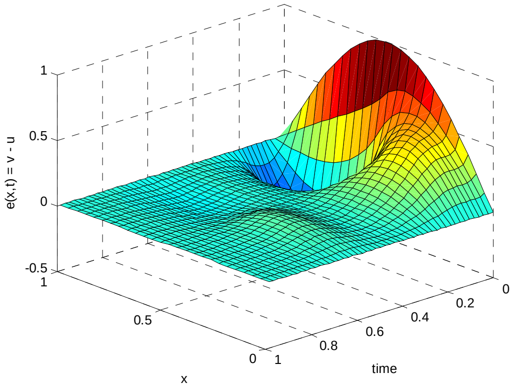


Fig. 14 Performance of infinite-dimensional technqiue

10.2 Disturbance Rejection in Robust Model Reference Adaptive Control of Parabolic and Hyperbolic Systems with Spatially-varying Parameters

1. Objectives and methods

Rejection of broad classes of disturbances in systems with unknown parameters, but known parameter structure is a nontrivial practically important problem. In the finite-dimensional case, this problem is typically addressed through adaptive control laws modified to reject the disturbance class of interest. However, the standard finite-dimensional adaptive control configurations, such as those falling under MRAC, do not, in general, transition into the infinite-dimensional setting in a well-posed manner. Therefore, attaining similar disturbance rejection performance in distributed parameter case presents a considerable challenge.

2. Results and Findings.

This problem is solved in [4]. Based on the well-posed MRAC configurations recently introduced [2], this work develops the well-posed error systems and the corresponding robust MRAC laws with disturbance rejection for a class of systems represented by parabolic or hyperbolic PDEs with spatially varying parameters. Disturbances are assumed to be generated by a known model and lie in the system input space. Control signal is, then, shown to include the disturbance estimate generated by the corresponding distributed parameter Luenberger-type observer. The well-posed error systems and the corresponding algorithms for parabolic and hyperbolic PDEs are derived, with the disturbance rejection properties exhibited in numerical simulations. For simplicity, derivations are carried out for a single spatial domain. The paper considers distributed sensing and actuation as well as distributed disturbance. This setting is of interest in a number of applications, such as continuous steel casting.

Plant: $u_t = (a(x)u_x)_x + b(x)u + f(x,t) + d(x,t)$

Reference Model: $v_t = (a_1(x)v_x)_x + b_1(x)v + r(x,t)$

Adaptive control law: $f = r + \varepsilon_0 e + \eta_{a1} v_{xx} + \eta_{a2} v_x + \eta_b v$

Disturbance model: $d_t = (a_d(x)d_x)_x + f_d$

Schematics of adaptive controller and disturbance observer is given by:

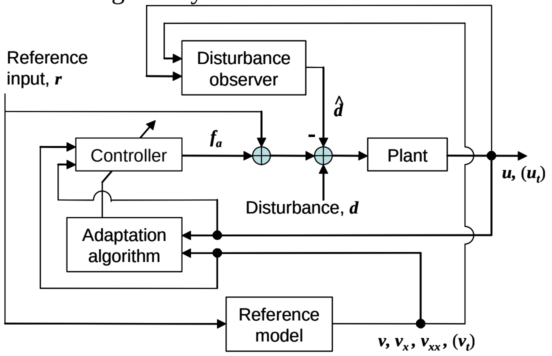


Fig.15 Adaptive controller and disturbance observer

The performance of this control law is shown in the following figure:

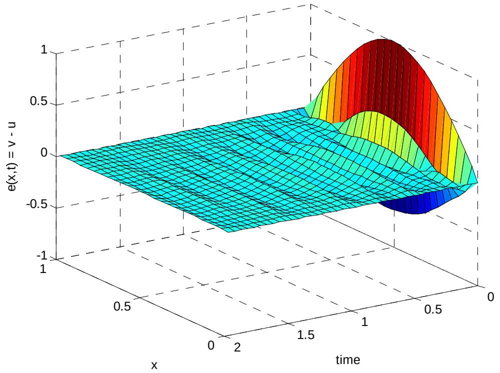


Fig. 16 Performance of adaptive control law

11. Significant Findings: A new online computer model-based control system is being created to control solidification and temperature development during the continuous casting of steel. It features an accurate and fundamentally-based dynamic software sensor of the spray-cooling region which is integrated with online measurements of mold heat extraction and other process parameters. By maintaining the steel temperature through operational transients, this system aims to enable faster and more efficient casting with improved quality of the steel product. This multi-faceted research project includes the development, validation, and calibration of the online control models, laboratory measurements to better characterize heat transfer during spray cooling, improved control algorithms, and increased understanding of defect formation in the continuous casting process. Work this past year has obtained several new findings, which are significant to the project goals. Most significant are:

- A novel modeling algorithm is able to update in real time, the complete solidification and temperature profile in two dimensions at every second during continuous online operation.
- The new control system maintains temperature more closely than the conventional control system currently in use at most plants.
- This new modeling tool is now available to study thin-slab casting behavior, to enable future process and control improvements
- New optimal control algorithms have been developed, with application to the equations governing heat transfer in continuous casting.

12. Acknowledgments: This work is supported by the National Science Foundation (Grant # DMI-0500453) and the Continuous Casting Consortium at the University of Illinois. Thanks are also extended to industry collaborators at Nucor Steel, Decatur, AL, including Ron O'Malley, Matt Smith, Rob Oldroyd, and Terri Morris. The authors also wish to thank the National Center for Supercomputing Applications at the University of Illinois for computing time.

13. References:

1. "World Steel in Figures," International Iron Steel Institute, Brussels, Belgium, www.worldsteel.org, 2004.
2. Kim, J. and J. Bentsman, "Robust Model Reference Adaptive Control of Parabolic and Hyperbolic Systems " IEEE Transactions on Automatic Control (submitted), 2005.
3. Kim, J. and J. Bentsman, "Multiresolution Finite-Dimensionalization of Parameter Update Laws in Adaptive Control of Distributed Parameter Systems," 45th IEEE Conference on Decision and Control, (San Diego, CA, Dec. 13-15, 2006), IEEE, submitted, 2006.
4. Kim, J. and J. Bentsman, "Disturbance Rejection in Robust Model Reference Adaptive Control of Parabolic and Hyperbolic Systems," 45th IEEE Conference on Decision and Control, (San Diego, CA, Dec. 13-15, 2006), IEEE, submitted, 2006.
5. Meng, Y. and B.G. Thomas, "Heat Transfer and Solidification Model of Continuous Slab Casting: CON1D," Metal. & Material Trans., Vol. 34B (5), 2003, 685-705.
6. Meng, Y. and B.G. Thomas, "Simulation of Microstructure and Behavior of Interfacial Mold Slag Layers in Continuous Casting of Steel," ISIJ International, Vol. 46 (5), 2006, May.
7. Brimacombe, J.K., P.K. Agarwal, S. Hibbins, B. Prabhaker and L.A. Baptista, "Spray Cooling in the Continuous Casting of Steel," Vol. 2, Continuous Casting, ISS/AIME, Warrendale, PA, 1984, 109-123.
8. Nozaki, T., "A Secondary Cooling Pattern for Preventing Surfcace Cracks of Continuous Casting Slab," Trans. ISIJ, Vol. 18, 1978, 330-338.
9. Hardin, R.A., H. Shen and C. Beckermann, "Heat Transfer Modeling of Continuous Steel Slab Caster Using Realistic Spray Patterns," Modelling of Casting, Welding and Advanced Solidification Processes IX, (Aachen, Germany, 20-25 Aug. 2000), TMS, Warrendale, PA, 2000, 729-736, 190.
10. Thomas, B.G. and C. Ojeda, "Ideal Taper Prediction for Slab Casting," ISSTech Steelmaking Conference, (Indianapolis, IN, USA, April 27-30, 2003), Vol. 86, 2003, 396-308.
11. Cicutti, C., MartinValdez, T. Perez, G. DiGresia, W. Balante and J. Petroni. Mould Thermal Evaluation in a Slab Continuous Casting Machine. Steelmaking Conference Proceedings. Vol. 85 (2002), 97-107.
12. Sengupta, J., B.G. Thomas, H.J. Shin, G.G. Lee and S.H. Kim, "Mechanism of Hook Formation during Continuous Casting of Ultra-low Carbon Steel Slabs," Metallurgical and Materials Transactions A (in press), 2006.