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

Activities

In this multifaceted project to improve control of spray cooling heat transfer in continuous casting of steel with the aid of fundamentally-based models, activities have proceeded on several different subprojects:

1) Efficient fundamental model of solidification and temperature in thin slab casting: CON1D
2) Software Sensor, CONSENSOR
3) Online control system development, CONONLINE
4) Laboratory measurement of water flow and heat transfer during spray cooling
5) Steel plant experiments for model validation
6) Understanding defect formation during continuous casting
7) Control of mold fluid flow
8) Advance Control Algorithm Development

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 continuously reads in operating conditions and mold temperatures and continuously adjusts 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 can be set by steel plant engineers, in order to minimize the formation of cracks and other defects. The system is currently being 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 being developed and investigated in this work must overcome many challenges, including the high speed of the process and increased relative importance of mold solidification.

1. Computational model of solidification and temperature development in thin slab casting: CON1D

The control system is based on a software sensor, which is based on a solidification model developed in previous work, CON1D.[1] Modifications made to the CON1D model as part of this project include:

a) changing the modeling of heat transfer in the mold to force the total heat flux to match the measured input value;

b) incorporating the increase in heat transfer that occurs during nucleate boiling, according to the Leidenfrost temperature;

c) Mesh and time-step studies were performed to optimize the program to run faster to enable it to serve as part of a real-time control model.

d) extending the model to simulate both inside and outside of the strand, as it was found that heat transfer was different in these 2 regions, and this affects both the temperature, and the final solidification point.

e) 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.[2, 3]

This work has enabled the model, which is now ready to calibrate, validate, and implement as a software sensor into a control system.

These activities can be better understood by examining the schematic of steel casting process **Fig. 1**, and the close-up of the region between two rolls in the spray zone given in **Fig. 2**.

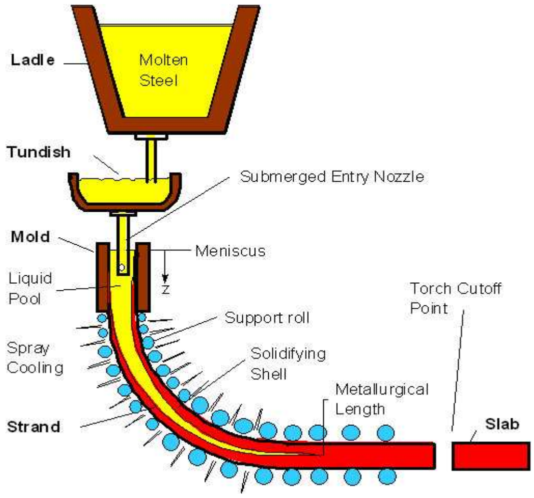

Fig. 1. Schematic of Steel Processing including ladle, tundish, and continuous casting

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.

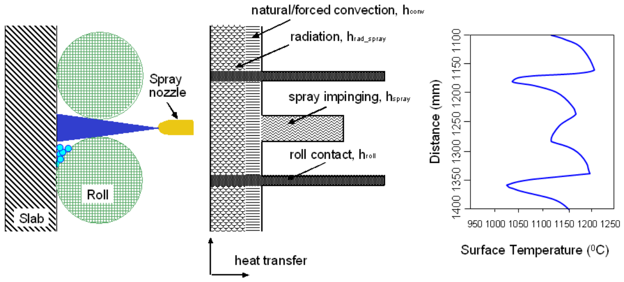

Fig. 2. Schematic of the spray region of the thin-slab steel caster, and corresponding heat transfer, and surface temperature profiles.

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 model 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.[1, 4] 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.

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 [5] of the following form:

$$h_{spray} = A \cdot Q^c_{water} \cdot \left(1 - b \cdot T_{spray}\right) \qquad [1]$$

where Q_{water} (l/m^2s) is water flux in spray zones and T_{spray} is the temperature of the spray cooling water. In Nozaki's empirical correlation [6], A=0.3925, c=0.55, b=0.0075, which has been used successfully by other modelers.[5, 7] 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^{o}C.

Radiation is calculated by:

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

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^{o}C. Beyond the spray zones, heat transfer simplifies to radiation and natural convection.

Further details on the model equations, boundary conditions, numerical discretization, previous validation efforts and other applications are given elsewhere.[1]

2. Software Sensor CONONLINE

In this project, the CON1D model described in the previous section has been adapted to serve as a "software sensor" in place of hardware temperature sensors for use in the control system. Traditional feedback control of the secondary cooling sprays has not been implemented in commercial casters, primarily due to the difficulty of operating sensors in the spray region. Optical pyrometers can be inaccurate due to emissivity variations from intermittent surface scale on the steel and diffraction through the water spray and steam. Even with reliable pyrometers, open-loop model-based estimation still would likely be needed to fill the gaps between their highly-localized readings to attain reasonable performance.

The CON1D model predicts the complete transient temperature history of a single slice through the caster. The software sensor must output the complete temperature history of every position in the caster, and update the entire two-dimensional temperature continuously with time. Adopting the CON1D model into the CONONLINE software sensor was thus a very challenging task.

3. Online Control System Development: CONCONTROLLER

A control system has been developed that integrates with the Level 2 system of a continuous caster, to control the spray water cooling flow rates in real time. The software implementation of this system includes 1) the software sensor CONONLINE, 2) a monitor to display the results in real time, and to manually enter temperature setpoint profiles (as desired), and 3) a control algorithm CONCONTROLLER to regulate the surface temperature, in addition to network software to maintain communications and shared memory. Fig. 3 shows a schematic of the control system developed in this work.

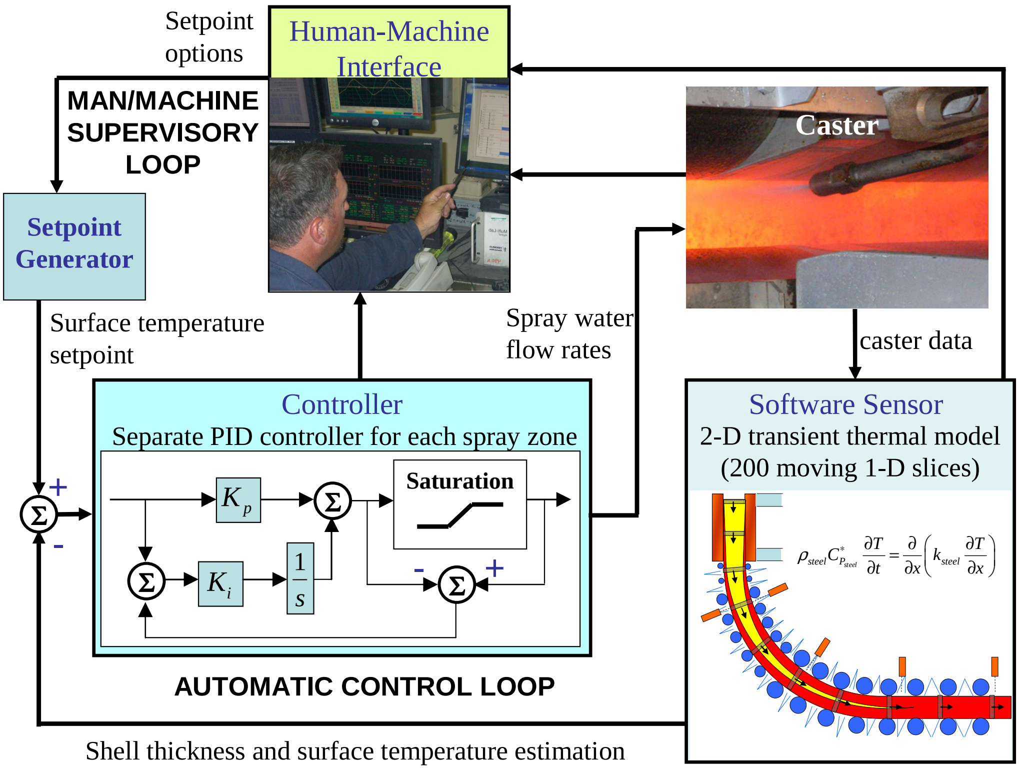

Fig. 3. Software sensor based control diagram

4. 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.[8] The research focuses 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. The boundary condition for secondary cooling in CONONLINE is presented in Eq. 2. The coefficients of this model depend on careful measurement.

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. These "air-mist" nozzles depend on the characteristics of spray, e.g. droplet size and velocity, 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 to developing and implementing better boundary conditions for heat transfer models in continuous casting and would allow better design of secondary cooling systems.

This research investigates the effects of 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.[9]

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.

The next (main) experiments aim to measure the heat extraction rate from the hot steel surface as a function of spray conditions, and to extract heat transfer coefficients to enable the models to accurately predict this behaviour. The apparatus shown in **Fig. 4**, 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. For transient experiments, the plate is first instrumented with thermocouples at appropriate locations (based on the water collector results). Then, it is heated up to between 700 and 1300°C, transported quickly to the spray station, and quenched down to room temperature.

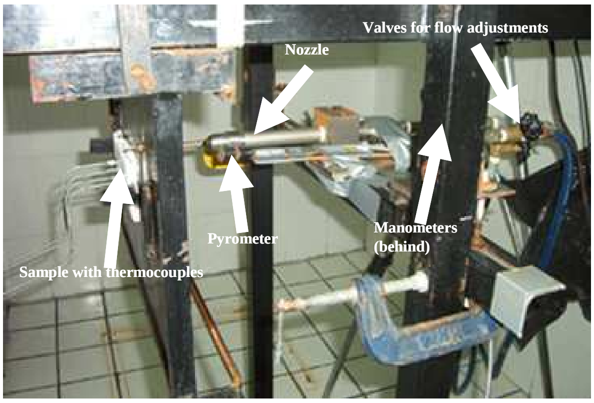

Fig. 4. Unsteady state measurement apparatus.

With the high cooling rates of air-mist nozzles, the temperature drops very quickly during the transient experiment, so heat transfer coefficients correspond with only a few seconds of data. However, forming a stable steam layer may take more time, especially with the small droplets of air-mist cooling. Thus, spray heat transfer is likely dynamic and is a complex function of droplet momentum, surface roughness, and surface temperature.

To overcome this problem, this work is adopting another approach to investigate spray cooling by maintaining the sample at a constant temperature while spraying it. An apparatus was designed and constructed for this purpose, as part of this project, as pictured in **Fig. 5**.

The sample is sprayed and a thermocouple is used to monitor 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 power needed for maintaining the temperature are recorded. From the recorded power 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.

To minimize oxidization, platinum is used as the sample material instead of steel for the initial experiments. To maintain constant temperature, the sample is heated by induction coils while it is sprayed. Induction current is controlled to maintain the temperature monitored by a thermocouple via closed-loop control.

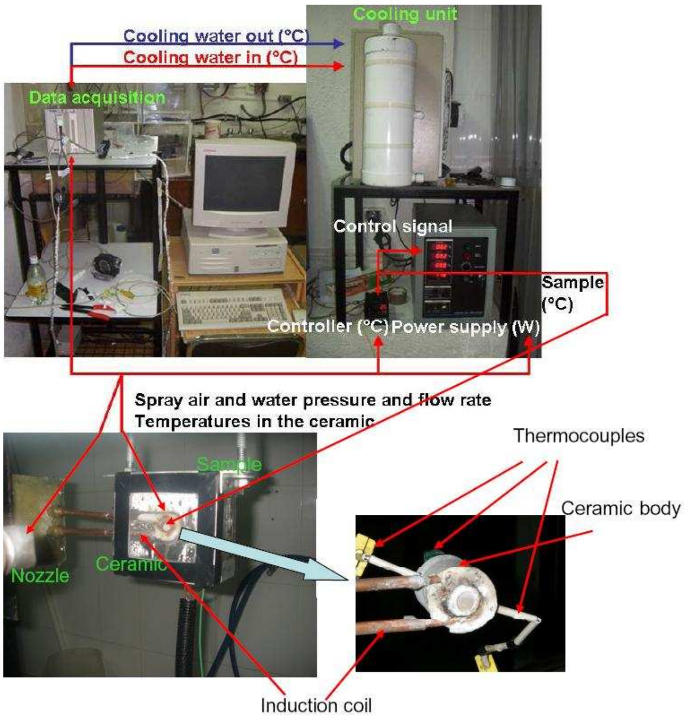

Fig. 5. New steady-state measurement apparatus.

A schematic of the new apparatus is given in **Fig. 6**.

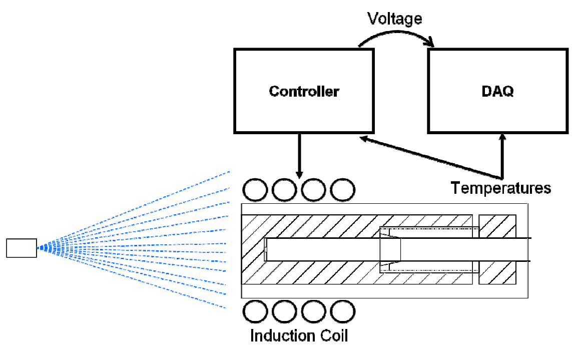

Fig. 6. New steady-state measurement apparatus.

5. Steel Plant Experiments for Model Validation and Calibration:

Experimental trials have been carried out at Nucor Steel, Decatur, Alabama, and at Mittal Steel, Riverdale, in order to measure slab surface temperature variations with optical pyrometers. In addition, mold heat flux is measured from the temperature rise of the cooling water, knowing the water flow rate. These results are being used to calibrate the CON1D model (and thereby also CONSENSOR for CONONLINE).

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 and software sensor, CONSENSOR. 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, as pictured in **Fig. 7**.

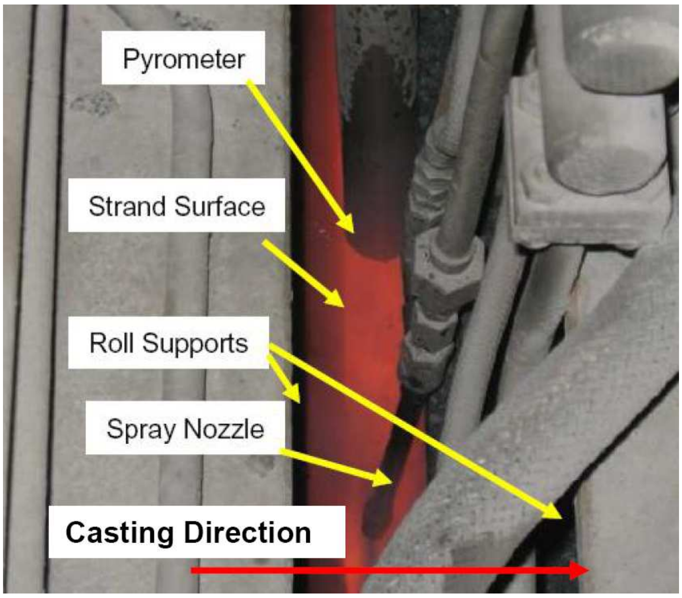

Fig. 7 Pyrometer arrangement in the south Nucor caster

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, 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 was 1548 $^{\circ}$C.

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

6. 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[4], especially at the meniscus[10], 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, and the formation of embrittling precipitates. Thus, oscillation mark depth, hook formation, and other defects are also being studied. As a first step to predict precipitate formation, a model has been developed, based on fundamental simulation of particle growth from individual molecules to real precipitates, using a size-grouping model approach[11].

7. Control of Mold Fluid Flow:

Many casting defects are caused by problems with fluid flow and heat transfer in the mold. To control fluid flow in the mold, an electromagnetic brake (EMBr) force is applied in many thin slab casters, including Nucor. A computational fluid flow model has been developed and applied to investigate the effects of varying SEN submergence depth and EMBr field strength on flow in the mold cavity [12]. The three-dimensional, steady k-ε model of the nozzle and liquid cavity in the mold used the magnetic induction method in FLUENT to incorporate the localized-type static EMBr field measured at a steel plant. This model can be used to predict optimal operation of the EMBr to minimize fluid flow problems. Combined with better control of spray cooling below the mold, the overall quality of the continuous-cast product can be improved.

8. 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 three such areas.

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

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. The novel globally stable algorithm structures have been investigated that aim at complete elimination of the algorithm blow-up and attainment of robust performance for arbitrary initial controller parameters.

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

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. To address this challenge, the novel globally stable disturbance rejection structures have been studied that incorporate the disturbance model.

8.3. Bumpless Transfer: Smooth Online Switching Between the Currently Used Controller and the New Controller:

Reliable and well-behaved switching among controllers, or bumpless transfer, is an important element of modern advanced control practice. One of its uses is the benchmarking of the new controller against the existing one - the goal of the current project, the other use is switching among several controllers to cover the entire operating load range of the plant. Modern bumpless transfer uses analytical models of the controller to set up the transfer configuration. However, in the complex computational/communication environment, like the one at Nucor, the analytical controller models cannot take into account time-varying computational/communication delays and other uncertainties. New algorithms for bumpless transfer are being developed to solve this problem.

Summary:

This document has summarized the activities of eight different sub-projects which comprise this multi-faceted research project. Further details can be found in 21 publications,[8, 11-30] a nonprovisional patent application,[31], and in the website http://ccc.mechse.uiuc.edu.

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