Online Control of Spray Cooling Using
Cononline

Bryan Petrus
BG Thomas
Joseph Bentsman

Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

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Overview

• Cononline Overview
  – Consensor: “software sensor”
  – Concontroller: PI controller bank
  – Monitor

• Real-time simulations
  – Startup
  – Tailout
  – Setpoint change

• Future research

Project Motivation: Approaches to Cooling Spray Control

1) Manual control:
   – Operator sets of water flow rates
   – Difficult at high casting speeds when response times must be short

2) Casting-speed-based control:
   – Set water flow rates according to casting speed
   – Results in non-optimal cooling during transient conditions

3) Conventional feedback control:
   – Limited measurement opportunities
   – Pyrometers etc. can be unreliable in spray zones

4) Software-sensor-based control:
   – Create “software sensor,” an accurate, real-time computational model to base control on
Overview

Surface temperature setpoint

Water flow rate command

Controller

Caster

Software Sensor
(CON1D subroutine)

Monitor

Parameters (updated every heat from level 2)

Parameters (updated at calibration through input file)

e.g. steel composition

e.g. caster and mold geometry

Measurements (updated every second), e.g. mold heat removal rate, casting speed

Slab temperature, shell thickness

Computer Architecture

Current control logic

Level 2

Consensor

Model Computer (CENT OS Linux)

CommServer

Controller Computer (Slackware Linux)

CommClient

AXServer

Concontroller

Monitor

TCP/IP connection

Shared memory connection
**Consensor Overview: CON1D**

- Fundamentally based transient finite-difference model:
  \[
  \rho_{\text{steel}}C_{\text{steel}} \frac{dT}{dt} = k_{\text{steel}} \frac{\partial^2 T}{\partial x^2} + \partial k_{\text{steel}} \left( \frac{\partial T}{\partial x} \right)^2
  \]

- CON1D predicts:
  - shell thickness
  - temperature distribution
  - heat flux profiles

- Suitable for real-time model
  - Can simulate entire caster in < 1 second
  - “Restart mode”: Can stop simulation at arbitrary point, continue later

**Consensor Overview**

- Multiple “slices”
  - Each second, simulate each slice for 1 second
  - 200 slice simulation for 1 second each takes ~ same time as 1 slice through entire caster: < 0.5 seconds

- Consensor
  - stores and manages 200 CON1D slices
  - Interpolates between slices to estimate full shell & temperature profile
Concontroller Overview: Spray Zones

- Zone 1
- Zone 2

Zone 3

Zone 4

Zone 5 (Inner/Outer)

Zone 6 (Inner/Outer)

Zone 7 (Inner/Outer)

4 x 1 + 3 x 2 = 10 controllers

Concontroller Overview

- Zone-based PI control: 10 individual PI controllers, one for each spray zone

- **Controller Algorithm:** At each second of time:
  1. Obtain surface temperature profile from CONONLINE.
  2. For all 10 zones:
     i. Compute the zone-based surface temperature average $T_{\text{avg}}$ for current zone. And form the tracking error $T_{\text{err}} = T_{\text{avg}} - T_{sp}$
     ii. Use $T_{\text{err}}$ to compute the water flow rate command:

\[
\Delta \text{flow}(t) = k_p T_{\text{err}}(t) + k_i \int_0^t T_{\text{err}}(s) ds
\]

  3. Send all water flow rate commands to Consensor, Caster, and Monitor
Setpoint Methodologies

1. Speed-based spray flow setpoints – current Nucor spray practices

2. Temperature setpoints (zone-averages) based on steady states for flows in (1)

3. Vary (2) based on casting conditions
   - Casting speed
   - Mold exit temperature (mold heat flux, superheat)

4. Operator-chosen temperature setpoints

<table>
<thead>
<tr>
<th>Zone</th>
<th>Speed 1</th>
<th>Flow Rate 1</th>
<th>Speed 2</th>
<th>Flow Rate 2</th>
<th>Speed 3</th>
<th>Flow Rate 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>0</td>
<td>0</td>
<td>15.7</td>
<td>26</td>
<td>31.5</td>
<td>26</td>
</tr>
<tr>
<td>Zone 2</td>
<td>0</td>
<td>0</td>
<td>15.7</td>
<td>26</td>
<td>31.5</td>
<td>26</td>
</tr>
<tr>
<td>Zone 3</td>
<td>0</td>
<td>0</td>
<td>15.7</td>
<td>26</td>
<td>31.5</td>
<td>26</td>
</tr>
</tbody>
</table>

Monitor Overview:
Profile Screen
Monitor Overview

Monitor Overview: Parameter Screen
Real-time Simulations

- Caster data recorded at Nucor Decatur
  - thanks to Terri Morris, Rob Oldroyd, and Alan Hable
- Simulations run in real-time at UIUC
  - HP DL380 G5 servers, Intel Xeon processors
- Situations:
  1. Casting startup
  2. Slab tailout
  3. Change in temperature setpoints

Startup

- Simulating recorded caster data at Nucor Decatur
- 0.03 % Carbon steel
- Played at 3x speed
Startup

Startup – With PI Control
Tailout

- Simulating recorded caster data at Nucor Decatur
- 0.05 % Carbon steel
- Played at 3x speed

Meniscus to Strand Tail Distance

![Graph showing Meniscus to Strand Tail Distance](image)

Mold Heat Removal (BFI)

![Graph showing Mold Heat Removal (BFI)](image)

Cast Speed

![Graph showing Cast Speed](image)

Mold Heat Removal (BFI)

![Graph showing Mold Heat Removal (BFI)](image)

Heat Flux (MW/m²)

![Graph showing Heat Flux](image)
Temperature Setpoint Change

- Casting conditions based on initial state in previous tailout simulation
  - 0.05 % Carbon steel
  - 3.0 m/min casting speed
  - 26 °C superheat
- Setpoint in 4th zone changed by operator
  - Initial value: 1071 °C (1960 °F)
  - Changed to: 1000 °C (1832 °F)
- Played at 3x speed
PI Control – Operator Changes

Setpoint

Advanced Control Development

- Anti-windup
  - Actuator saturation can lead to windup of integral controller
  - Simple anti-windup scheme added

- Optimal control law development
  - In progress
  - Control laws have been designed for 1-D heat equation with spatially varying parameters

- Metallurgical length (ML) control
  - In progress
Future Research

• Software sensor
  – Make model robust to casting conditions and data errors
  – Improve accuracy of model by adding physical behavior
    • More accurate heat transfer coefficients (Sami, Xiaoxu’s research)
    • Possible hysteresis effects during spray changes

• Intelligent metallurgical length control
  – Temperature tracking does not guarantee shell profile
  – Need to balance temperature tracking versus metallurgical length control
    • System “envelope” to describe safe temperature setpoints?
    • Moving boundary control, optimal, or predictive controller design?