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Online Control of Spray Cooling Using Cononline

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- Nucor Decatur
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- Other CCC grad students
  - Huan Li, Sami Vapalahti, Xiaoxu Zhou

Overview

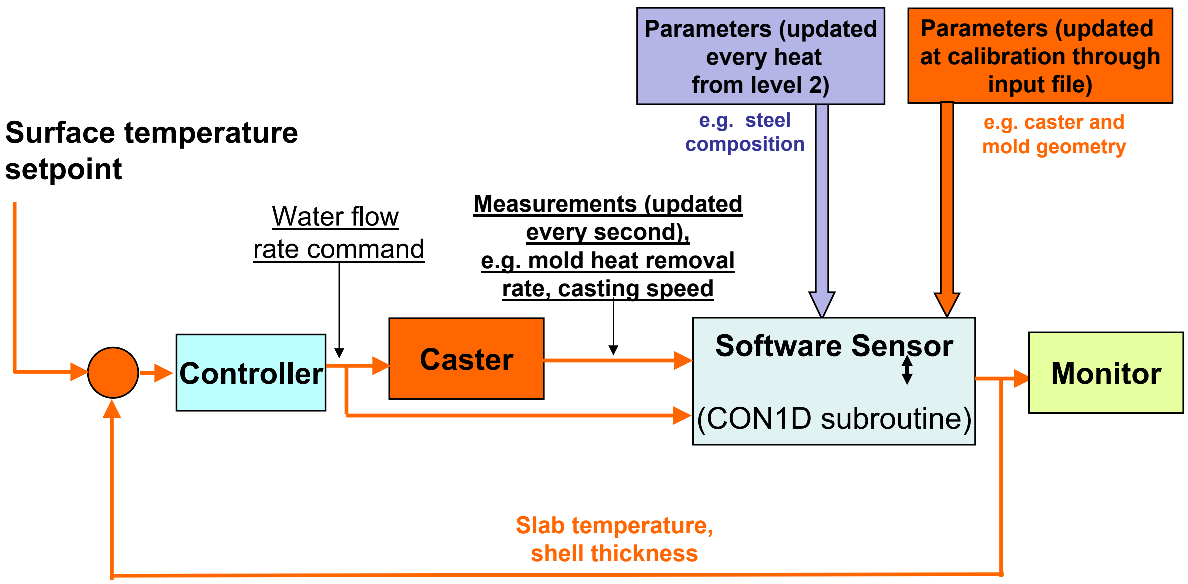
- Cononline Overview
  - Consensor: “software sensor”
  - Concontroller: PI controller bank
  - Monitor
- Real-time simulations
  - Startup
  - Tailout
  - Setpoint change
- Future research

Project Motivation: Approaches to Cooling Spray Control

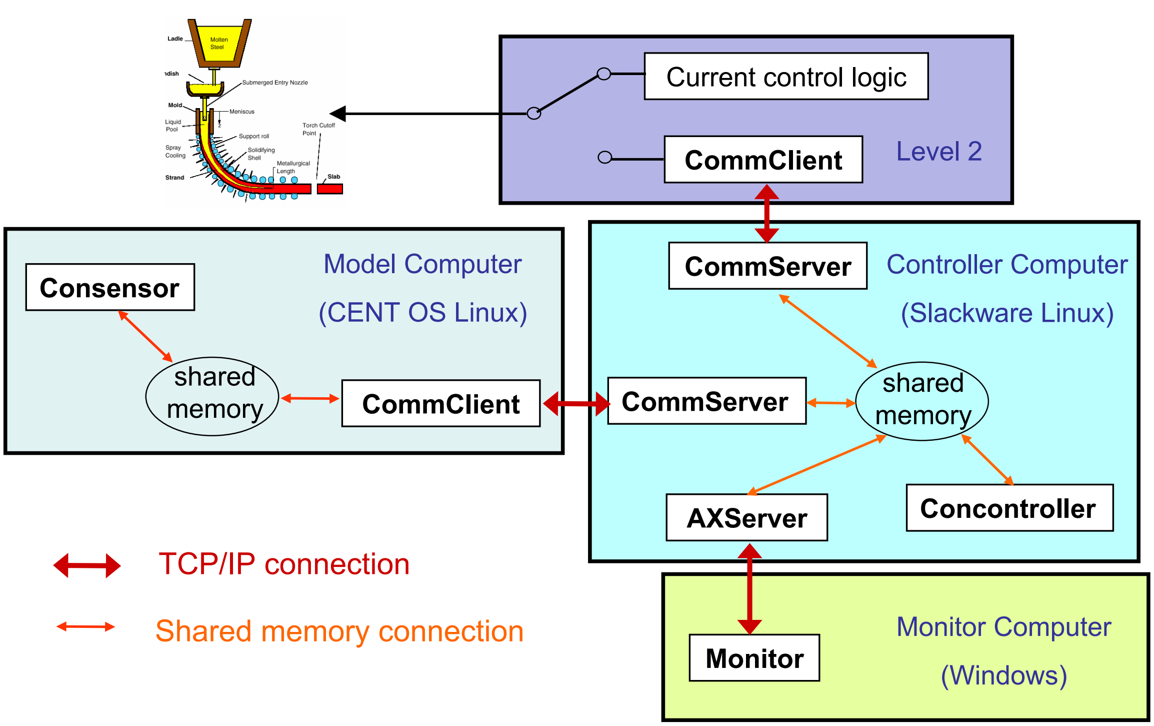
1) **Manual control:**
   - Operator sets of water flow rates
   - Difficult at high casting speeds when response times must be short
2) **Casting-speed-based control:**
   - Set water flow rates according to casting speed
   - Results in non-optimal cooling during transient conditions
3) **Conventional 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



Computer Architecture



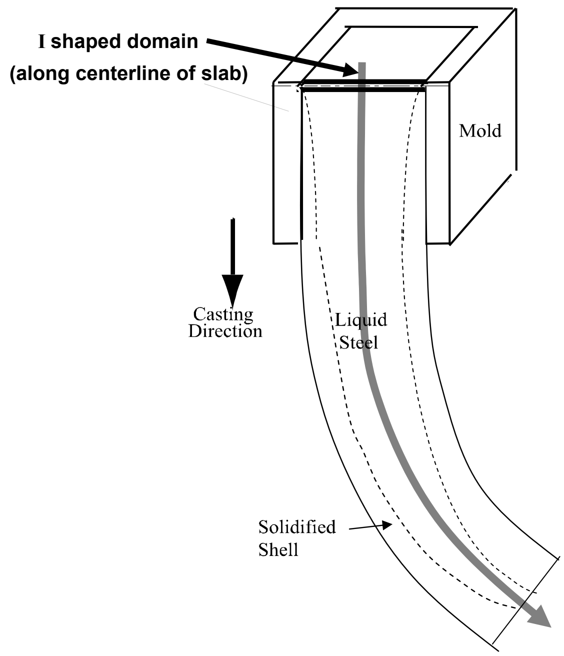
Consensor Overview: CON1D

- Fundamentally based transient finite-difference model:

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

- 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

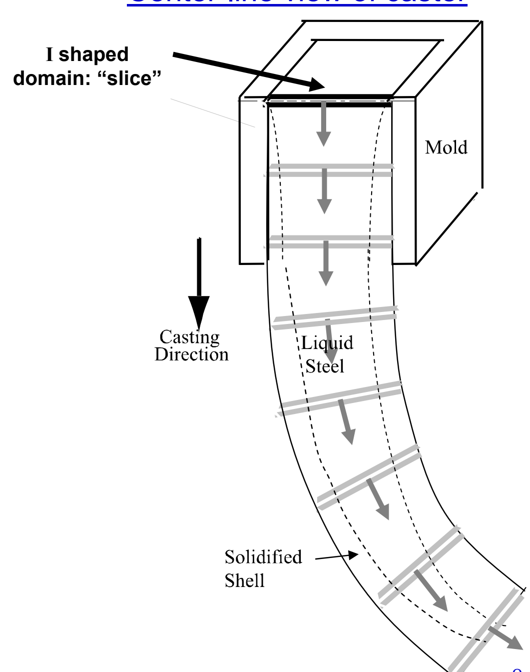
Center-line view of caster



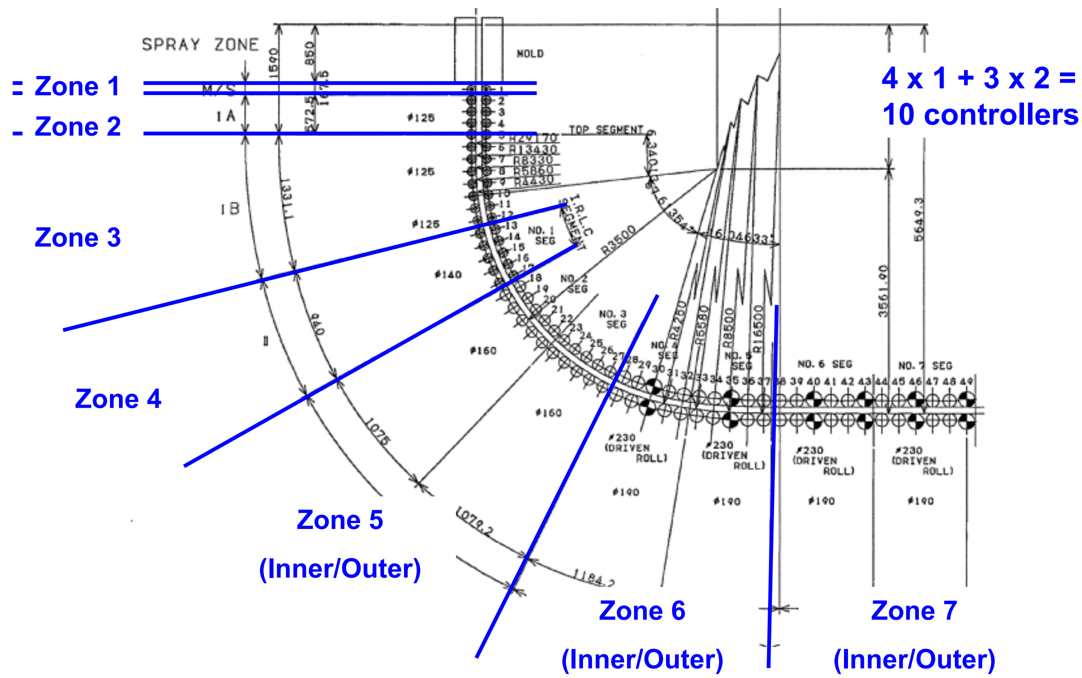
Consensor Overview

- 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

Center-line view of caster



Concontroller Overview: Spray Zones



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_{avg} for current zone. And form the tracking error $T_{err} = T_{avg} - T_{sp}$
     ii. Use T_{err} to compute the water flow rate command = Nominal_flow + Δflow(t),

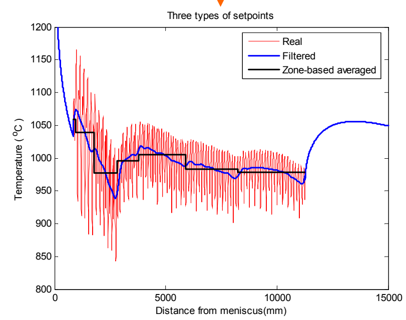
$$\Delta flow(t) = k_p T_{err}(t) + k_i \int_0^t T_{err}(s)ds$$

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

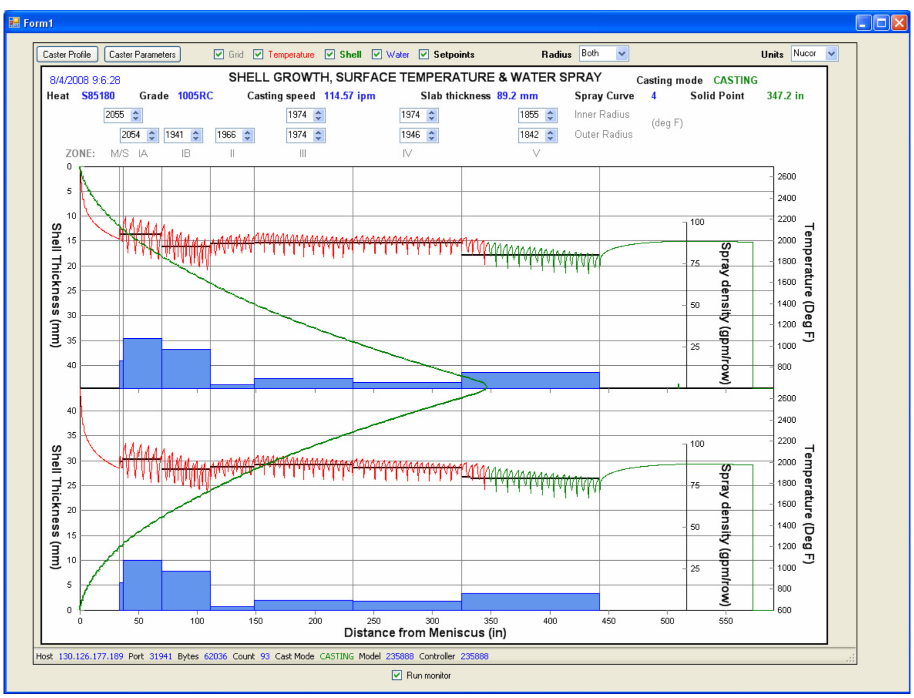
Setpoint Methodologies

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

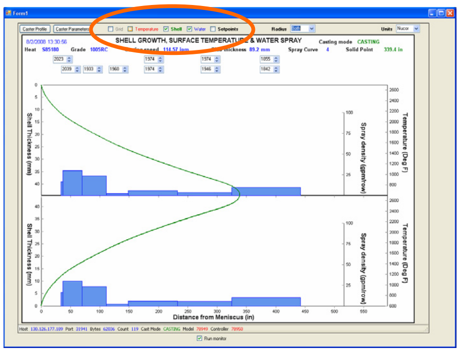
	Pattern 1 (i/min) (gal/min)	Pattern 2 (in/min) (gal/min)	Pattern 3 (in/min) (gal/min)	Pattern 4 (in/min) (gal/min)
Zone 1, Speed 1	0	0	0	0
Zone 1, Flow Rate 1	0	0	0	0
Zone 1, Speed 2	15.7	15.7	15.7	15.7
Zone 1, Flow Rate 2	26	24	26	23
Zone 1, Speed 3	31.5	31.5	31.5	31.5
Zone 1, Flow Rate 3	26	24	26	23

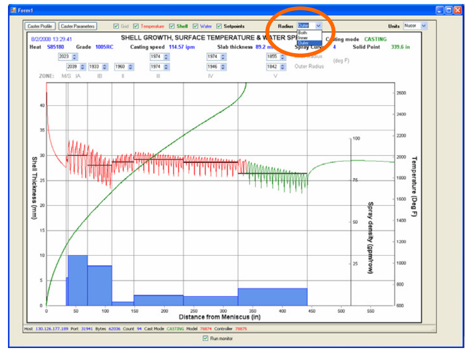


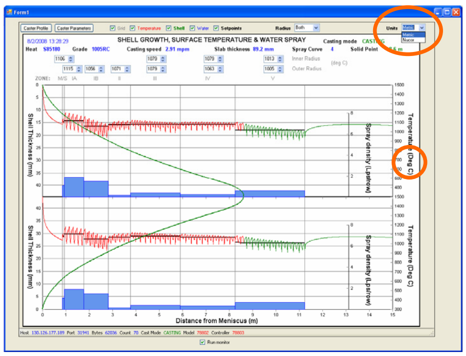
Monitor Overview: Profile Screen

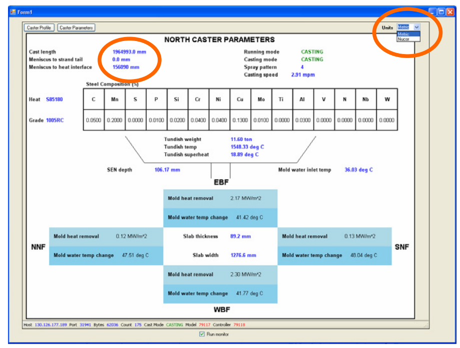


Monitor Overview

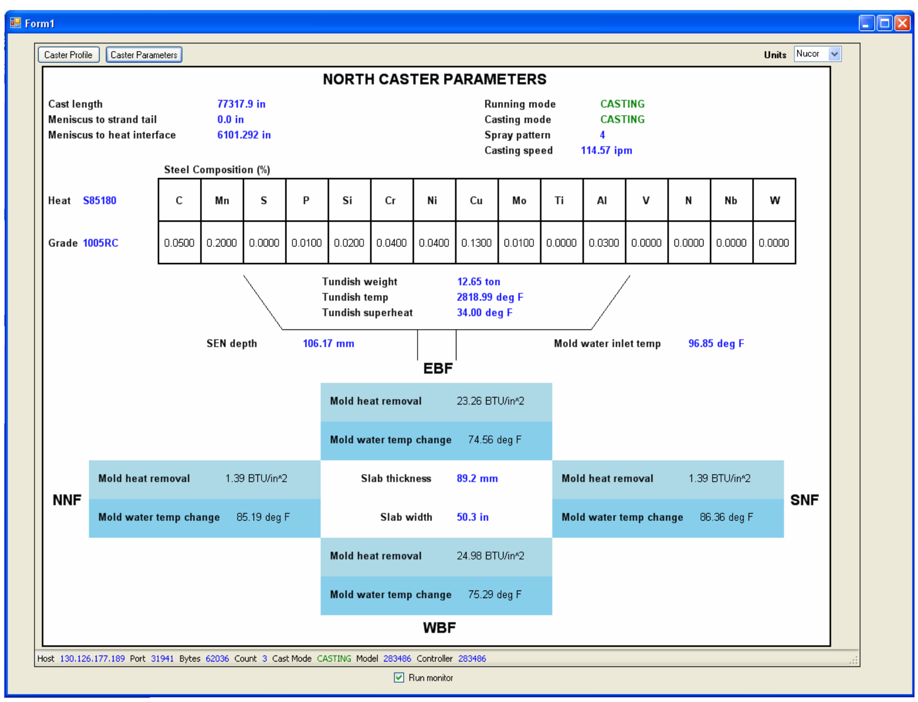








Monitor Overview: Parameter Screen

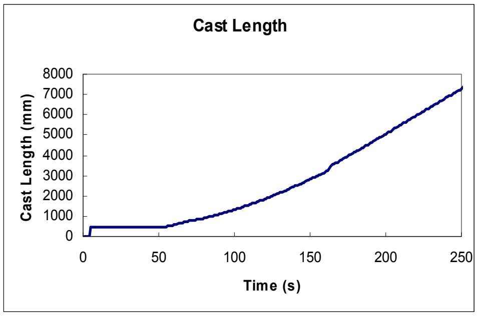


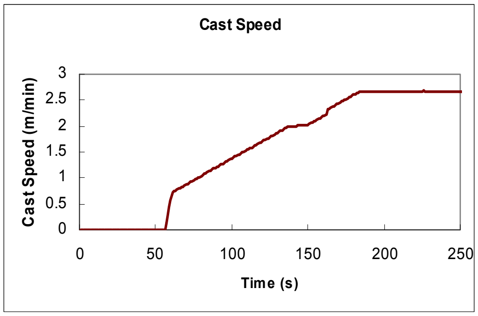
Real-time Simulations

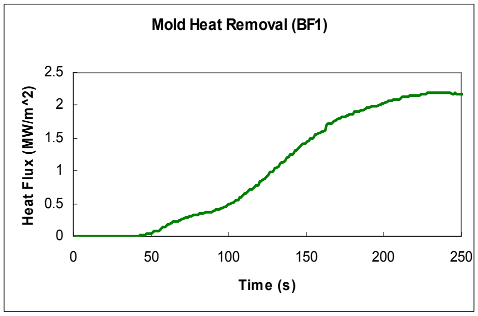
- Caster data recorded at Nucor Decatur
  - thanks to Terri Morris, Rob Oldroyd, and Alan Hable
- Simulations run in real-time at UIUC
  - HP DL380 G5 servers, Intel Xeon processors
- Situations:
  1. Casting startup
  2. Slab tailout
  3. Change in temperature setpoints

Startup

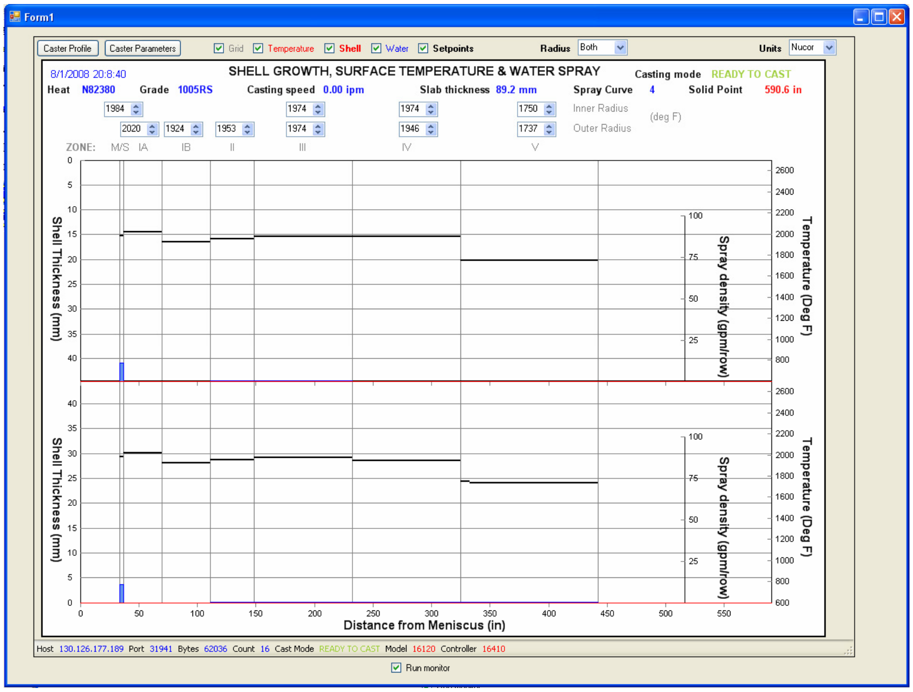
- Simulating recorded caster data at Nucor Decatur
- 0.03 % Carbon steel
- Played at 3x speed



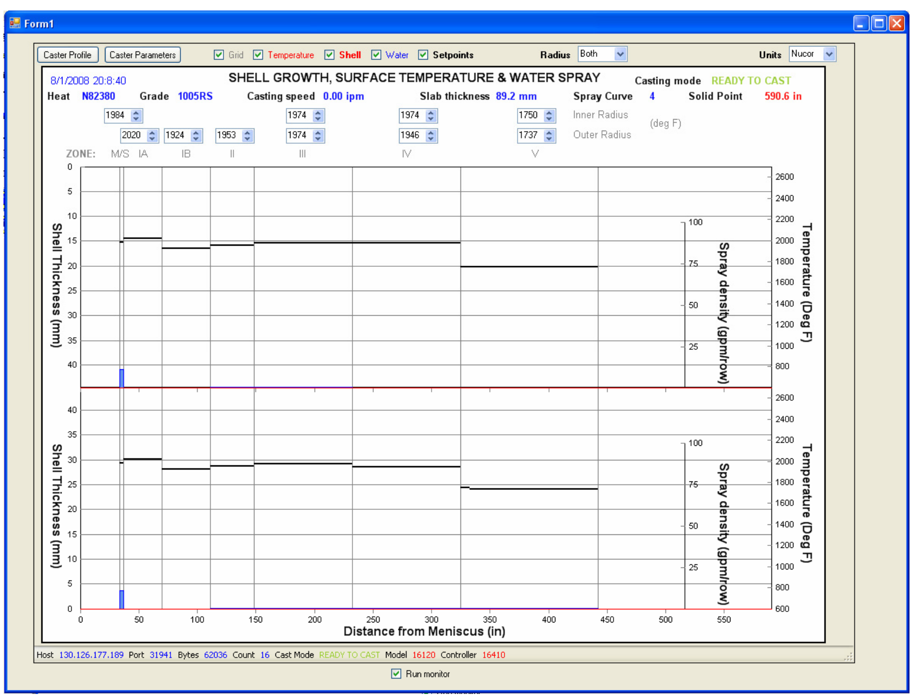




Startup

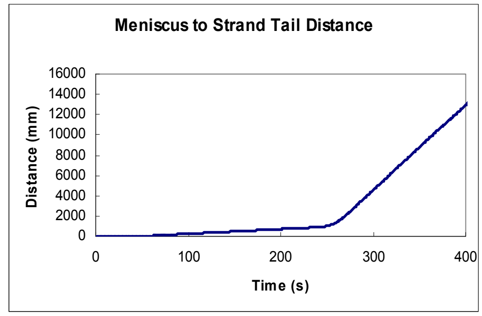


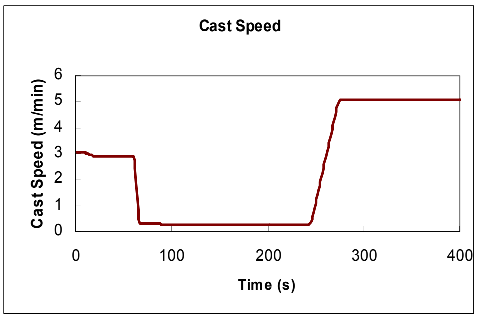
Startup – With PI Control

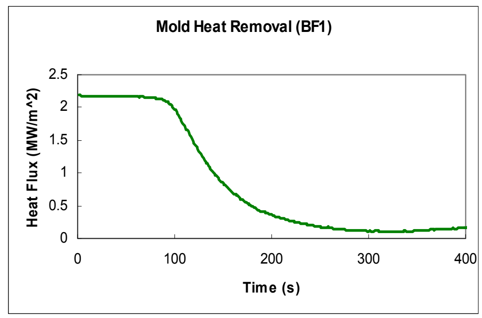


Tailout

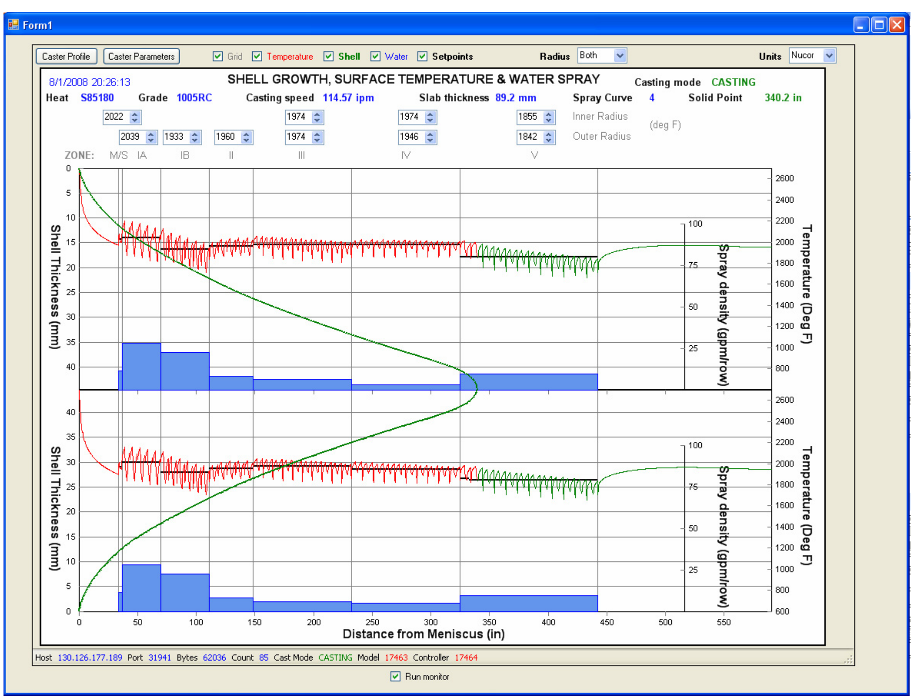
- Simulating recorded caster data at Nucor Decatur
- 0.05 % Carbon steel
- Played at 3x speed



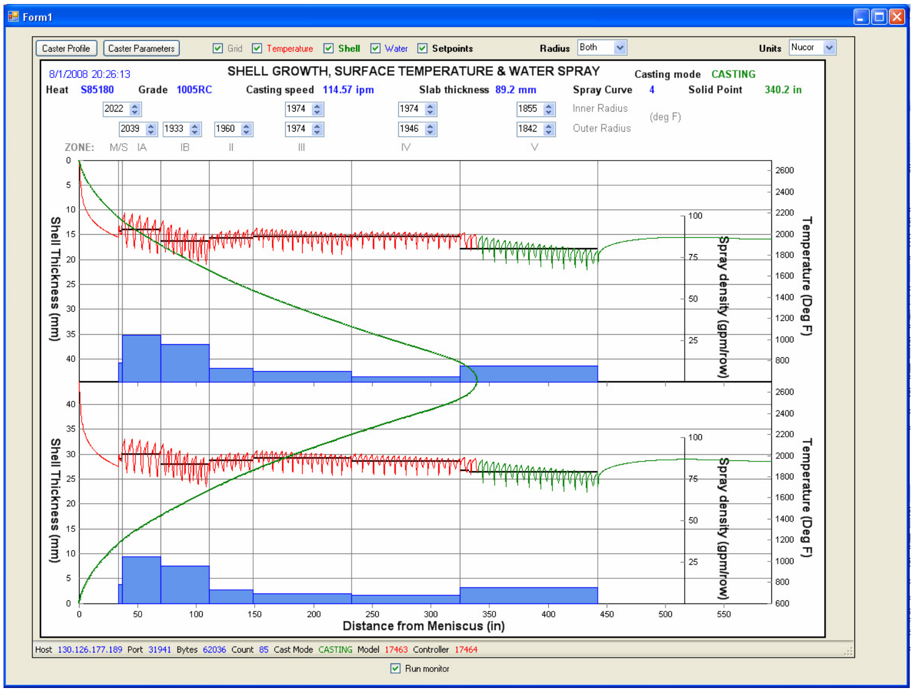




Tailout



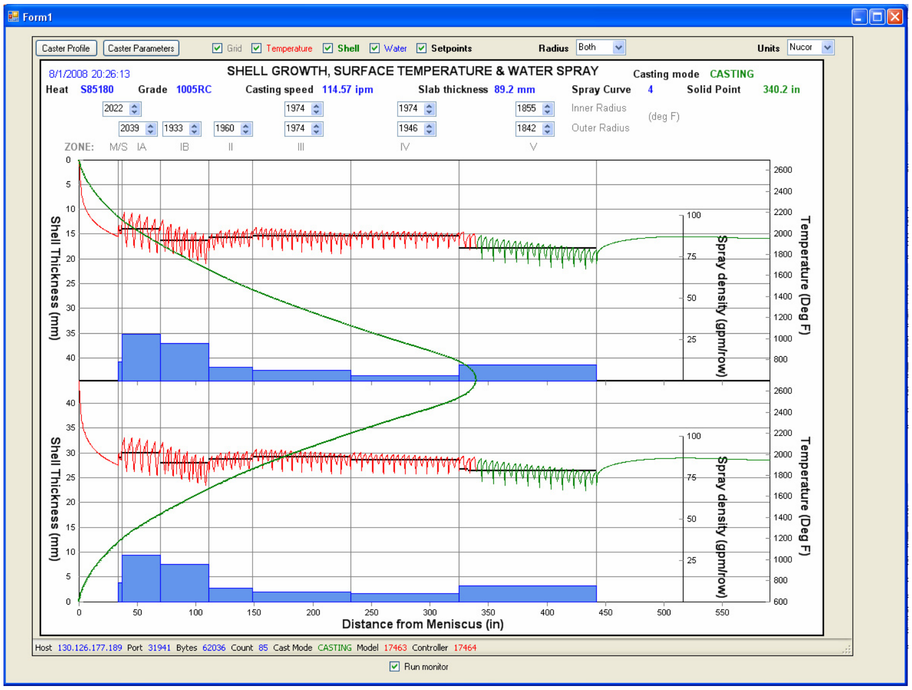
Tailout – With PI Control



Temperature Setpoint Change

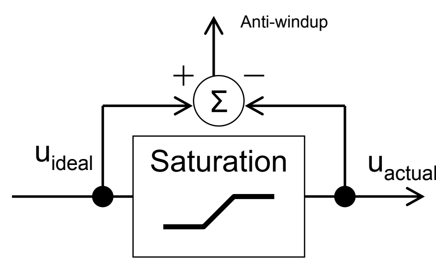
- Casting conditions based on initial state in previous tailout simulation
  - 0.05 % Carbon steel
  - 3.0 m/min casting speed
  - 26 °C superheat
- Setpoint in 4th zone changed by operator
  - Initial value: 1071 °C (1960 °F)
  - Changed to: 1000 °C (1832 °F)
- Played at 3x speed

PI Control – Operator Changes Setpoint

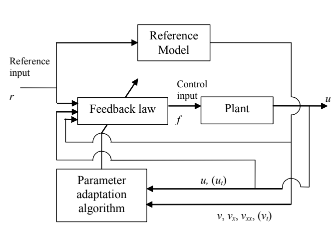


Advanced Control Development

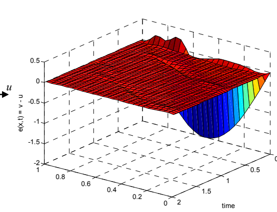
- Anti-windup
  - Actuator saturation can lead to windup of integral controller
  - Simple anti-windup scheme added
- Optimal control law development
  - In progress
  - Control laws have been designed for 1-D heat equation with spatially varying parameters
- Metallurgical length (ML) control
  - In progress



Control Law



Performance



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?