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Online Control of Spray Cooling Using CONONLINE

Software Sensor Development (CONONLINE)

Control Design & System Performance

Kai Zheng, Bryan Petrus
Joseph Bentsman & Brian G. Thomas
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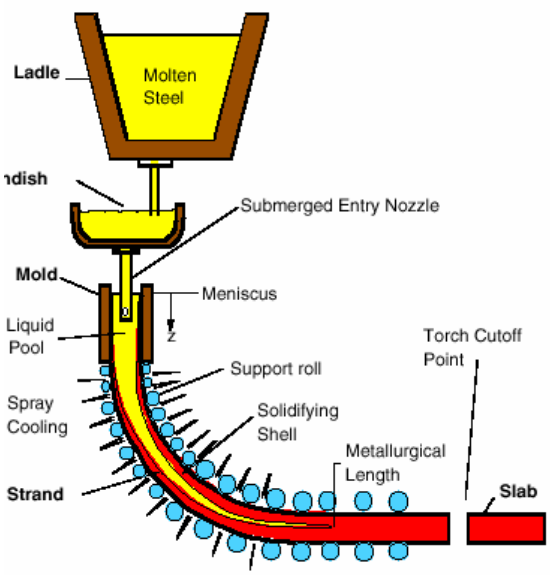
Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

Outline

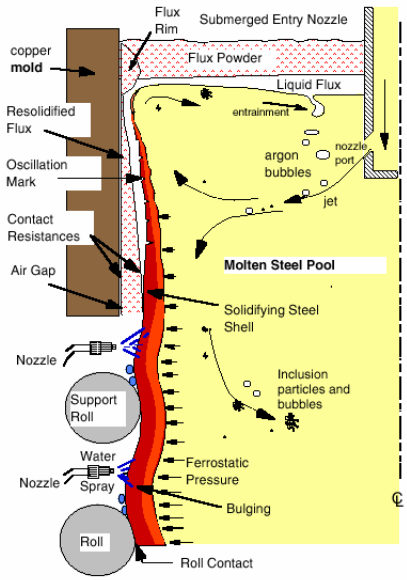
- Project Description
- Software Sensor Development (review)
- Model-based Control Design
  - Shell surface temperature control
- Control Performance
- Scenario analysis
- Metallurgical length overshoot control
- Ongoing work

INTRODUCTION

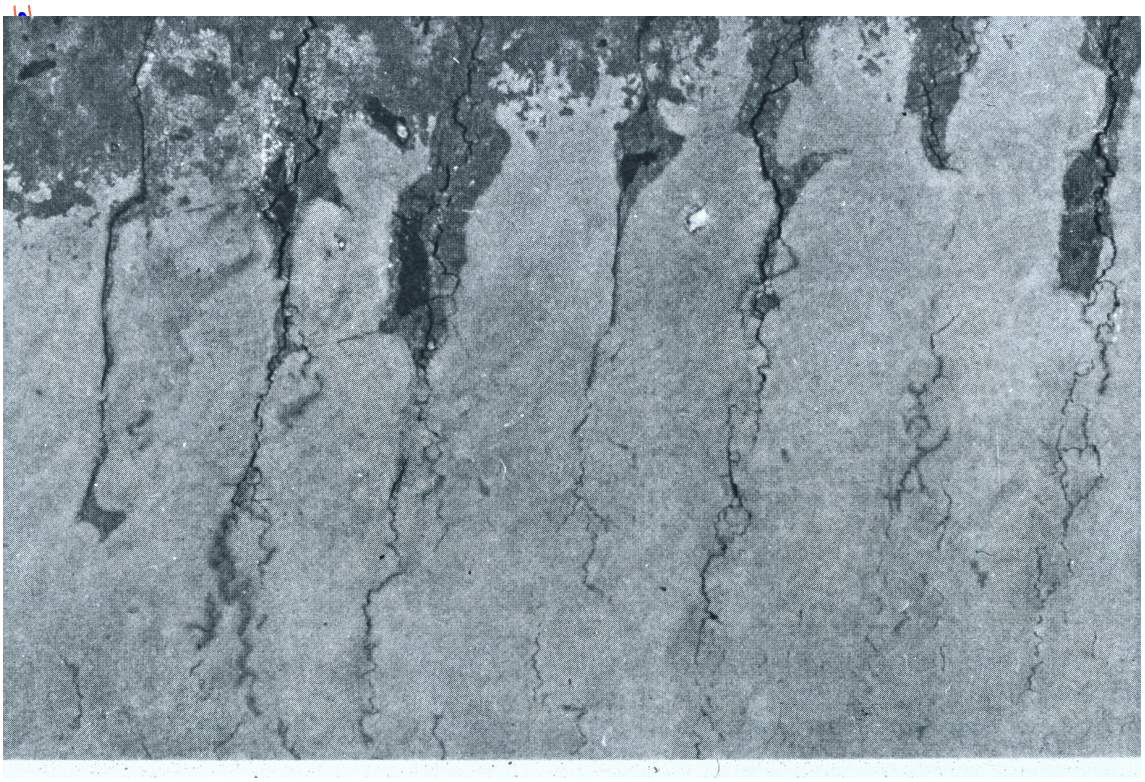
CONTINUOUS CASTING OF STEEL



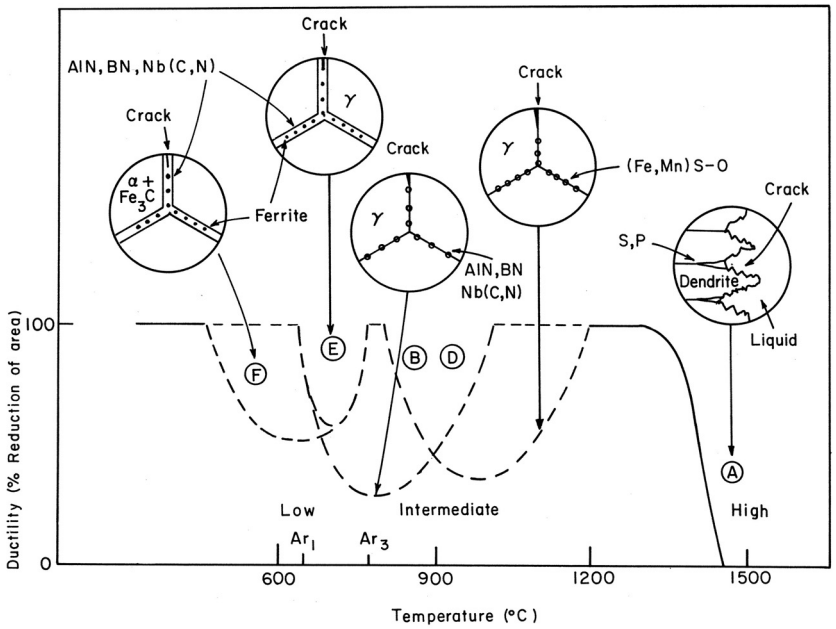
PHENOMENA IN THE MOLD

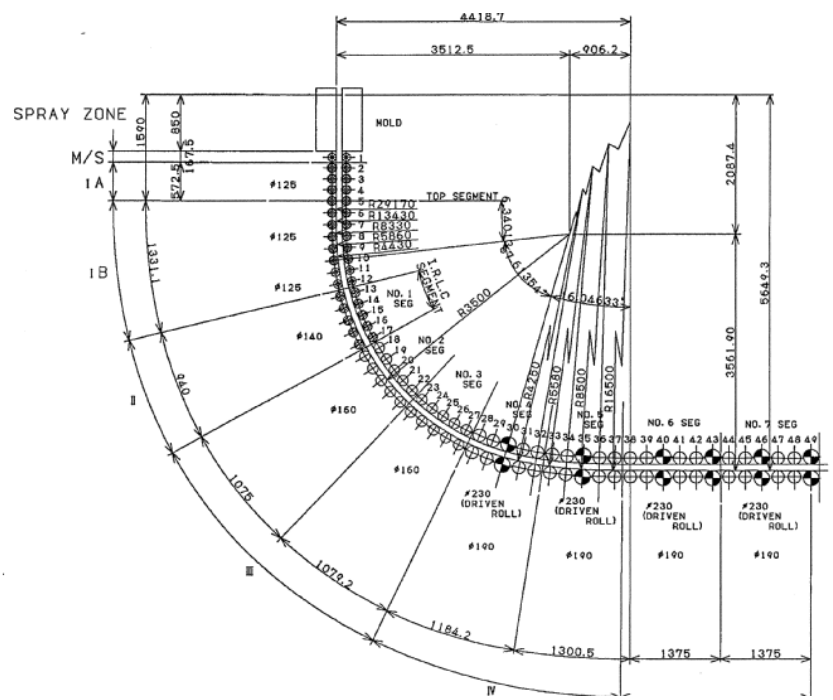


"Continuous casting consortium website" ccc.me.uiuc.edu



Temperature zones of reduced hot ductility of steel





Project Objectives

- Goal
  - Maximize casting speed while minimizing cracks, and avoiding “whale” problem
- Methodology
  - Design and implement a control system that generates water flow rates such that:
    - desired surface temperature setpoint profile is maintained
    - metallurgical length ≤ max allowable (distance from meniscus to last roll)

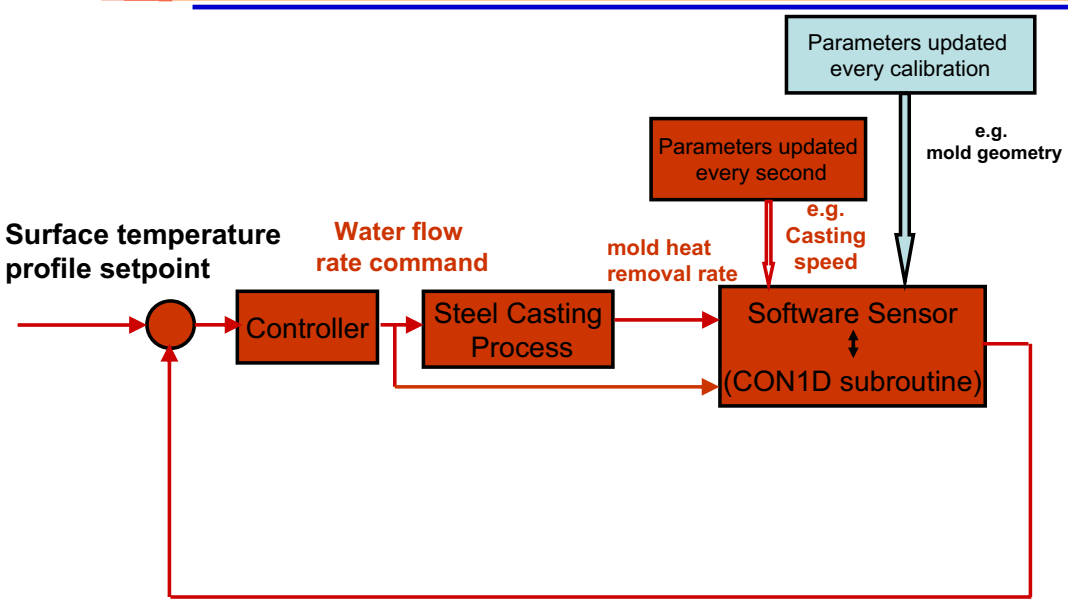
Current control approaches

1) **Manual control:**
operator setting of water flow rates, which is difficult when casting speeds are high and response times must be short

2) **Casting speed proportional control:**
Setting water flow rates according to casting speed, which results in non-optimal cooling when transient conditions are encountered

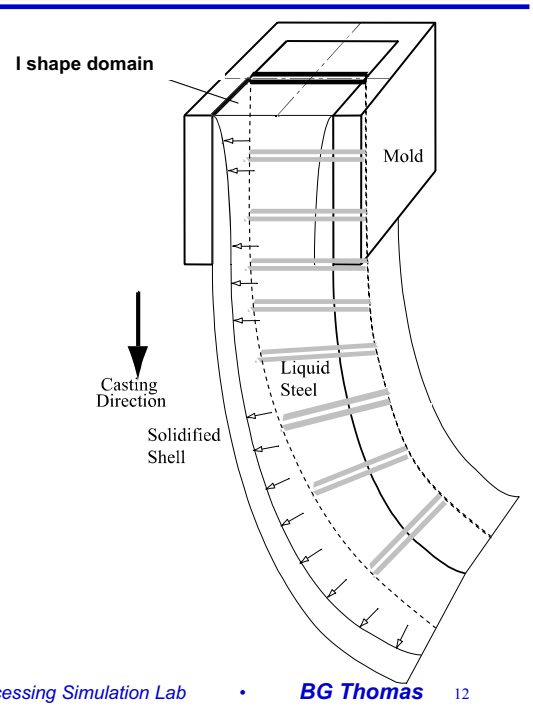
– Conventional feedback control has never been successfully implemented due to unreliability of temperature sensors.

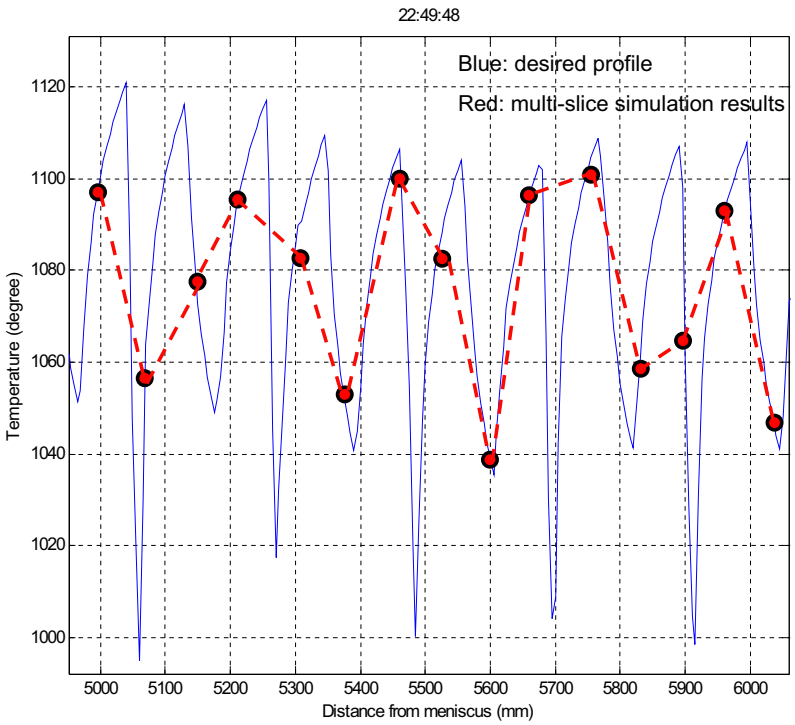
New Control System Strategy



Software Sensor: CON1D

- CON1D is a fast, accurate and robust tool to predict temperature and other related phenomena in a continuous slab caster.
- It predicts temperature and other phenomena for only one slice at a time.
- For a given time, we need the temperature profile of the whole slab
- Solution: multiple slices





200 slices, 75 mm between adjacent slices

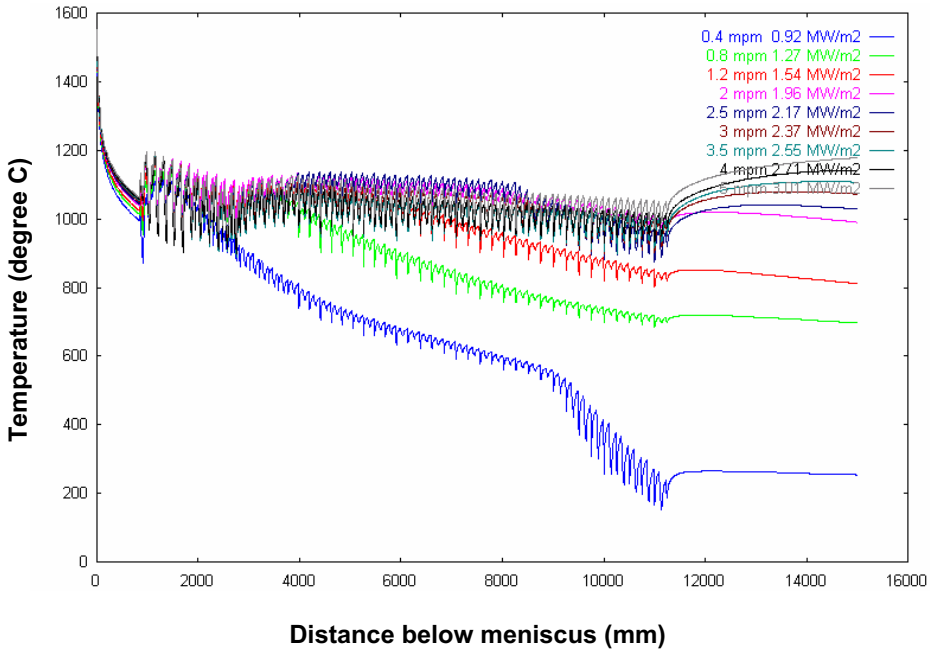
•Temp peaks and dips can be missing

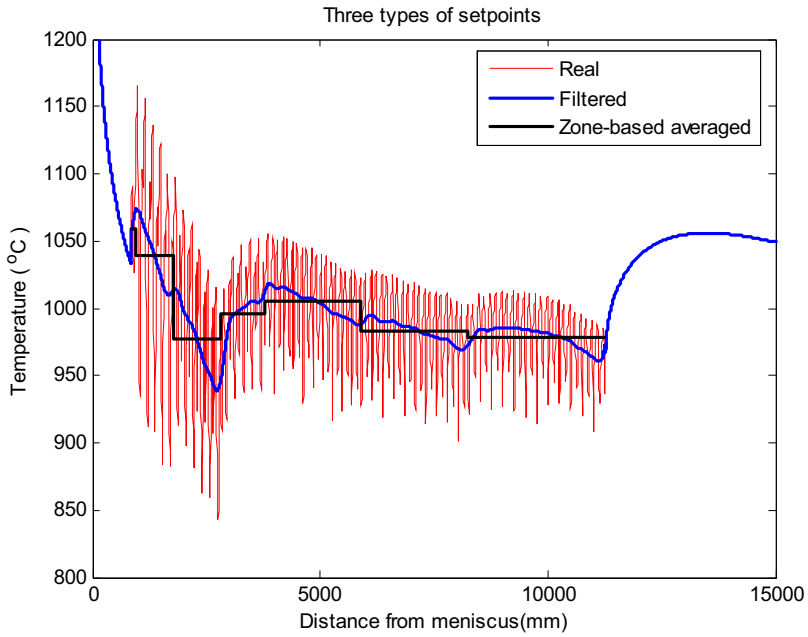
•Addressed by "delay-interpolation"

Setpoint generation

- Spray water flow rate set points
  - Empirically based: From metallurgical study (to avoid cracks)
  - Casting-speed-dependent
- Convert to surface temperature profiles
  - Output from CON1D
  - Conditions:
    - 9 Casting speeds
    - 8 Spray patterns

Setpoints = f(casting speed)



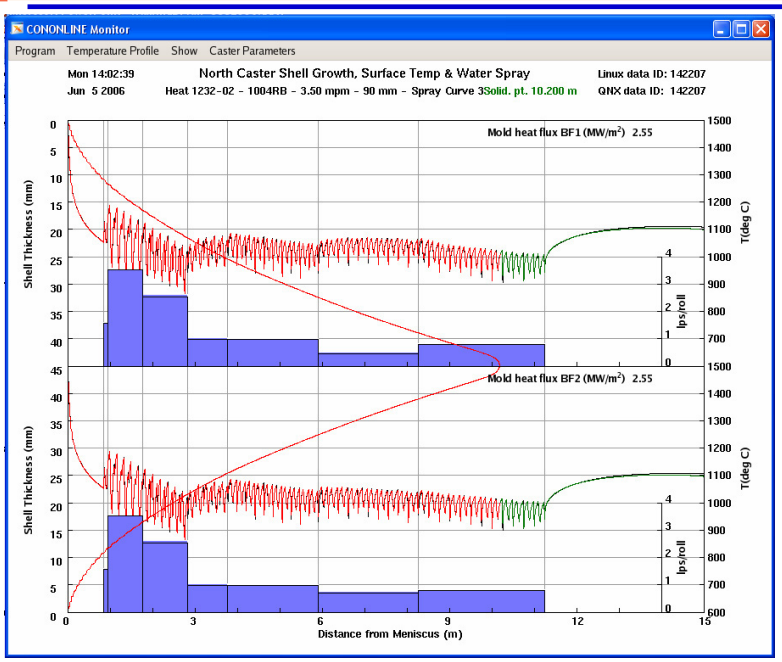


Model-based PI temperature controller design and control algorithm

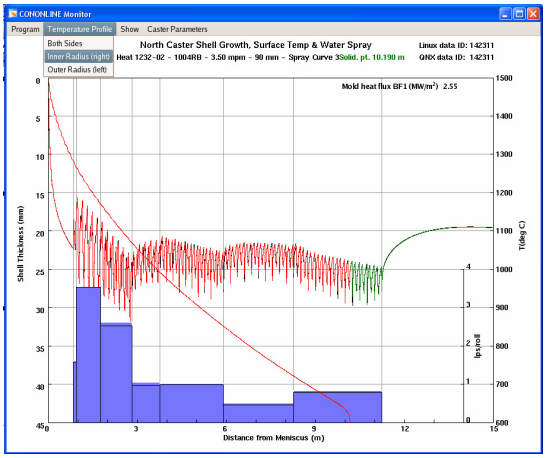
- Design
  - Find the individual Proportional – Integral – Derivative parameters
  - Zone-based design: 14 subcontrollers, one for each of 7 zones for each side of caster.

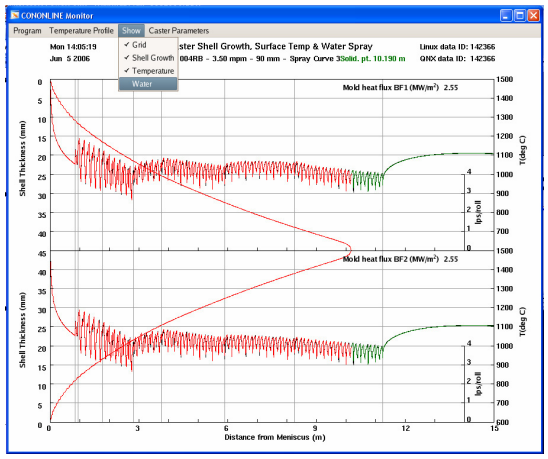
- Algorithm: At each second of time:
  1. Obtain the surface temperature profile from CONONLINE.
  2. Repeat the following 2 steps over all 14 zones:
     1. Compute the zone-based surface temperature average T_{avg} for current zone. And form the tracking error $T_{err} = T_{avg} - T_{sp}$
     2. Use T_{err} to compute the water flow rate command = Nominalwaterflow + Δwaterflow(t), $\Delta waterflow\ (t) = k_p T_{1err}(t) + k_i \int_0^t T_{1err}(s)\,ds$
  3. Send all water flow rate commands to CONONLINE, Caster, and Monitor

CONONLINE Interface

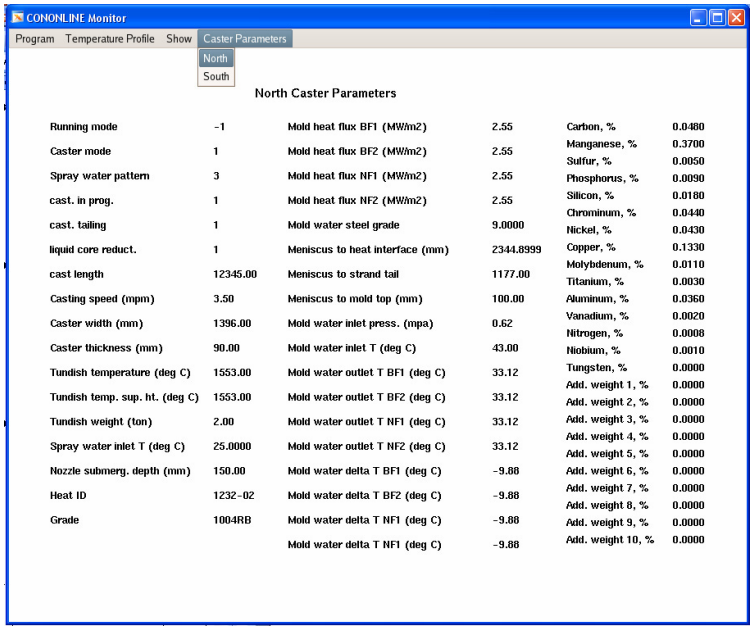


CONONLINE Interface





CONONLINE Interface

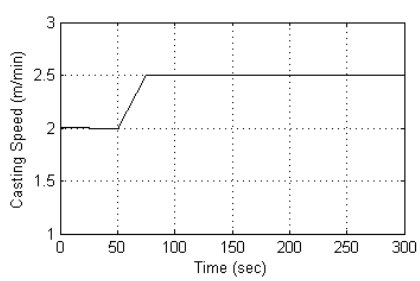


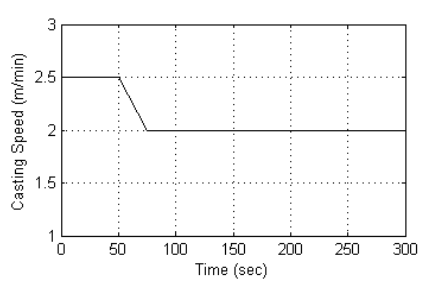
Running mode	-1	Mold heat flux BF1 (MW/m2)	2.55	Carbon, %	0.0480
Caster mode	1	Mold heat flux BF2 (MW/m2)	2.55	Manganese, %	0.3700
Spray water pattern	3	Mold heat flux NF1 (MW/m2)	2.55	Sulfur, %	0.0050
cast. in prog.	1	Mold heat flux NF2 (MW/m2)	2.55	Phosphorus, %	0.0090
cast. tailing	1	Mold water steel grade	9.0000	Silicon, %	0.0180
liquid core reduct.	1	Meniscus to heat interface (mm)	2344.8999	Chrominum, %	0.0440
cast length	12345.00	Meniscus to strand tail	1177.00	Nickel, %	0.0430
Casting speed (mpm)	3.50	Meniscus to mold top (mm)	100.00	Copper, %	0.1330
Caster width (mm)	1396.00	Mold water inlet press. (mpa)	0.62	Molybdenum, %	0.0110
Caster thickness (mm)	90.00	Mold water inlet T (deg C)	43.00	Titanium, %	0.0030
Tundish temperature (deg C)	1553.00	Mold water outlet T BF1 (deg C)	33.12	Aluminum, %	0.0360
Tundish temp. sup. ht. (deg C)	1553.00	Mold water outlet T BF2 (deg C)	33.12	Vanadium, %	0.0020
Tundish weight (ton)	2.00	Mold water outlet T NF1 (deg C)	33.12	Nitrogen, %	0.0008
Spray water inlet T (deg C)	25.0000	Mold water outlet T NF2 (deg C)	33.12	Niobium, %	0.0010
Nozzle submerg. depth (mm)	150.00	Mold water delta T BF1 (deg C)	-9.88	Tungsten, %	0.0000
Heat ID	1232-02	Mold water delta T BF2 (deg C)	-9.88	Add. weight 1, %	0.0000
Grade	1004RB	Mold water delta T NF1 (deg C)	-9.88	Add. weight 2, %	0.0000
		Mold water delta T NF1 (deg C)	-9.88	Add. weight 3, %	0.0000
				Add. weight 4, %	0.0000
				Add. weight 5, %	0.0000
				Add. weight 6, %	0.0000
				Add. weight 7, %	0.0000
				Add. weight 8, %	0.0000
				Add. weight 9, %	0.0000
				Add. weight 10, %	0.0000

Scenario analysis

- Speed ramps
- Caster startup
- Slow down
  - "Dip"
  - Sudden slow down (emergency)
- Spray pattern change
- Superheat change

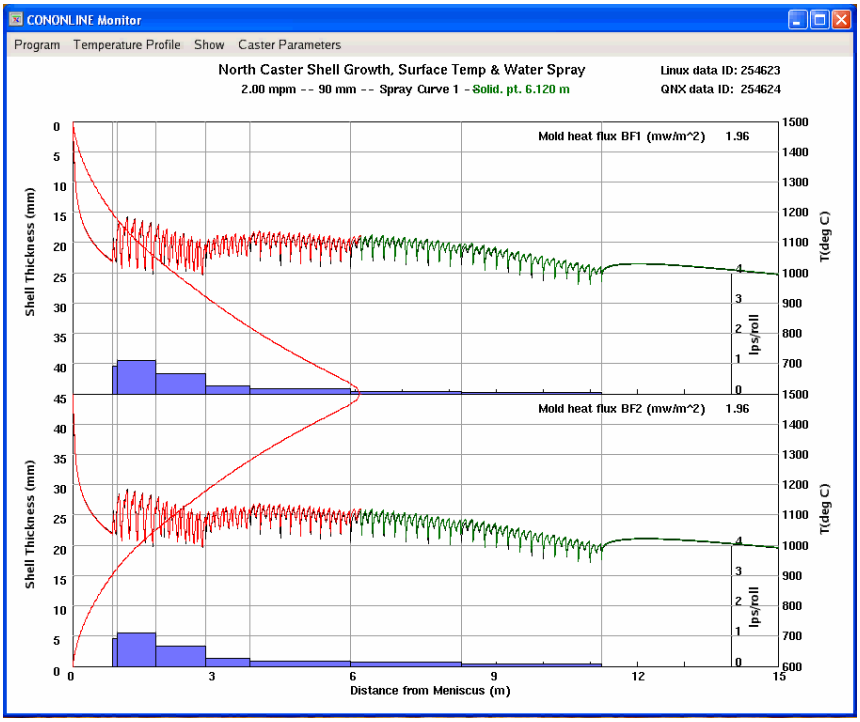
Simulation Results – speed ramp scenarios



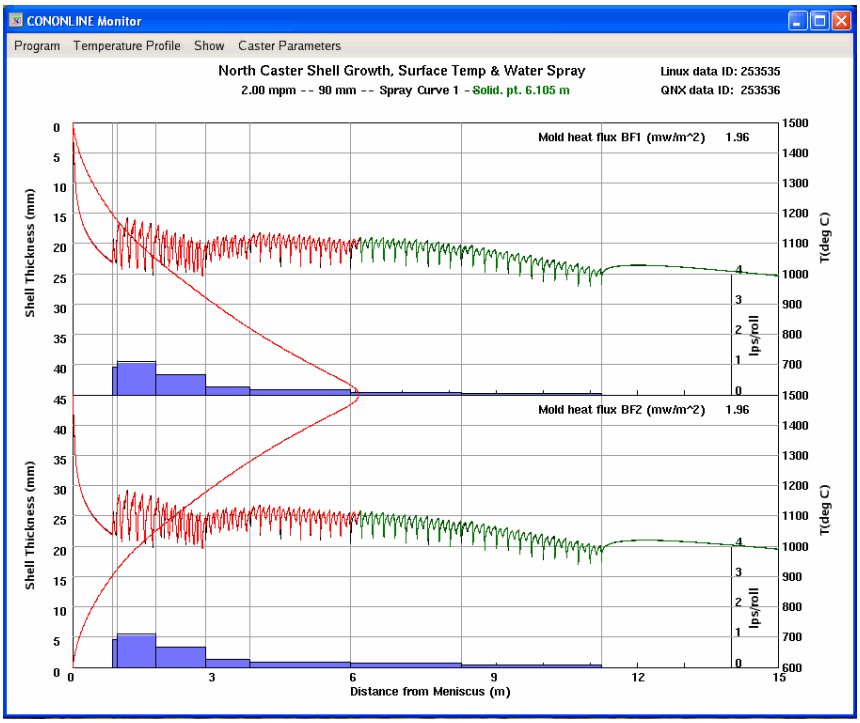


– Compare
  - Casting-speed-based proportional controller: setting water flow rate proportional to casting speed
  - Model-based PI controller

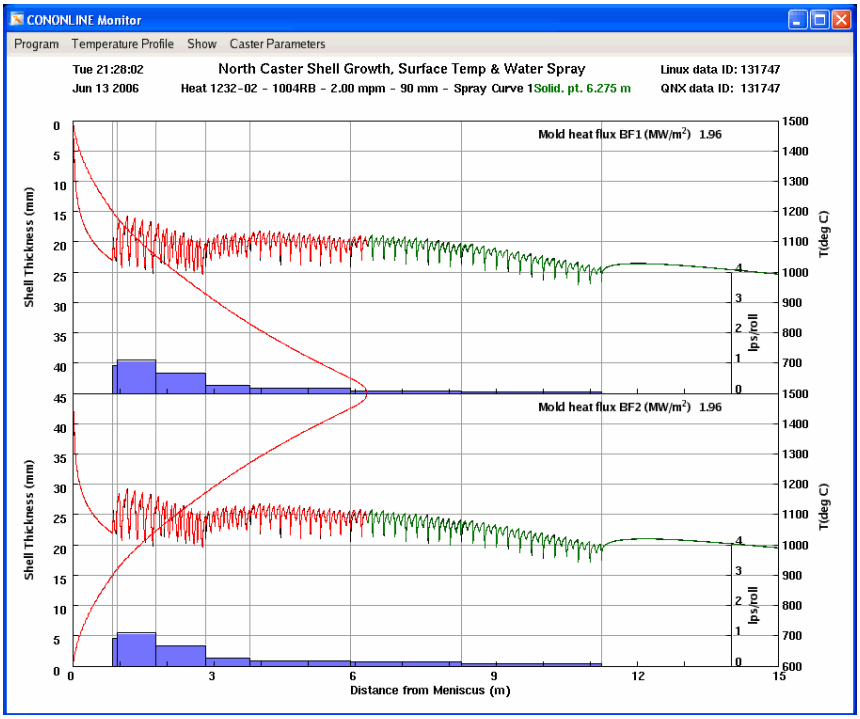
Casting-speed-proportional (old) Controller Performance
Casting Speed Ramp Up



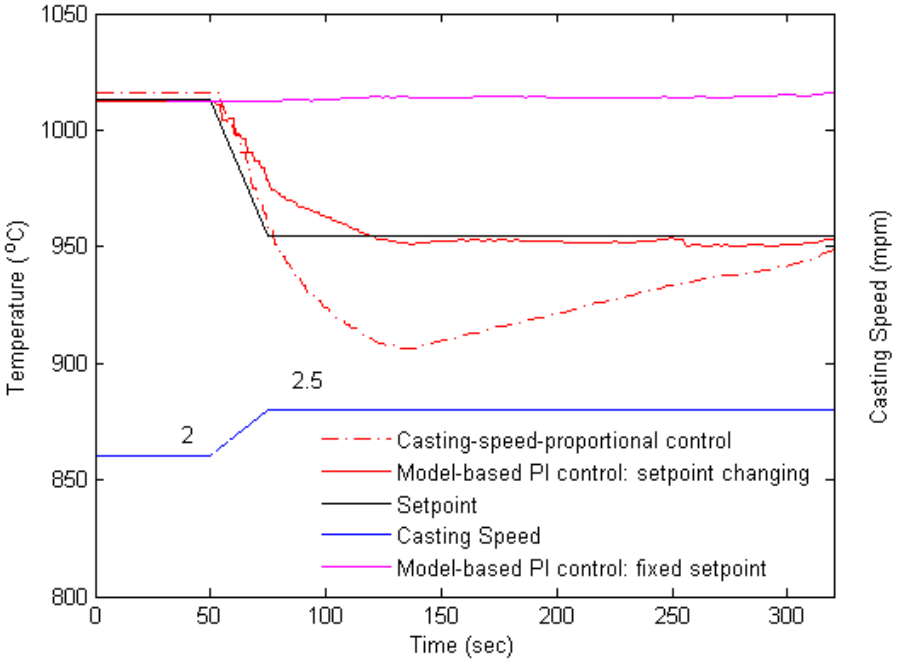
Model-based Control Performance
Casting Speed Ramp Up – casting-speed-based temperature setpoint



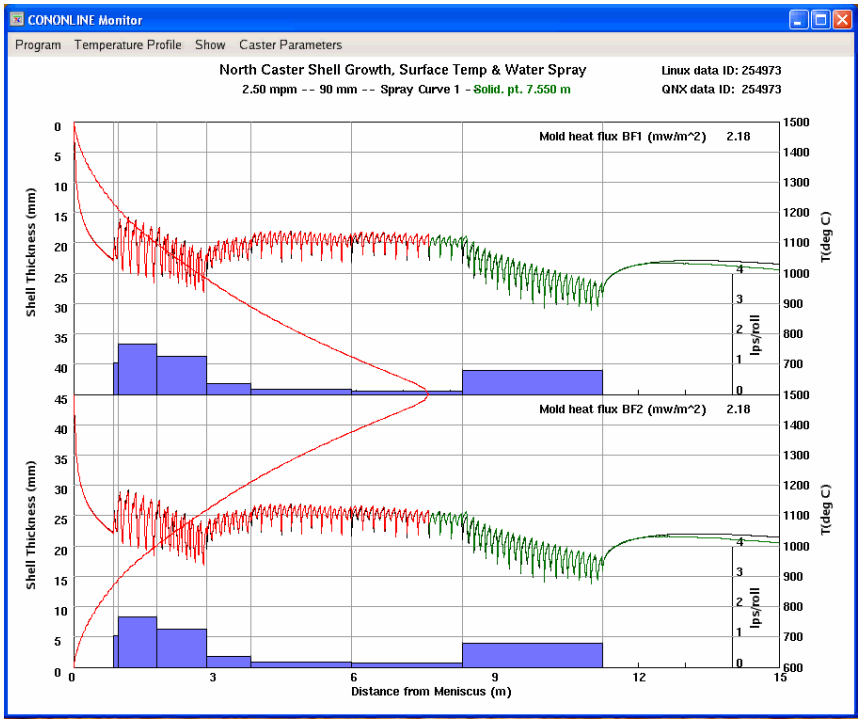
Model-based Control Performance
Casting Speed Ramp Up – fixed temperature setpoint



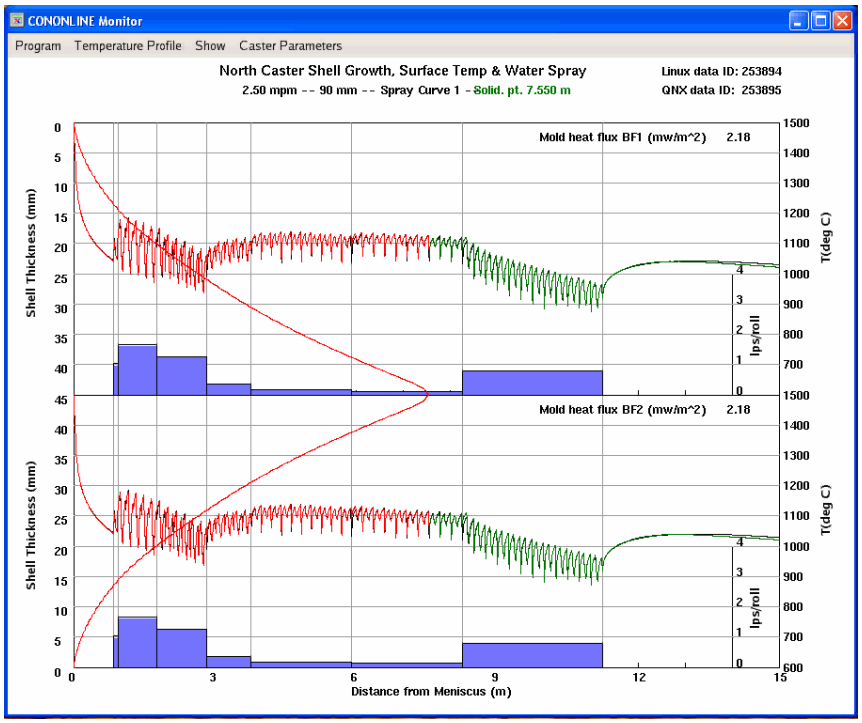
Temperature history at 11.2m



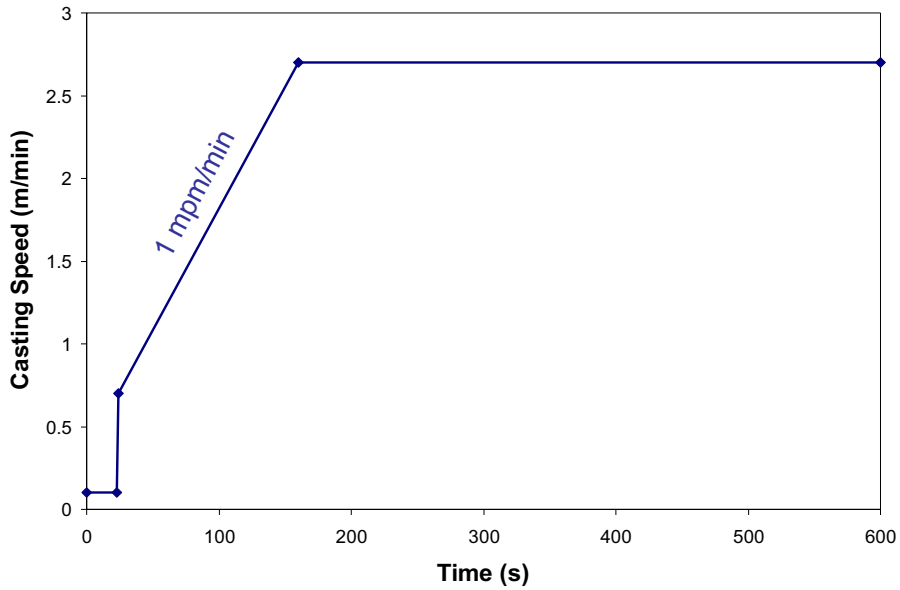
Casting-speed-proportional (old) Controller Performance
Casting Speed Ramp Down



Model-based Control Performance
Casting Speed Ramp Down

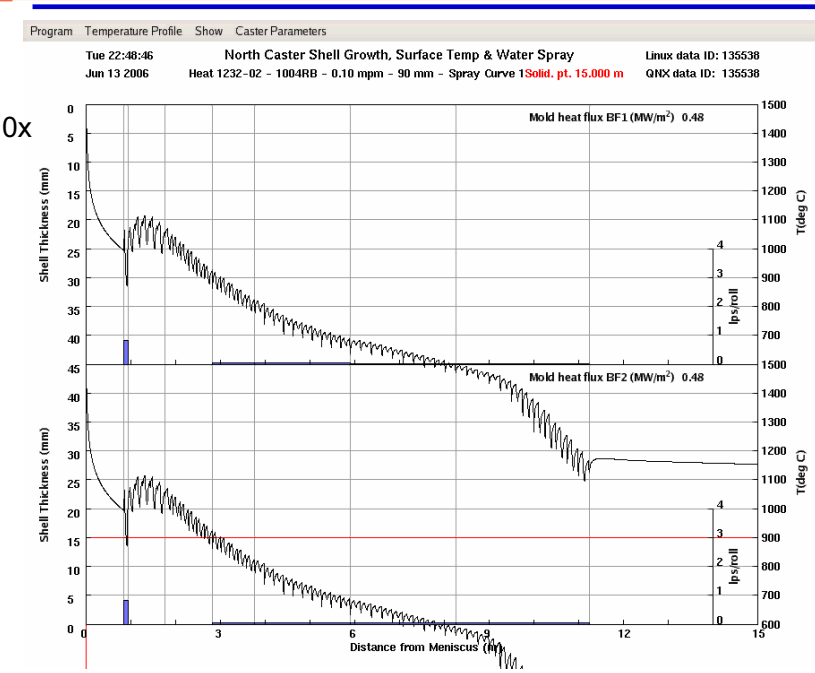


Caster start up
Speed profile

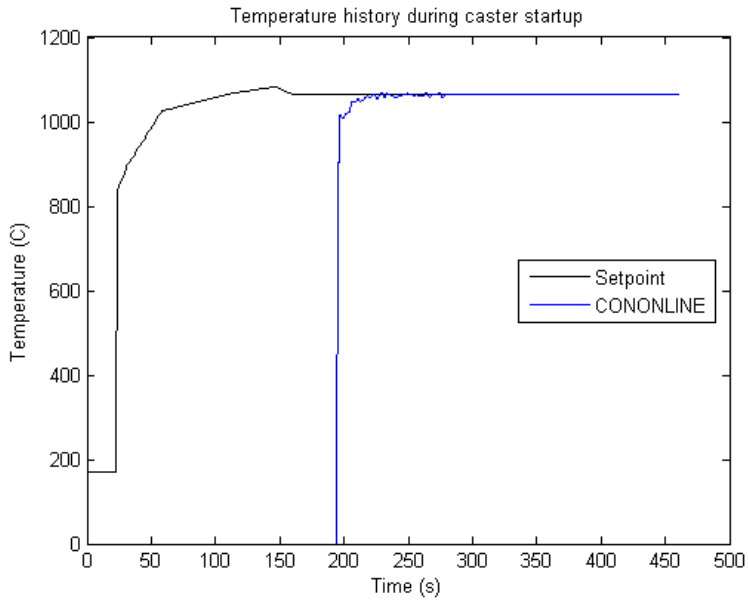


Caster start up

Sped up 10x

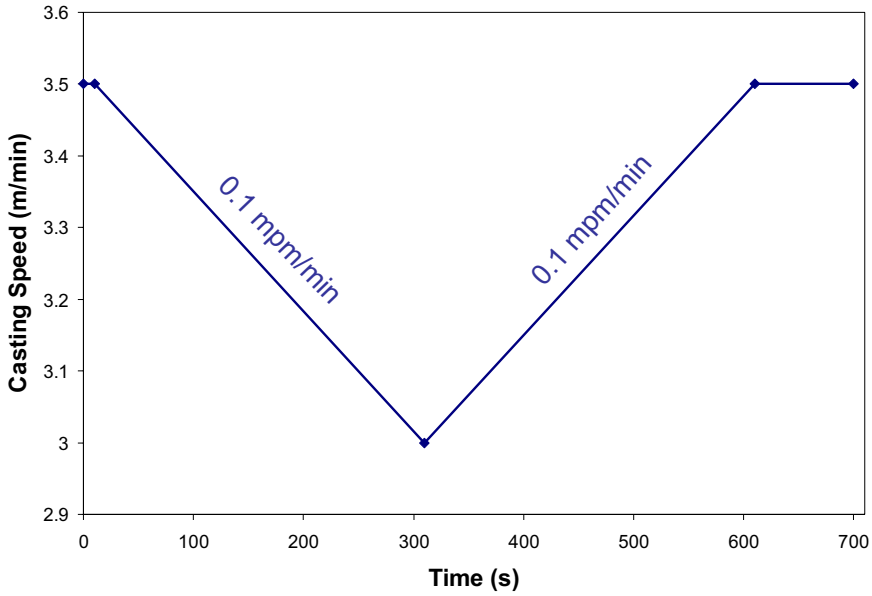


Caster start up temperature history



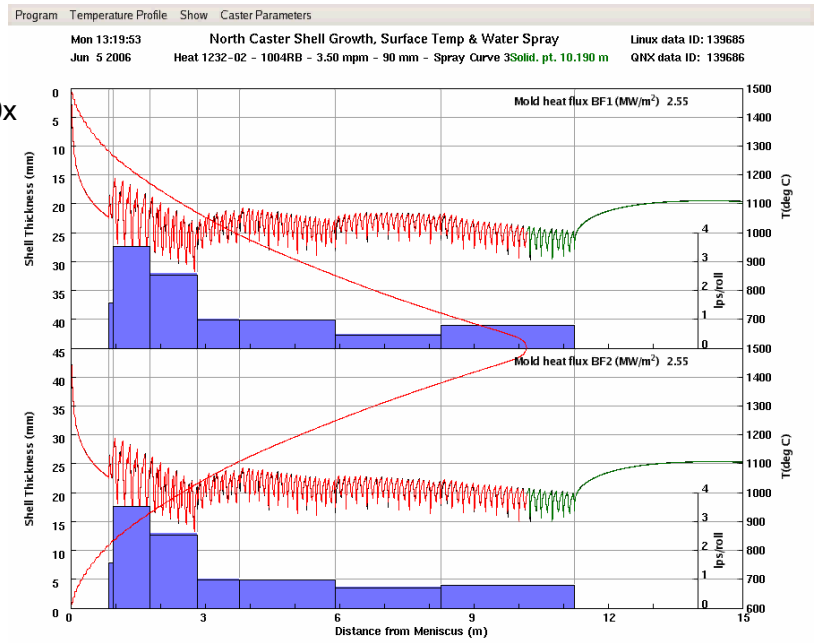
5.5 m from mensiscus

Casting Speed "Dip"

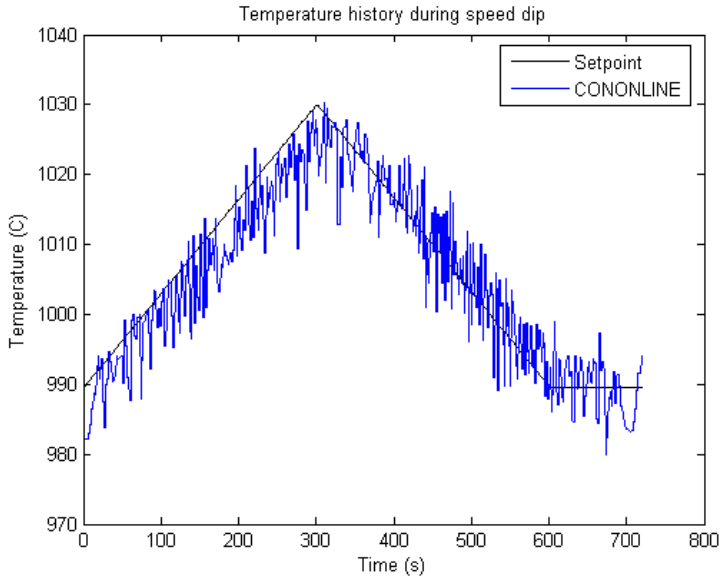


Casting Speed "Dip"

Sped up 10x

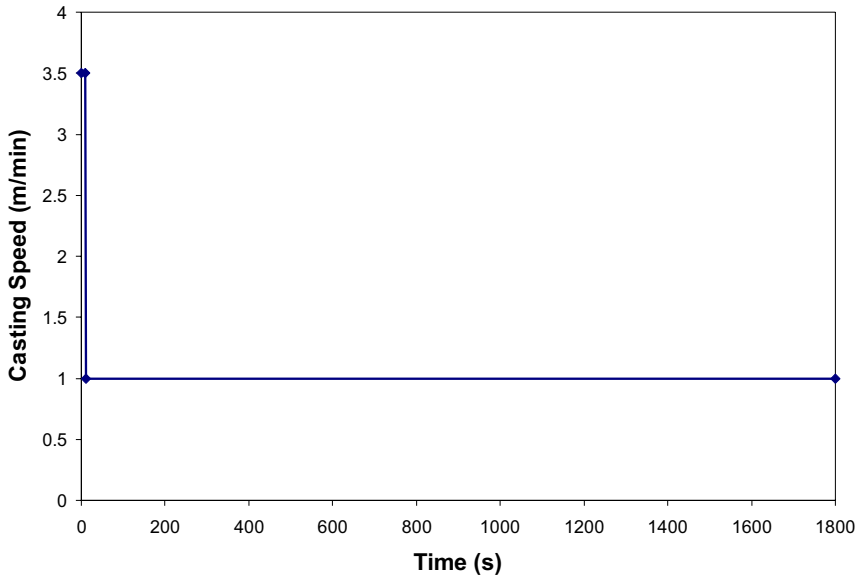


Casting Speed "Dip" Temperature History



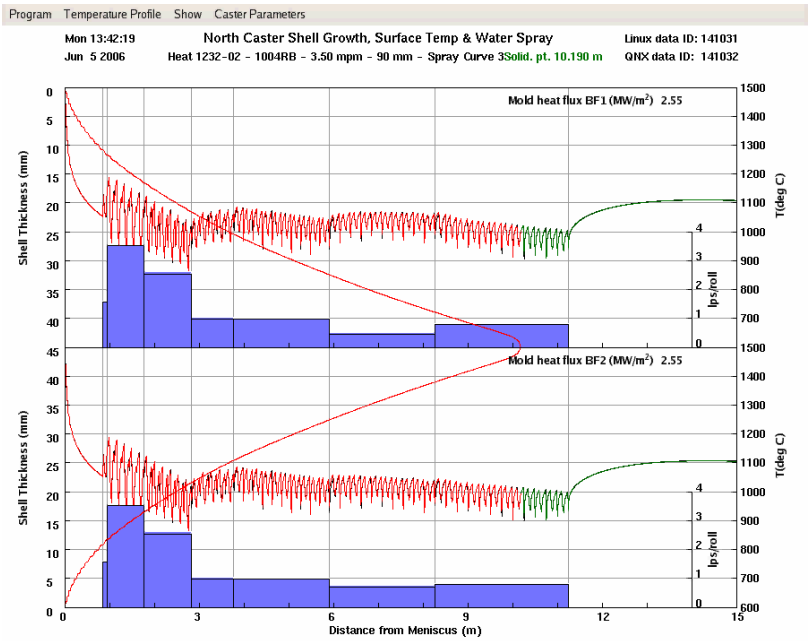
5.5 m from mensiscus

Sudden slowdown
Speed profile



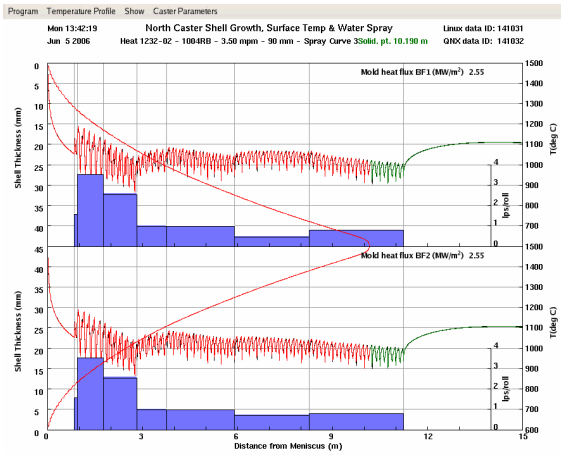
Sudden slowdown

Sped up 6x

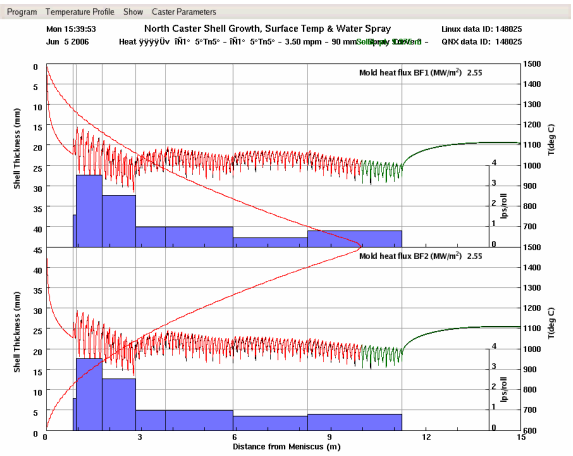


Sudden slowdown
Comparison with old controller

Concontroller

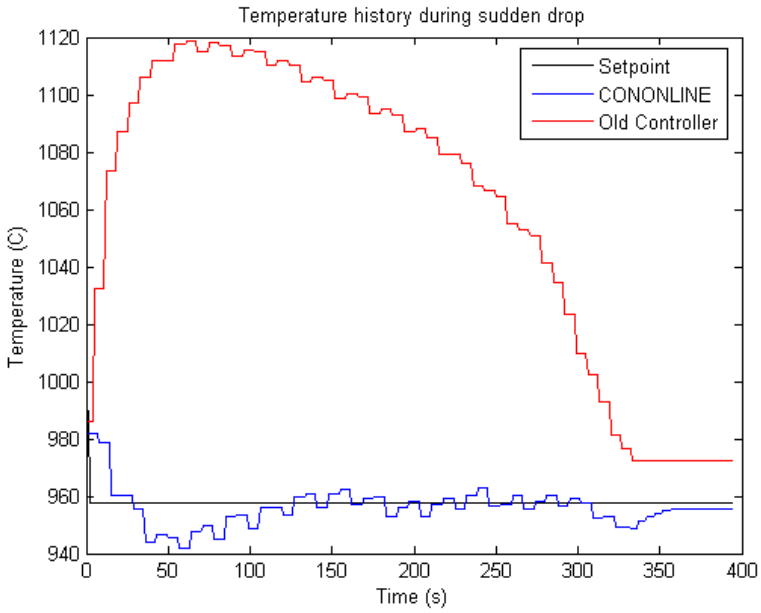


Old Controller



Sped up 6x

Sudden slowdown
Temperature history



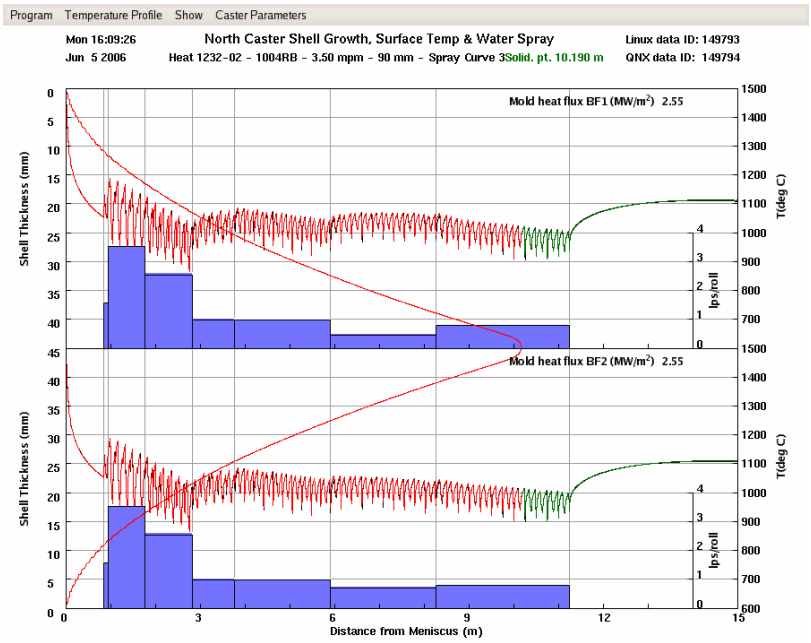
5.5 m from mensiscus

Spray pattern change --- speed profile

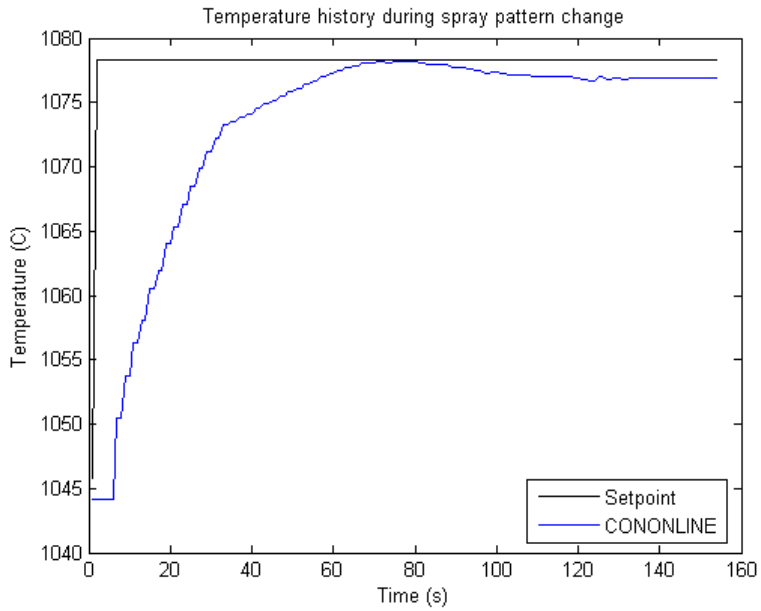
- Sprays change from pattern 3 to pattern 5
  - Pattern 3 has lower temperature setpoints

Spray pattern change from type 3 to 5 (decreasing water flow)

Sped up 2x



Spray pattern change --- temperature history



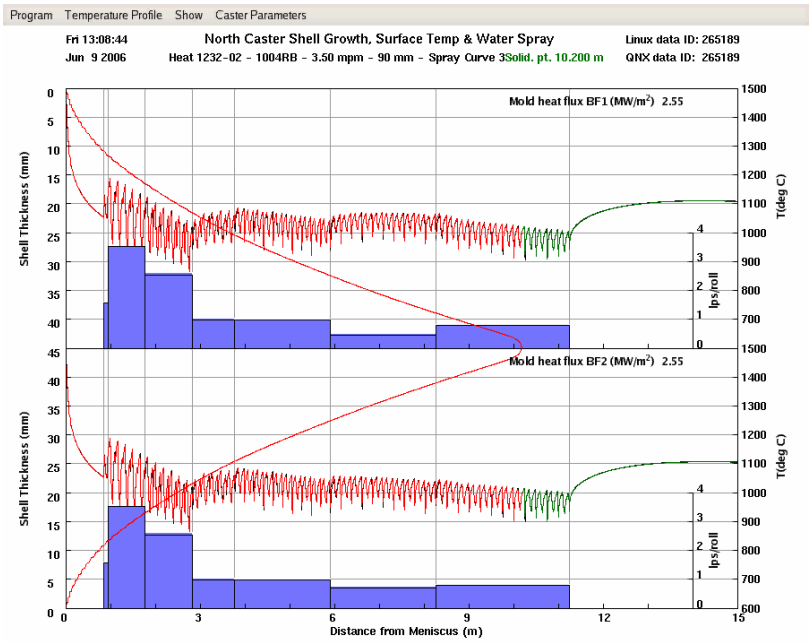
5.5 m from mensiscus

Superheat change --- speed profile

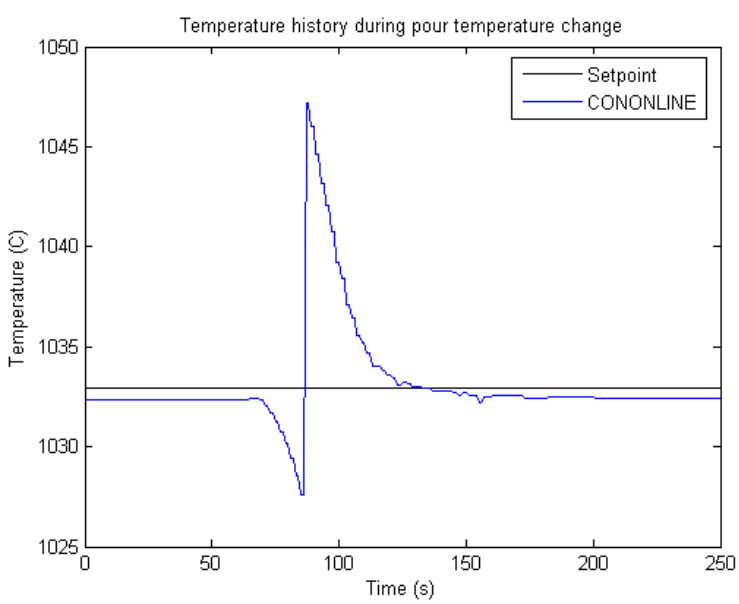
- Pour temperature increases from 1553°C to 1603°C

Superheat change --- what happened

Sped up 6x



Superheat change --- temperature history



5 m from mensiscus

Metallurgical length control

- Ensure the steady state metallurgical length is within bound by examining it offline and increasing the water flow rate if necessary
- As a first step: design a transient metallurgical length controller to ensure the metallurgical length does not overshoot when changing from one safe condition to another.

Transient Metallurgical length control

- A small amount of overshoot (0.1m) results under good temperature control.
- Must trade the performance of temperature control, I.e. overcool the shell surface, for that of the metallurgical length control
- The trade can be done by temperature setpoint conditioning

Temperature setpoint conditioning

- No conditioning when it is safe, i.e. the metallurgical length is far within limit.
- Lower the temperature profile setpoint for the last two spray zones when the metallurgical length is
  - Close to the limit as well as
  - Approaching the limit steadily

Conditioning formula

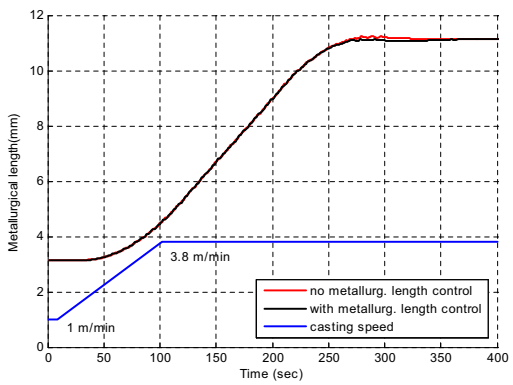
- Tsp_c = Tsp * drop%, for the 6th, and 7th spray zones, where
- drop = $c1(V_{solidpt})^{c2}(Z_{solidpt} - c3)^{c4}$, when
  - $V_{solidpt} > 0$, and
  - $Z_{solidpt} - c3 > 0$
- drop = 0 otherwise

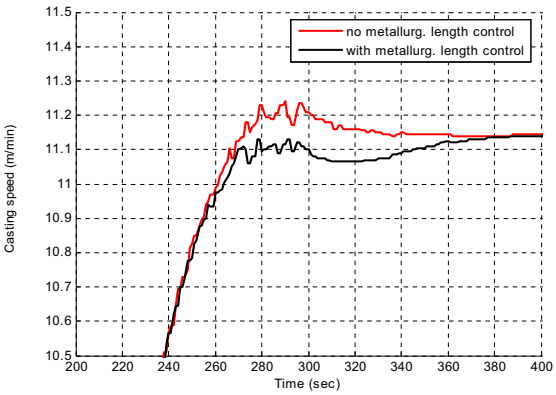
Design

- Design goal: choose c1, c2, c3 and c4 such that metallurgical length overshoot is zero and surface temperature overcooling is minimal.
- A good design
  - c1 = 30
  - c2 = c4 = 1
  - c3 = 8260mm ---- the beginning of the last spray zone

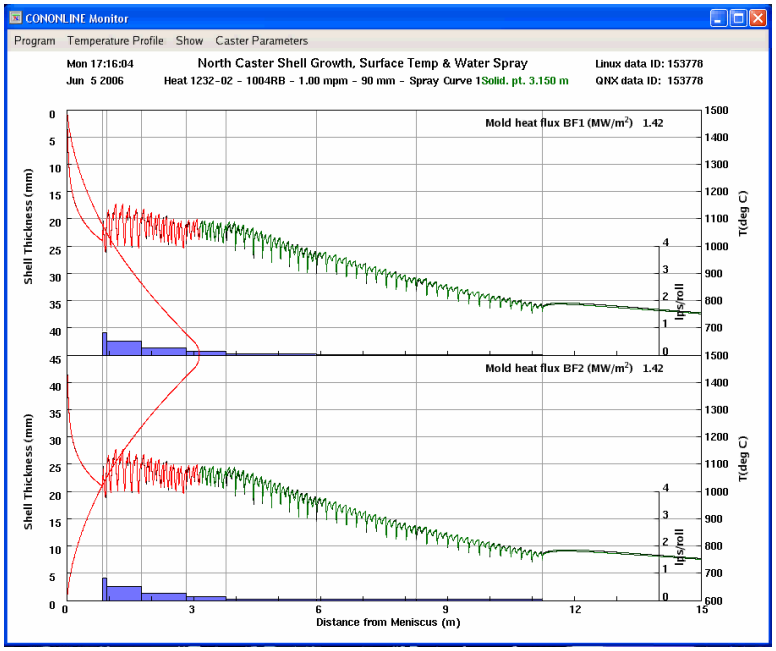
Performance

- Metallurgical length overshoot eliminated!





Performance: very little temperature control performance is sacrificed!



Ongoing work

- Further calibration:
  - incorporate water spray jet heat transfer coefficients from lab experiments.
  - Use different spray cooling parameters on innner/outer radii
- Test and implement at steel plant.
- Intelligent metallurgical length control
  - Not only control transient, but also steady state metal. length.
  - Does not rely on spray table to maintain safe metal. length, moreover, will help optimize the water setpoints in the spray table.

- Other features:
  - Use the shell surface temperature profile to calculate the ideal roll gap to avoid bulging or compression problems, etc.
- New control strategies:
  - avoid cracks by keeping surface temperature above Ar3 temperature until after unbending, or
  - get the temperature down below Ar3 for a significant time prior to unbending.
- Next generation control:
  - output optimal casting speed profile so that cracks can be minimized.

Thank You!