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CON1D and Cononline Spray-cooling Heat Transfer Model and Validation

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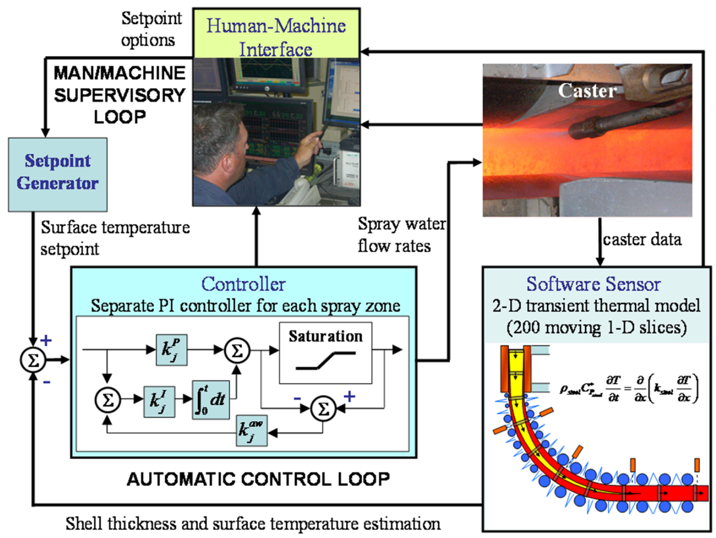
Overview

- (Bryan) Overview of Cononline
- Introduce Conoffline
- Calibration of heat transfer model for Nucor Decatur spray chamber
- (Roger) Study of heat transfer in caster
- Effect 1: Total amount of heat removal
- Effect 2: Location of heat removal
- Effect 3: Local variations in heat removal
- (Bryan) Observations and conclusions

Cononline

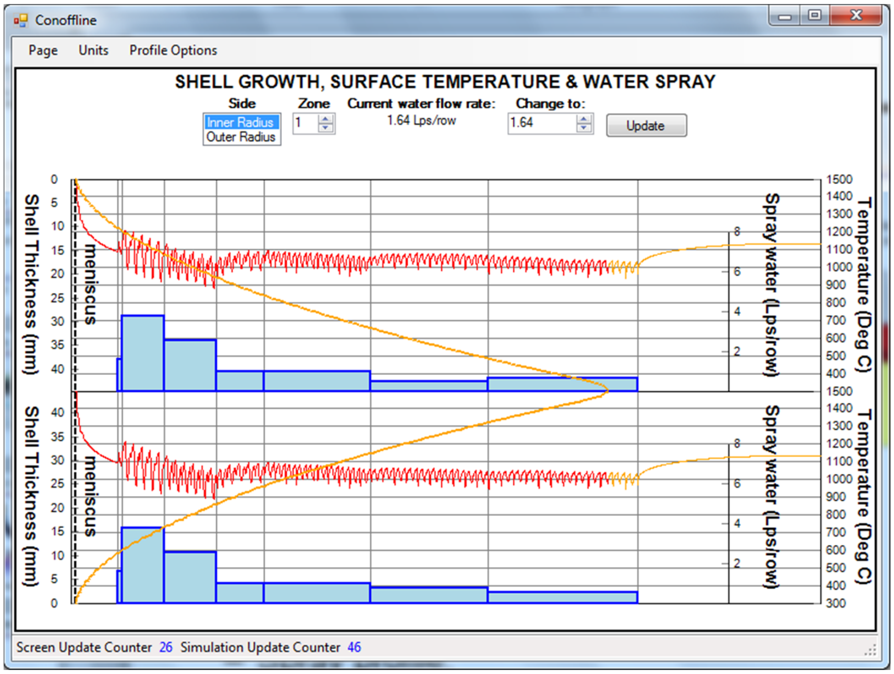
- Online control system for secondary cooling water sprays in caster
- Real-time model ("Consensor") of heat transfer and solidification in the strand predicts surface temperature.
- Control algorithm ("Concontroller") regulates the Consensor-predicted surface temperature



Conoffline

- New tool for simulation of continuous caster
- Based on Cononline, but runs on a single Windows PC instead of multiple Linux servers
- Purposes
  - Troubleshooting and improving Concontroller
  - Studying transient behavior in caster
  - Startup design
  - Operator training
- User input
  - CON1D input file (plain text) for caster geometry and initial conditions
  - Comma-separated-value spreadsheet for dynamic scenario running
  - Also allows changing casting conditions on the fly through user interface
- Goals, and ongoing work
  - Allow user control of update speed
  - Allow more general choices of data output
  - Implement various versions of Concontroller for testing and comparison

Conoffline demonstration



Calibrating CON1D – Modeling

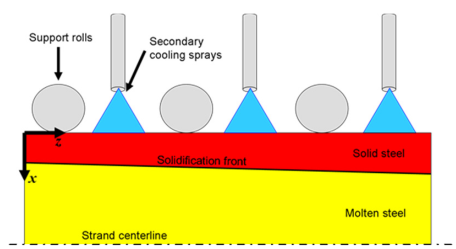
- CON1D spray chamber model is based on Nozaki et al.
  - Spray and roll heat removal are quantified by heat transfer coefficients

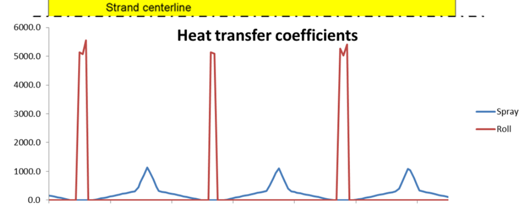
    $$q = h\left(T_{surf} - T_{\infty}\right)$$

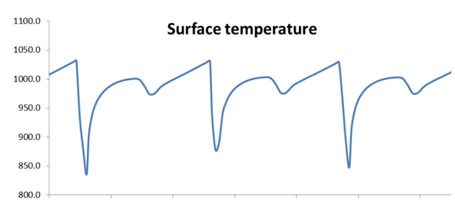
  - Spray heat transfer coefficient is a function of spray rate and water temperature

$$h_{roll} = C \cdot 1.57 \cdot Q_{water}^{0.55} \cdot \left(1 - 0.0075 \cdot T_{water}\right)$$

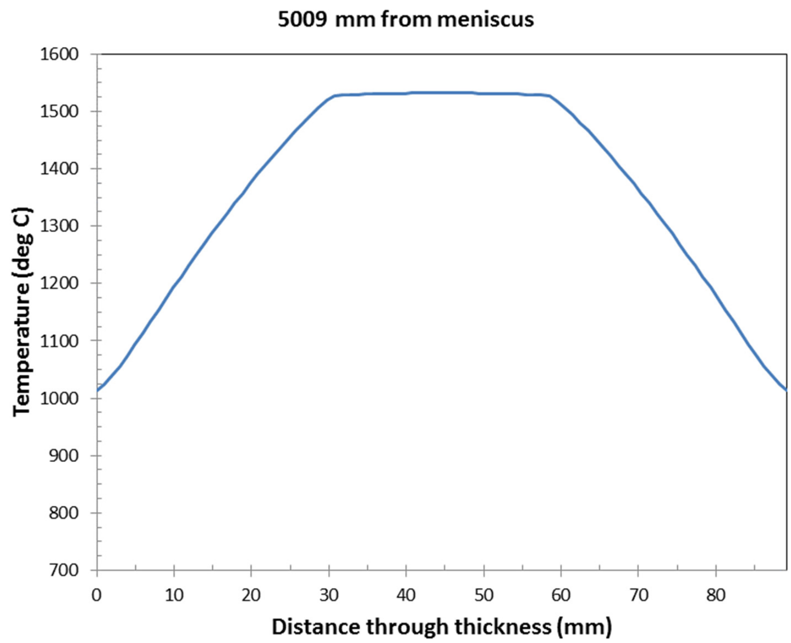
    - "Spray coefficient" C = 1 reported from lab experiments
    - C = 0.25 reported for average heat transfer coefficient over spray zone, based on caster experiments
  - Roll heat transfer coefficient is a fraction of other heat losses







Calibrating CON1D – Effect of sprays on temperature profile



Nozaki vs Cinvestav spray cooling correlations

Nozaki Model

$$q_{spray} = 1.57 \cdot Q_{water}^{0.55} \cdot (1 - 0.0075 \cdot T_{water}) \times (T_{surface} - T_{water})$$

- Heat flux depends on
  - Water flux, Q_{water}
  - Water temperature, T_{water}
  - Surface temperature, $T_{surface}$
- does not depend on
  - Droplet size or velocity

Cinvestav model

$$q_{spray} = 0.307 \cdot Q_{water}^{0.319} u_{z,v}^{0.317} T_{surface}^{0.144} d_{30}^{-0.036}$$

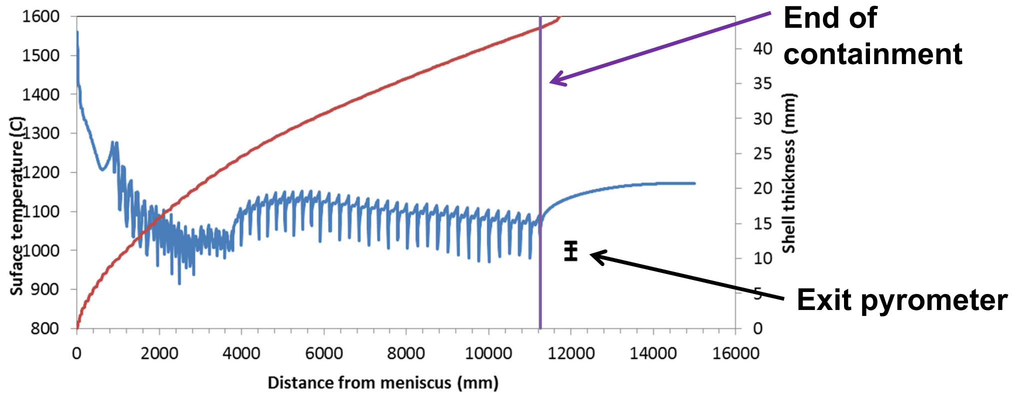
- Heat flux depends on
  - Water flux, Q_{water}
  - Water normal velocity, $u_{z,v}$
  - Droplet size, d_{30}
- does not depend much on
  - Surface temperature
- does not depend at all on
  - Water temperature

<u>Example: Delavan nozzle W19822, measured in Cinvestav paper</u>
At center, Q_{water} = 20.6 L/m²s, d_{30} = 32.1 μm, $u_{z,v}$ = 35.2 m/s
Assume T_{water} = 25 °C, $T_{surface}$ = 1000 °C

Nozaki:
- q_{spray} = 6.57 MW/m²
  h_{spray} = 6.73 kW/m²K

Cinvestav:
- q_{spray} = 5.95 MW/m²
  h_{spray} = 6.12 kW/m²K

Calibrating CON1D – Test cases

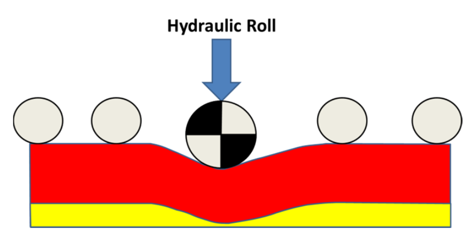


- Accurate and reliable temperature and shell thickness measurements are difficult in the spray zone
- Temperature
  - Exit pyrometer measurements
- Shell thickness
  - Whale cases
  - Cracked slab

Calibrating CON1D – Shell thickness measurements

- Whales
  - 2004 – predates records in Level 2 database, so casting conditions are not available
  - 2006
  - 2008 – flow meter for spray water in upper bender was broken, so measurement is not reliable
- Cracked slab
  - Hydraulics misfired on a drive roll, causing strand to be crushed from 90 mm down to 70 mm
  - Segregate bands are visible where the steel was almost completely solid
  - This gives a good measurement of the shell thickness at the location of the drive roll
    - 34 mm thick at 6.8 m from meniscus

Thick slab caster

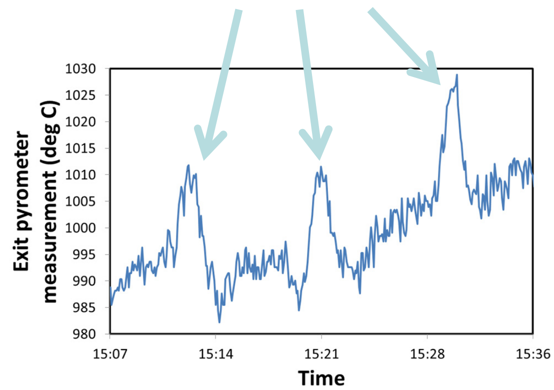


Nucor Decatur, (thin slab) Oct. 2008

Calibrating CON1D – Pyrometer measurements

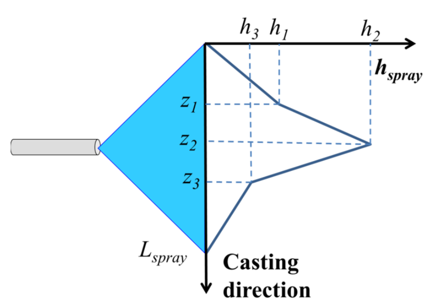
- Cononline and CON1D currently match shell thickness measurements, but overpredict pyrometer
- First question: why does exit pyrometer temperature peak once each slab?
  - Descaling sprays are located at the shear cut
    - Usually, they spray back along the slab, cooling it slightly
    - During shear, the water runs off, so the slab is heated
  - The maximum temperature is likely the most reliable.

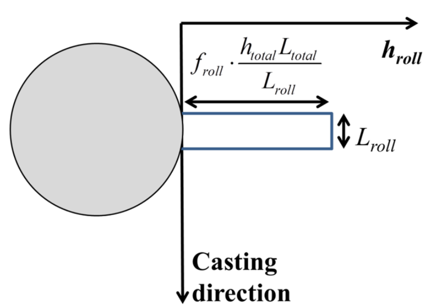
Pyrometer records peaks in temperature near every slab cut



Calibrating CON1D – Unknown parameters in model

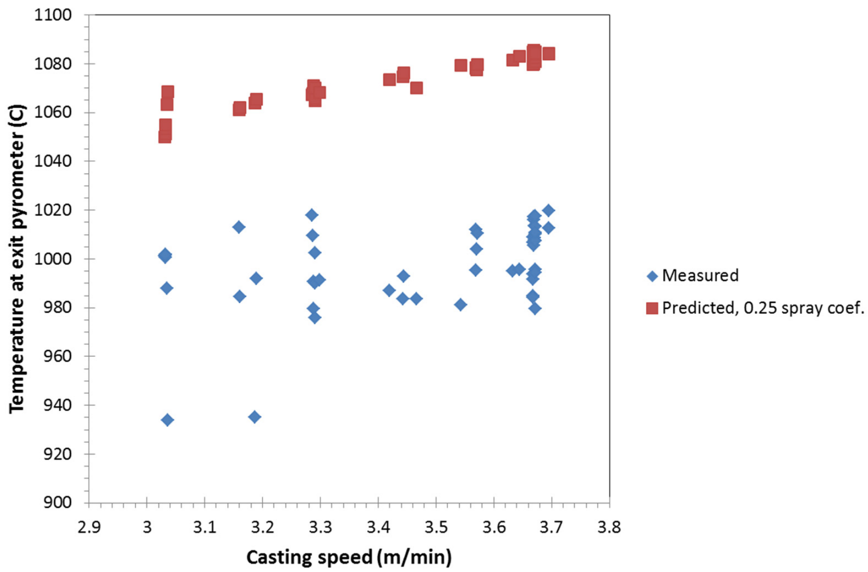
- Second question: why is CON1D 75 – 100 °C hotter than the peak pyrometer measurements?
- We can adjust parameters in the model to try to match the actual heat transfer in the caster
  - Spray profile, shown at top left
  - Magnitude of spray heat transfer, through spray coefficient, C
  - Fraction of heat removed through rolls, f_{roll}
  - Roll contact length, L_{roll}
- However, doing this intelligently requires an understanding of how heat transfers through the secondary cooling region





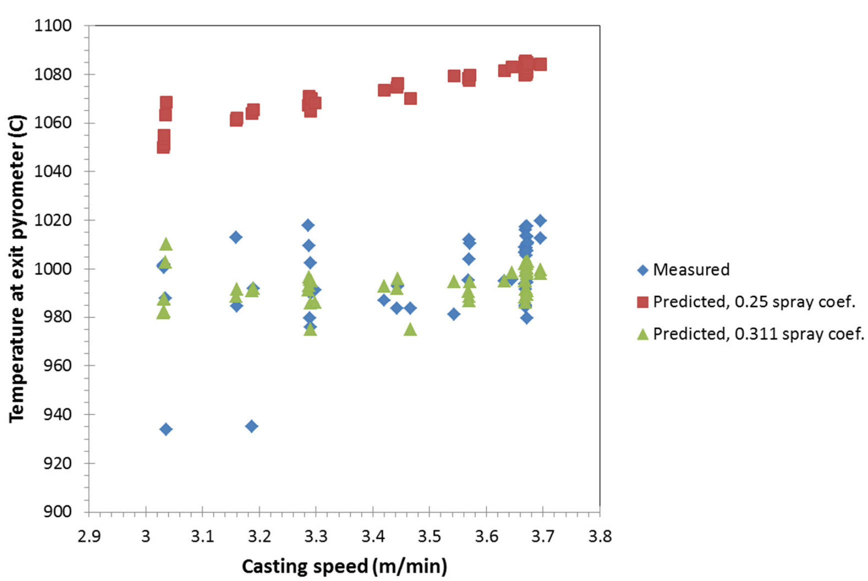
Current situation

- Over prediction of pyrometer temperature using current model spray/roll parameters (Zhou, Aug10)



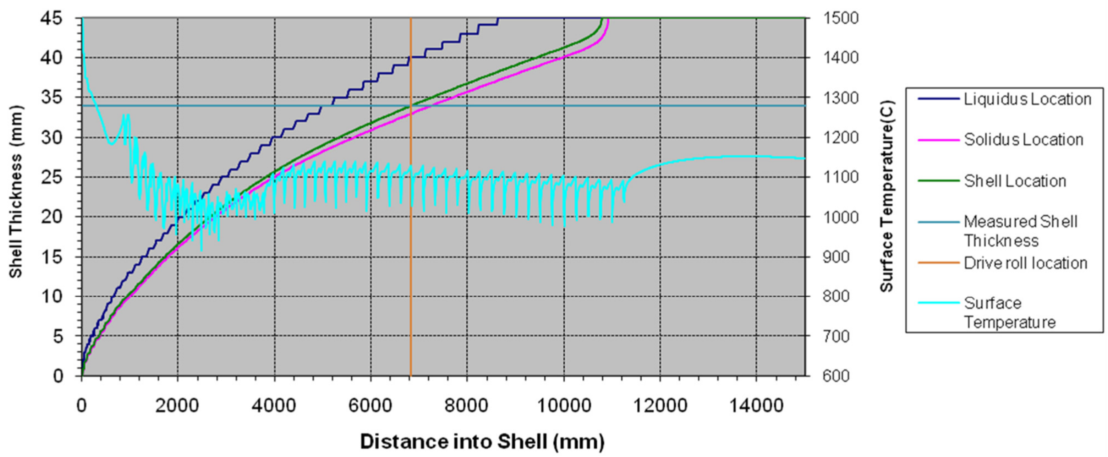
Increasing heat transfer coefficients to match pyros

- Can match the pyrometer measurements by increasing the spray coefficient in the Nozaki model from 0.25 to 0.311



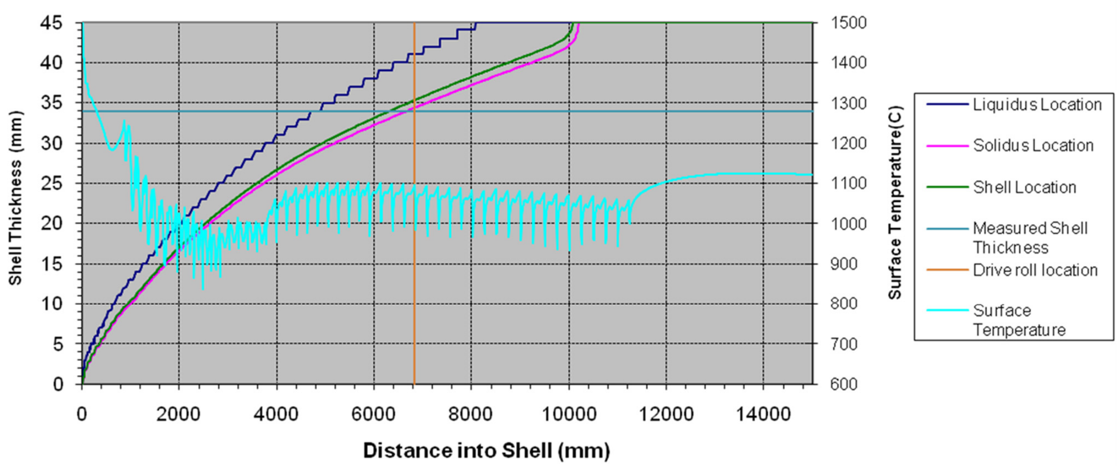
Current model matches shell thickness

Cracked slab case with spray coefficient C =0.25



Increasing spray coefficient over-predicts shell thickness

Cracked slab case with spray coefficient C =0.311



Casting conditions for example slab at Nucor Decatur

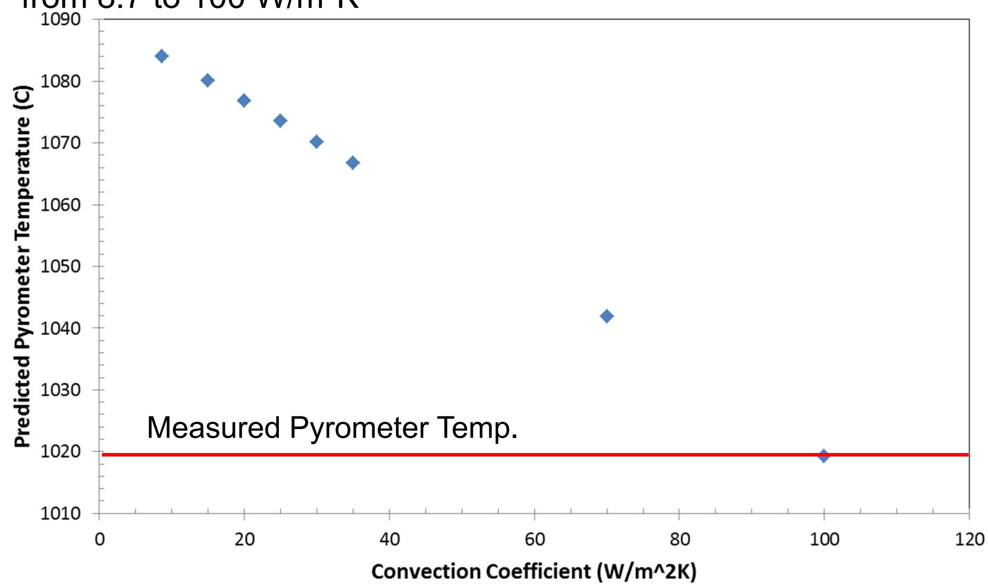
- Following simulations study the effect of changing heat transfer in an example slab
  - 0.05 % Carbon steel
  - Thickness = 89.2 mm
  - Casting speed = 3.7 m/min
  - Nominal spray and roll model parameters

Zone	1	2	3	4	5	6	7
Nominal roll fraction	0.01	0.08	0.22	0.2	0.36	0.36	0.36
Nominal spray coefficient	0.25	0.25	0.25	0.25	0.25	0.25	0.25

  - Measured pyrometer temperature = 1020 °C

Increasing convection coefficient after exiting spray chamber

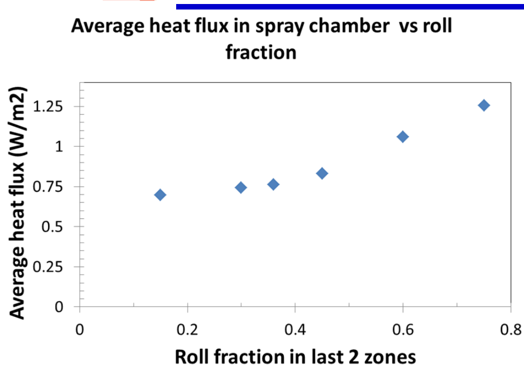
- To account for the pyrometer measurement by additional cooling, from descaler spray, requires convection coefficient be increased from 8.7 to 100 W/m^{2}K



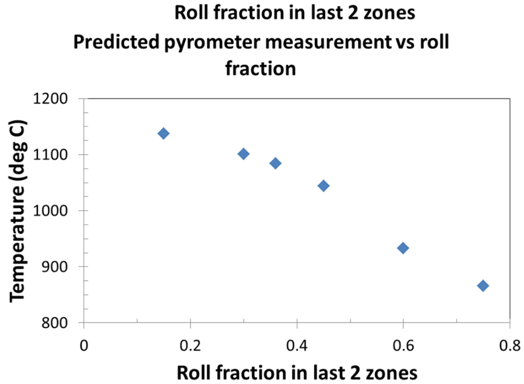
Three effects to check

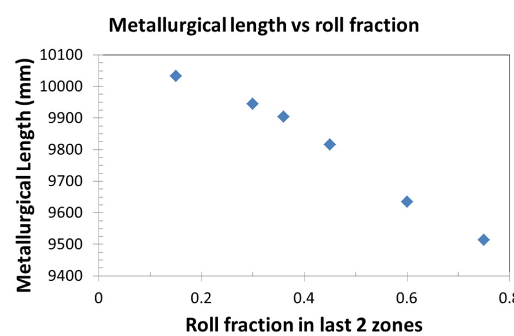
1. Total heat removal rate
   – Adding heat removed outside the spray chamber from descaler roll
   – Adding heat removed inside the spray chamber, by increasing heat removed due to sprays or rolls
2. Location of heat removed (fraction in higher zones versus lower zones in caster)
3. Local variation in heat extraction
   – difference between roll contact / spray impact (local maxima) and regions in between (local minima)

1) Effect of f_{roll}, fraction of heat removed by rolls

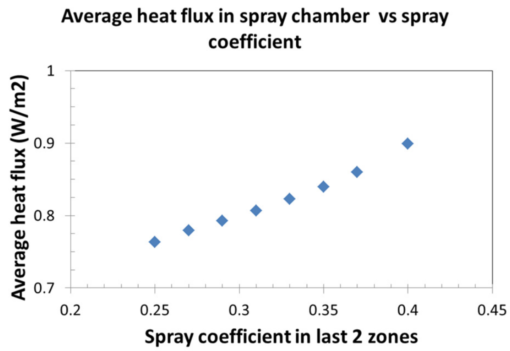


- Increasing f_{roll} in CON1D increases total heat removal
  - Lower pyrometer reading
  - Lower metallurgical length

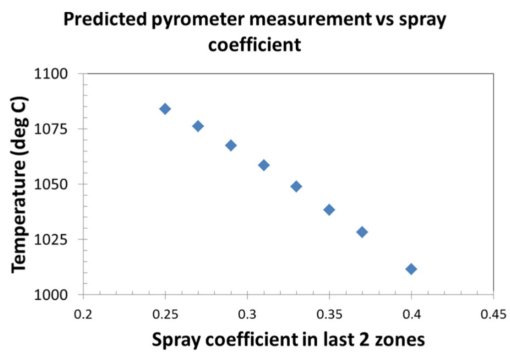


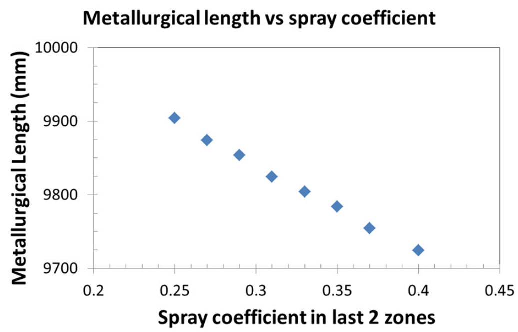


1) Effect of *C*, spray coefficient in Nozaki model

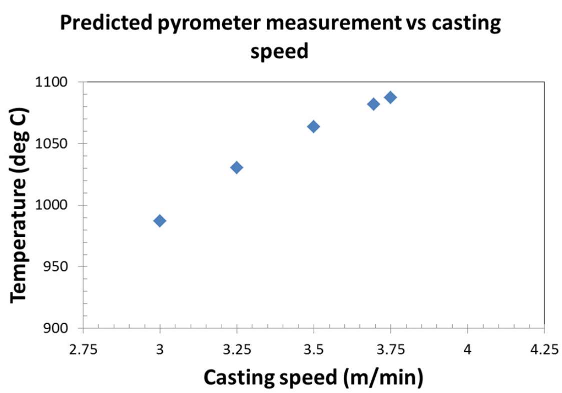


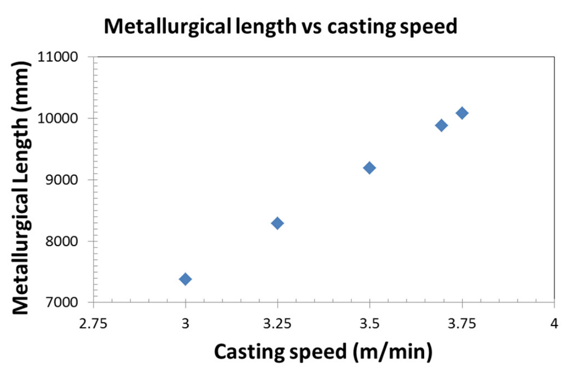
- Increasing *C* in CON1D increases total heat removal
  - Lower pyrometer reading
  - Lower metallurgical length





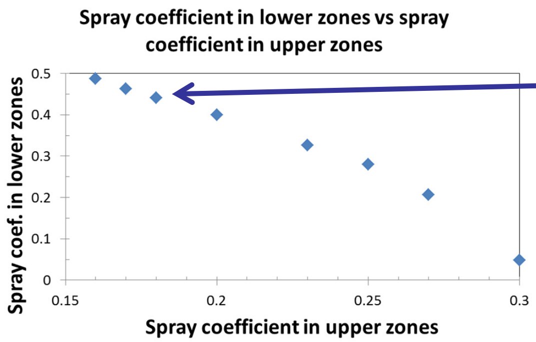
Effect of casting speed





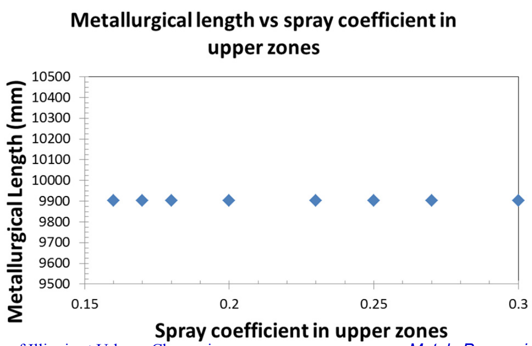
- Note: casting speed is much more important than spray water in controlling heat transfer
  - Increasing casting speed by 25% increases metallurgical length by ~30%
  - Increasing effectiveness of sprays by 60% in last 2 zones only has effect of ~2% on metallurgical length

2) Effect of location of heat removal



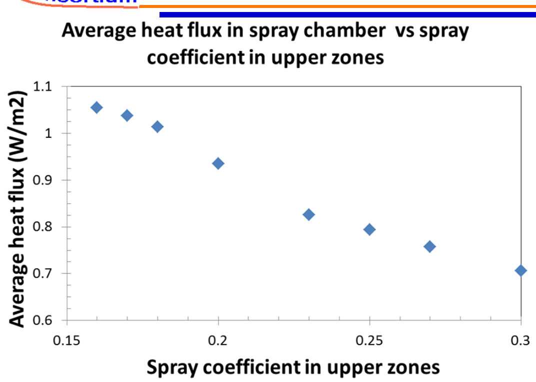
Less cooling earlier (Higher fraction of heat removed low in caster)

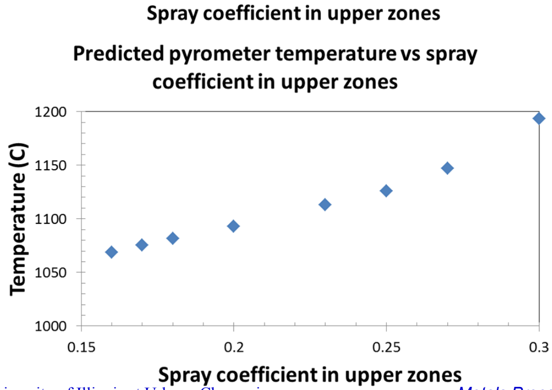
More cooling earlier (Lower fraction of heat removed low in the caster)



- Spray coefficient is varied in first 4 zones, then spray coefficient is chosen in last 3 zones to keep metallurgical length constant

2) Effect of location of heat removal

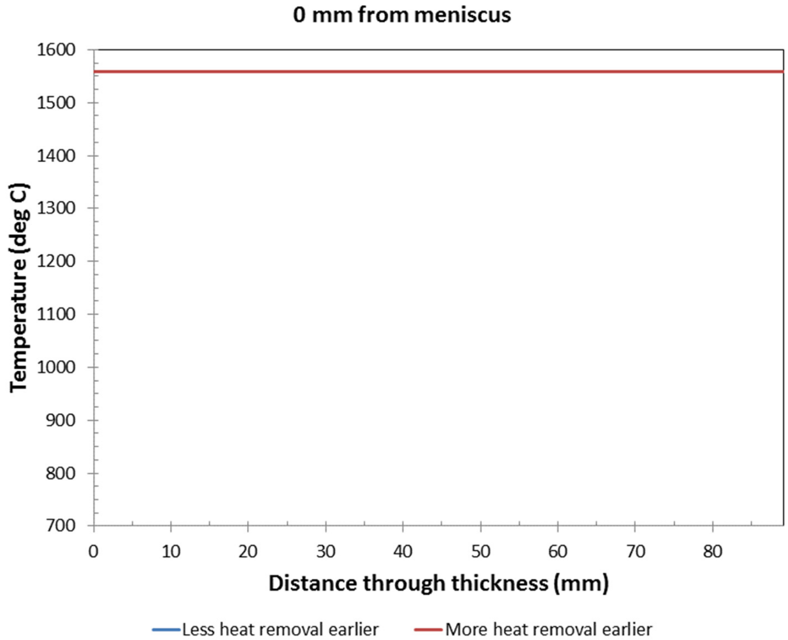




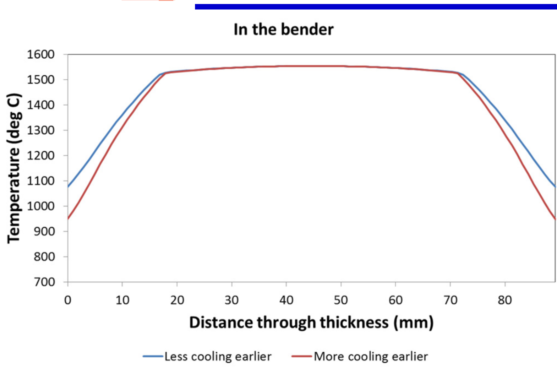
- Sprays in zones higher in the caster have a stronger affect on shell thickness
- Therefore, increasing sprays in early zones and decreasing sprays in later zones attains the same metallurgical length with less total heat removal
- Consequently, pyrometer temperature will be lower

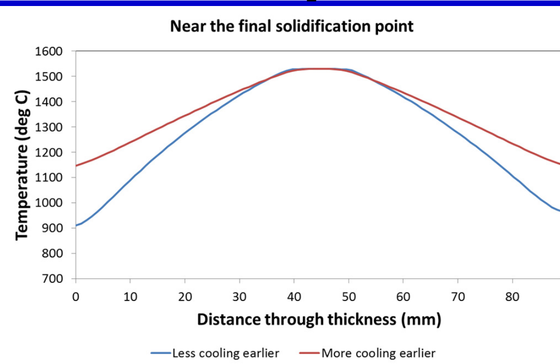
2) Effect of heat removal location on internal temperature

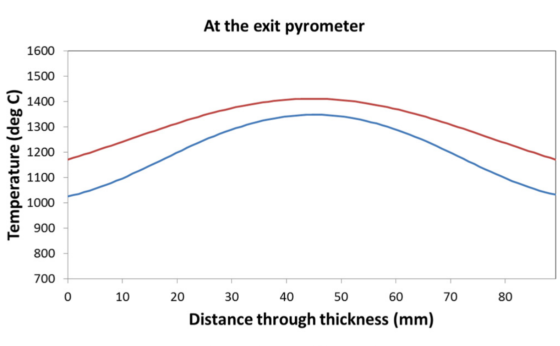
	Less cooling earlier	More cooling earlier
Spray coef. in top zones	0.2	0.3
Spray coef. in bottom zones	0.4	0.048

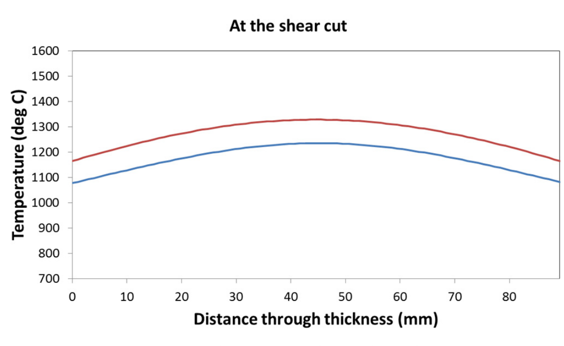


2) Effect of heat removal location on internal temperature

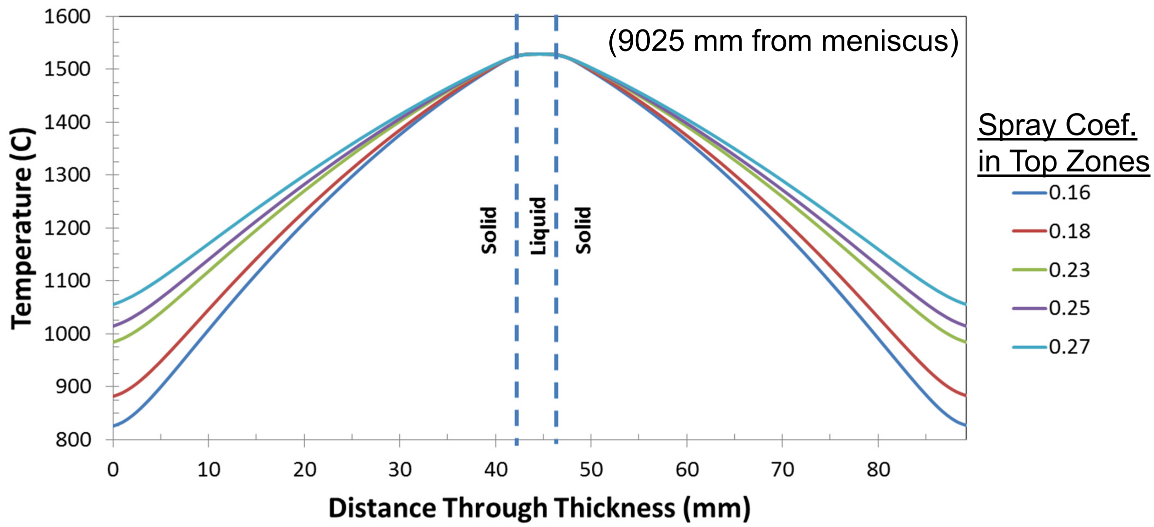






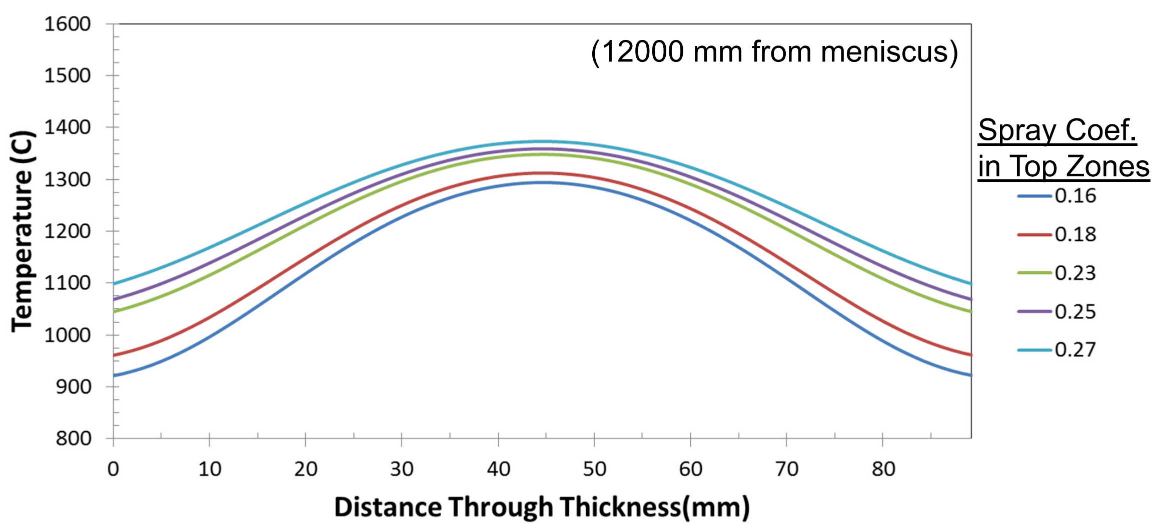


2) Internal energy near metallurgical length



For the same metallurgical length, the surface temperature is higher when more heat is extracted high in the caster (less low)

2) Internal energy at exit pyrometer



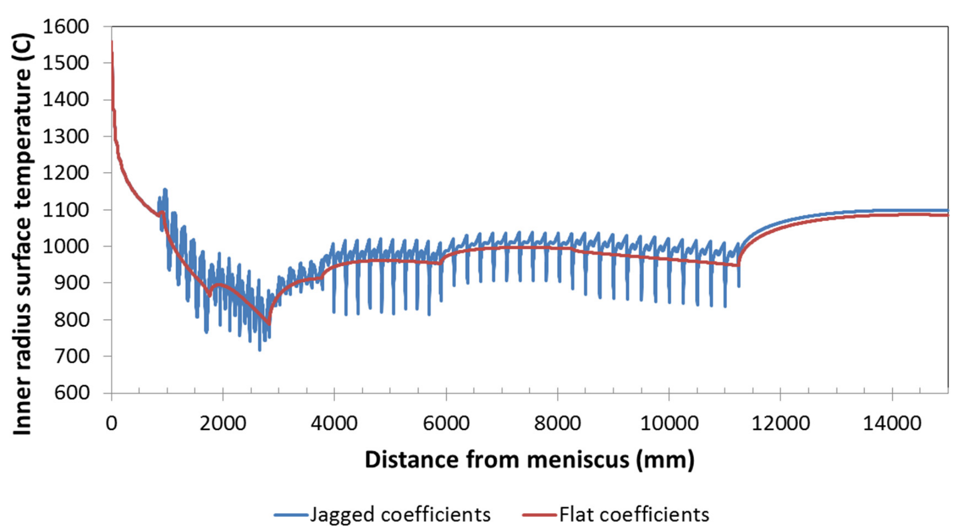
As a result, average temperature and internal energy content leaving the caster are higher when more heat is removed early in caster.

3) Effect of local heat flux variations

- By changing the length and height of the heat transfer coefficients, the surface temperature can be made flat without changing the total heat removed
- Two cases follow:
  1. Flat heat transfer coefficients within zones
  2. Jagged heat transfer coefficients, adjusting the spray coefficient to keep the average surface heat flux in each zone constant

Spray Zone (Inner Radius)	1	2	3	4	5	6	7	over all
Average heat flux from flat coefficients (MW/m^2)	1.79	2.16	1.52	0.77	0.62	0.56	0.48	0.80
Average heat flux from jagged coefficients (MW/m^2)	1.77	2.17	1.51	0.76	0.62	0.56	0.48	0.80

3) Surface temperature with local variations in heat removal



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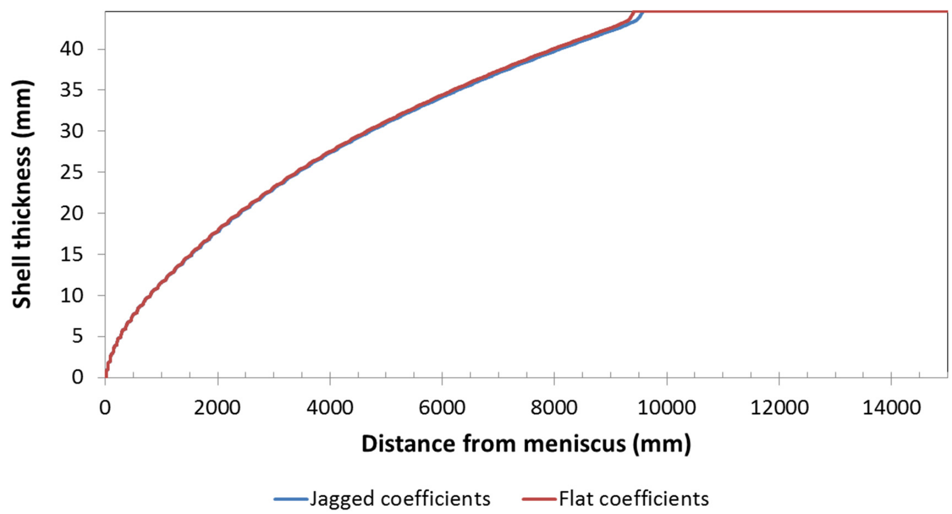

Conclusions

- The model mismatch with pyrometers cannot be accounted for by changing the total heat removed only. The *distribution* matters too.
  - Convection outside the spray zone
    - Matching pyrometer requires 100 W/m^2K extra convection
    - Corresponds to 0.121 L/m^2s water flux, using Nozaki et al.
    - For comparison, last spray zone typically has average of 1-10 L/m^2s
  - Location of heat removal
    - More heat removed higher in the caster, and less lower → same metallurgical length, higher pyrometer measurement
  - Local variability
    - Seems to have an effect, but is still unclear
- The second finding affects caster operation
  - More spray cooling higher in the caster and less lower in the caster → same metallurgical length, but higher steel temperature leaving the caster
  - Implications for spray control

Effect of heat transfer on quality/production goals

- Quality and production goals can be described as desired constraints on the slab temperature profile. For example:

Plant Goal	Model constraint / condition
• Prevent whales	• Keep centerline temperature below solidus temperature
• Prevent defects (eg. transverse cracks)	• Keep surface temperature in straightener above or below 700-900 °C ductility trough
• Save energy in reheating furnace and rolling mill	• Maximize average internal temperature at entry to reheating furnace
• Avoid centerline segeregation	• Keep metallurgical length within the distance range of a soft-reduction system

- In addition, there may be casting speed constraints
  - Maximize speed
  - Match speed to upstream or downstream production requirements
  - Minimize transient changes in speed (also flow-rates, etc.)

Implications for caster spray cooling strategies

- Challenge comes from trying to balance more than one goal or constraint
- Understanding the underlying heat transfer suggests potential strategies
- Specifically, the concept of higher cooling in upper caster and less low in caster can be used to optimize several examples
  - Keep metallurgical length constant (for soft reduction) while keeping a given surface temperature in unbending (for transverse cracks), with varying casting speeds
  - Save energy, while maintaining speed and preventing whales
  - Maximize speed, while preventing whales and keeping desired surface temperature in unbender (for transverse cracks) by focusing on highest spray zones, which have largest effect on shell thickness

Future Work

- Model calibration: likely approaches so far
  - Redistribute heat transfer so more heat is removed lower in the caster
    - First determine if this is valid, using the Cinvestav model to compare spray heat transfer between zones
  - Investigate further the effect of local variability
    - Possibly indicates way to determine ratio of heat lost to sprays versus roll contact
  - Validate using plant pyrometer measurements inside spray chamber

- Multi-objective control: achieve quality goals by regulating the temperature profile to well-chosen setpoints
  - Possible next-generation Concontroller

- Develop Conoffline as tool for simulation and testing
  - We welcome any input

Acknowledgments

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)

- Hemanth Jasti and Xiaoxu Zhou, former grad students in CCC, further developed CON1D

- Nucor Decatur
  - Ron O'Malley, Bob Williams, Kris Sledge, Rob Oldroyd, Terri Morris, and many, many others