CCC Annual Report

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Spray-Cooling Control for Maintaining Metallurgical Length During Speed Drop

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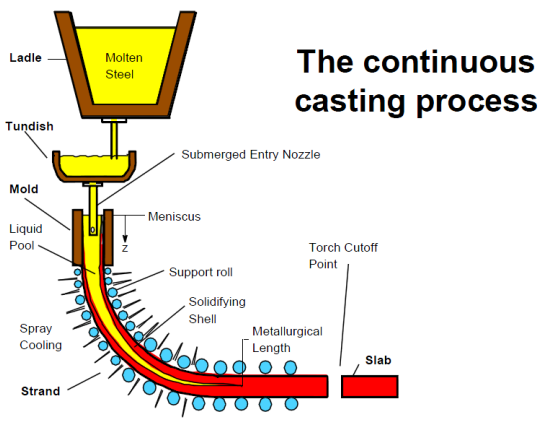
Motivation

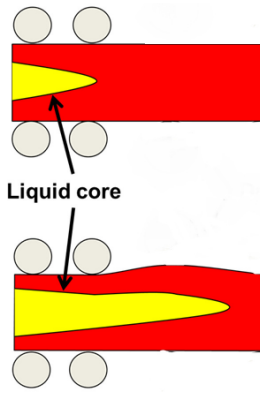
- **Maintaining ML during speed changes** within certain bounds is helpful for many operations:
  - Unbending to prevent cracks
  - Staying inside support zone to prevent whales
  - Soft reduction to prevent centerline segregation

- **Objective**: explore the potential to avoid metallurgical length change during a casting speed drop for a thick-slab caster using different control methods.

'Whale' Formation



The continuous casting process

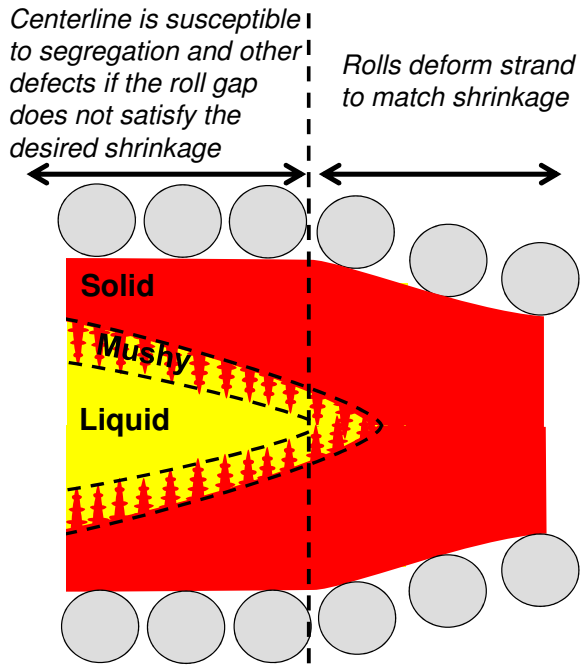


From CCC

- Ferrostatic pressure is transmitted from the meniscus via the liquid pool acting internally on the steel shell.
- If ML exceeded the machine length, final portion of solidifying steel is not supported by rolls, steel will bulge out.

Soft Reduction

- In soft reduction operation, roll gap should match the shrinkage to prevent centerline defects
- During speed change, ML should stay within soft reduction region.

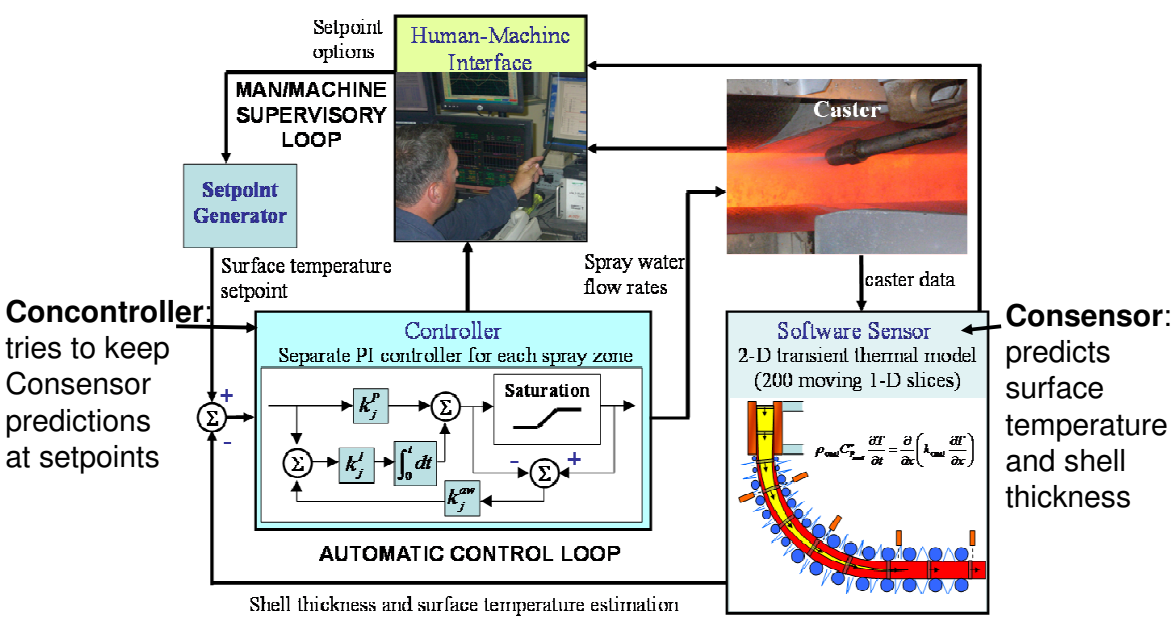


Objective

- Choose realistic caster and conditions to explore control methods to maintain ML during a speed drop
- Caster studied: thick slab caster at JFE Steel
- Steel grade: not sensitive to surface cracks but may be sensitive to centerline defects.
- Small speed drop: 1.7m/min to 1.5m/min.

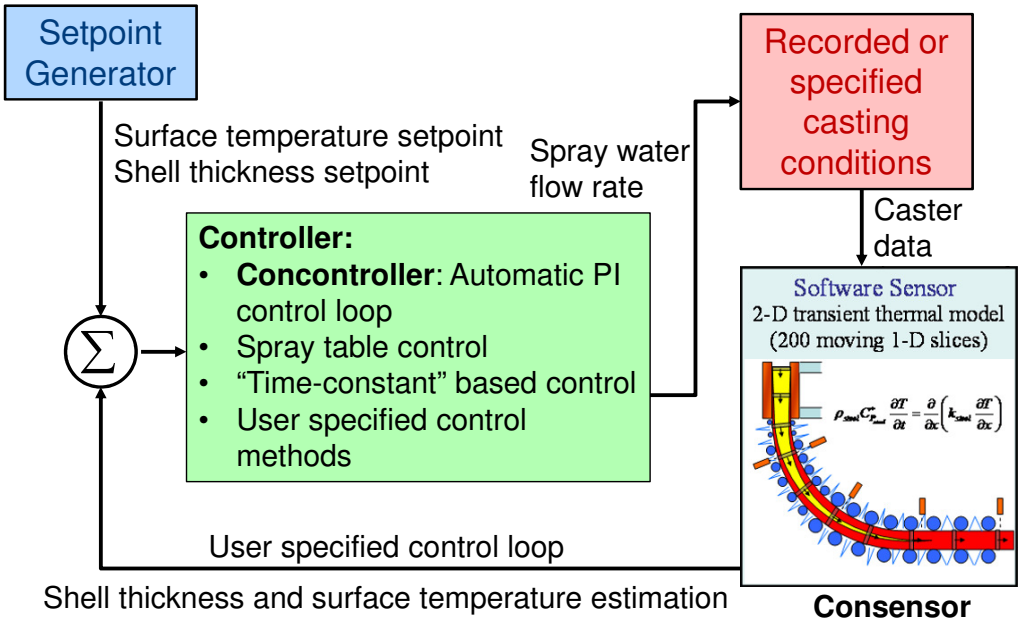
  - maintaining constant ML during steady state is achievable by changing water flow rates.

Cononline: On-line Control System for Secondary Cooling Water Sprays



[1] Petrus, B., K. Zheng, X. Zhou, B.G. Thomas, and J. Bentsman, "Real-Time Model-Based Spray-Cooling Control System for Steel Continuous Casting", *Metallurgical and Materials Transactions B*, Vol. 42B:2, 87- 103, 2011

Conoffline



- Currently runs on one Linux server.

Example of Conoffline "replay" File

- Generate scenarios by editing CSV files in Excel:
  -- each row contains all (83) CON1D casting conditions at specified time.

Casting speed

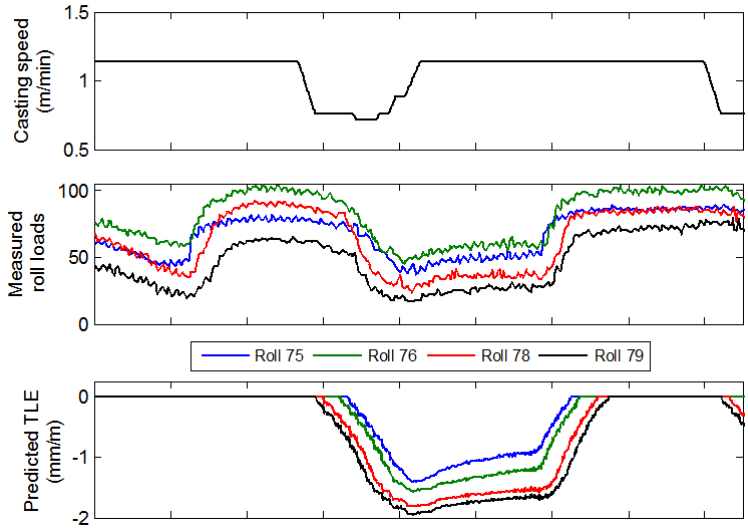
sample_time	distance from meniscus to mold top	tundish nozzle submergence depth	speed	width	thickness	Pouring temp.	Slab Chemistry
	mm	mm	m/min	mm	mm	deg_C	
21:30:00	90	250	1.7	2095	221	1557	
21:40:09	90	250	1.7	2095	221	1557	
21:40:52	90	250	1.5	2095	221	1557	

•••

Time

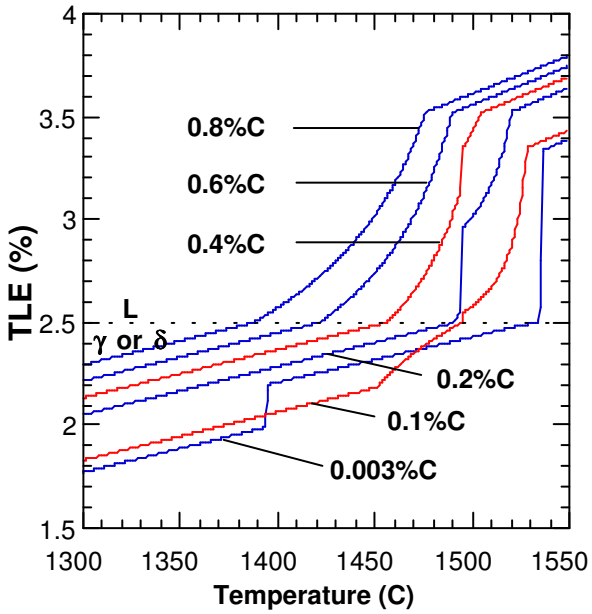
Casting conditions

Validation of Cononline with Roll Force Measurements [4]



- Predicted thermal linear expansion of strand thickness (depends on liquid shrinkage & metallurgical length) **matches closely** with timing of changes in measured roll loads during speed changes at Burns Harbor caster [5].

Thermal Linear Expansion of Carbon Steels



Liquid data from: Jimbo & Cramb, Met. Trans. B, 24B, 1993, 5-10.
Solid data from: Harste, Jablonka & Schwerdtfeger, 4th Int.Conf. on Continuous Casting, CRM, 1988, Brussels, 633-644

Casting Condition

Slab Size

Slab thickness	221	mm
Slab width	2095	mm

Liquidus Temperature	1516.10	°C
Solidus Temperature	1468.37	°C
Density of solid steel	7400	kg/m^3
Steel emissivity	0.8	-
Fraction solid for shell thickness location	0.3	-
Specific heat of solid steel	670	J/kgK
Thermal conductivity of solid steel	30	W/mK
Thermal diffusivity of solid steel	6.0508 e-6	m^2/s
Latent heat of fusion	271	kJ/kg
Initial cooling water temperature	29.67	°C
Pour temperature	1545	°C
Mold conductivity (WF/NF)	418.7/355	W/mK
Time step	0.01	s
Mesh size	0.55	mm

Surface Heat Removal Eqs

- **Mold heat flux**: varies with casting speed, based on empirical correlation for a thin slab caster [2]

$$\bar{Q}_{\mathrm{m}}\left[\mathrm{MW/m^2}\right] = 1.2154\left(v_c\left[\mathrm{m/min}\right]\right)^{0.47}$$

Average mold heat flux — Casting speed

- **Heat flux due to water sprays**: empirical relation of Nozaki [3]

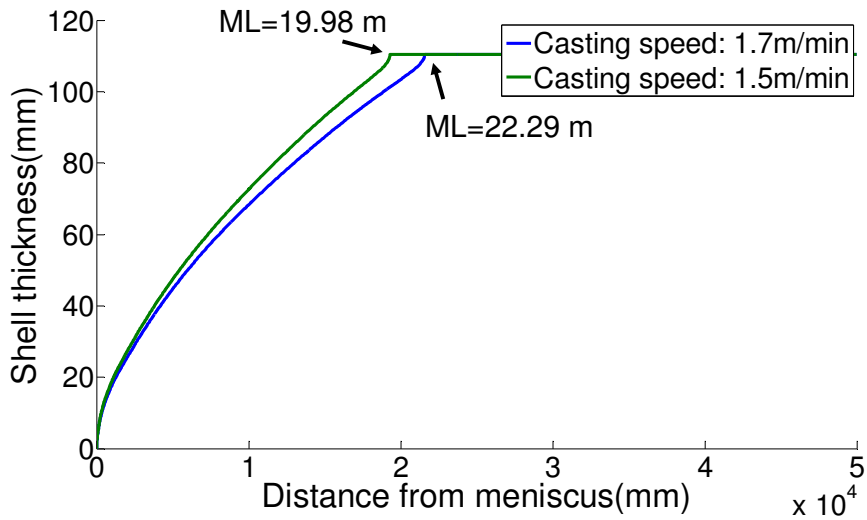
Steel surface temperature — Spray water temperature

$$q_{\mathrm{sw}} = h_{\mathrm{sw}}\left(T_{\mathrm{surf}} - T_{\mathrm{sw}}\right)$$

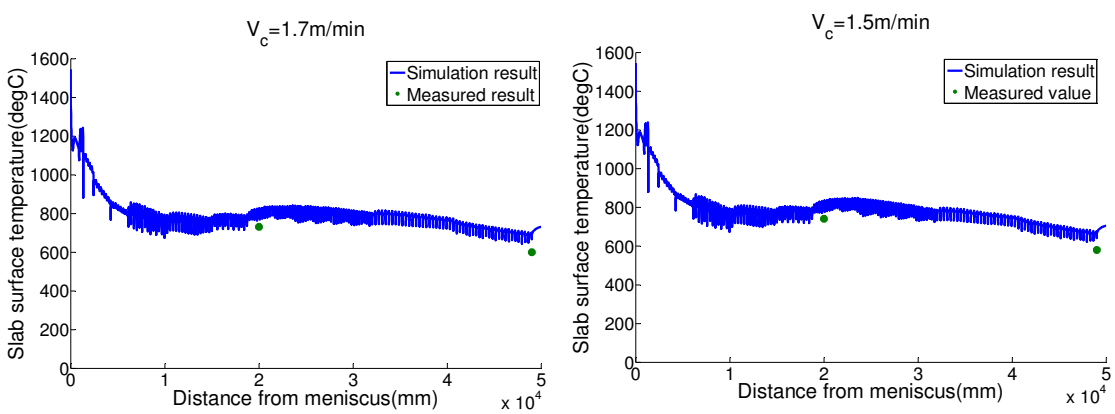
$$= 0.3925 \cdot Q_{\mathrm{sw}}^{0.55} \cdot \left(1 - 0.0075 \cdot T_{\mathrm{sw}}\right)\left(T_{\mathrm{surf}} - T_{\mathrm{sw}}\right)$$

Spray water flux in $L/m^2/min$

Shell Thickness at Steady State



Calibration of Conoffline



- Calculated surface temperatures agree with measurements under steady state.

Example Concontroller Setup for Cononline/Conoffline PI Control

- **Control setpoints:** Controller setpoints is generated based on the Cononline result of steady state at 1.7 m/min.

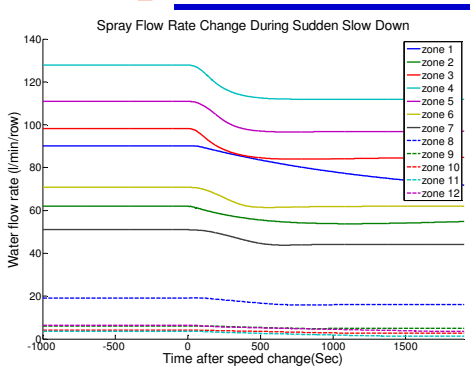
Zone #	Setpoint (deg)
1	1214.62
2	1122.15
3	1071.99
4	932.26
5	840.31
6	795.21
7	771.47
8	780.88
9	822.50
10	816.52
11	792.28
12	726.04

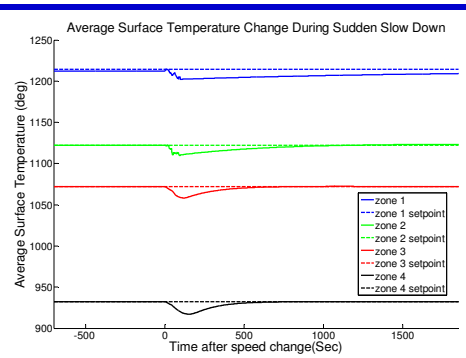
Zone #	Kp (/60)
1	0.5
2	2
3	2
4	2.5
5	2.5
6	3.5
7	3.5
8	3.5
9	2.5
10	2.5
11	4.5
12	4.5

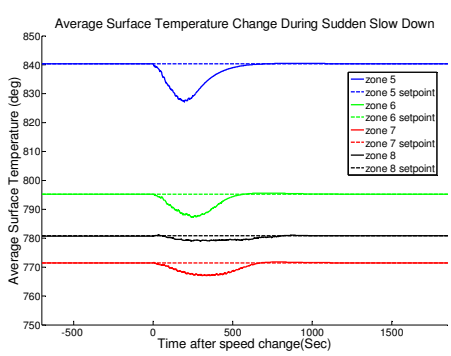
Zone #	Ki (/60)
1	0.1
2	0.1
3	0.25
4	0.25
5	0.25
6	0.25
7	0.25
8	0.25
9	0.25
10	0.25
11	0.35
12	0.35

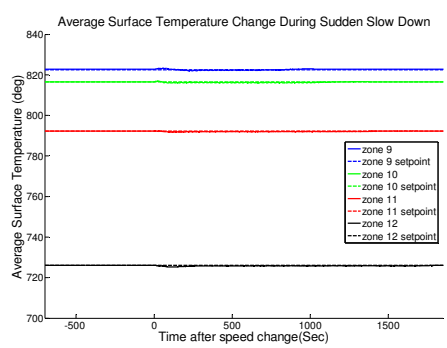
First 2 zone is very short and right after the mold exit and their behavior will largely affect the surface temperature for the following zones, so choose smaller kp and smaller damping (ki)

Simulation Results for PI Control: Surface Temperature Histories (12 zones)

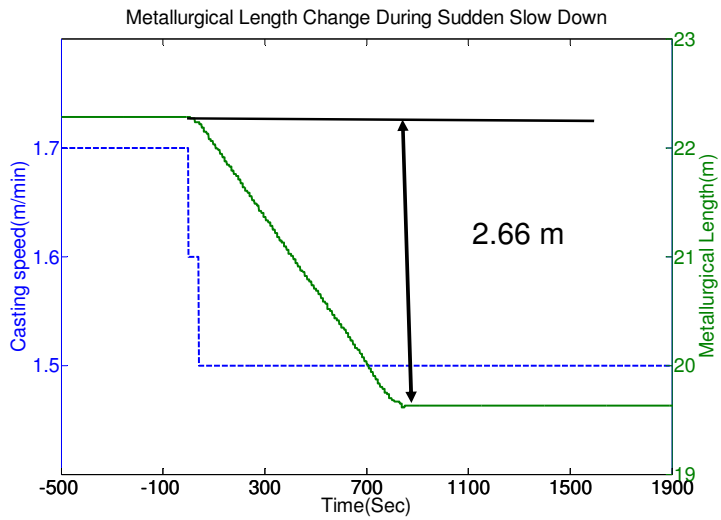






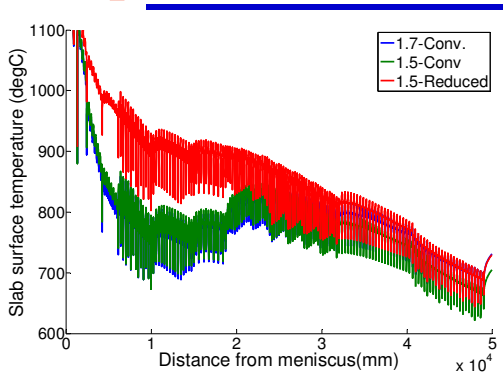


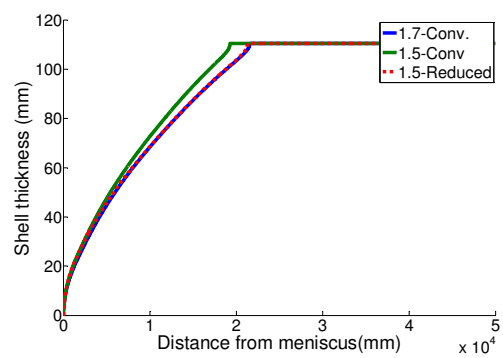
ML Behavior during Speed Change under PI Control



Cononline can maintain constant surface temperature during speed change, but its performance on maintaining ML is not good.

Reduce water flow rates at lower speed: match ML at steady-state





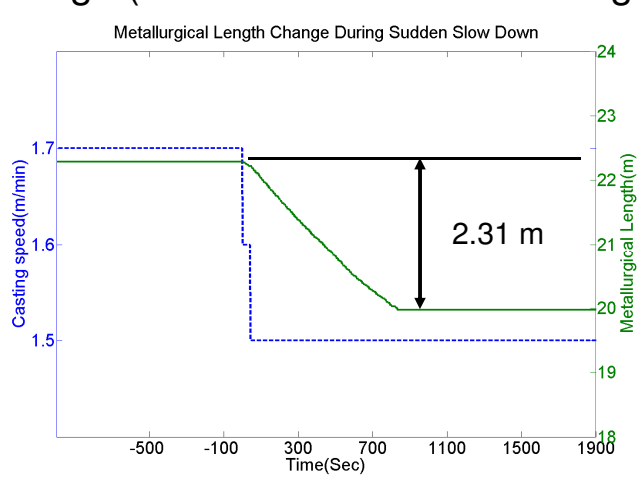
No.	1.7-Conv.	1.5-Conv.	1.5-Reduced.
v_c	1.7 m/min	1.5 m/min	1.5 m/min
Spray pattern	Conventional	Conventional	1-2Z: Conv. 3Z: Conv. x 0.7 4Z: Conv. x 0.45 5-8Z: Conv. x 0.35 8-12Z: Conv. x 0.7
ML (f_s=0.7)	22.29 m	19.98 m	22.17 m

Control Methods for ML in Transient Conditions (i.e. speed drop)

- Spray table control (1.7 to 1.5 m/min)
  - conventional (conv.) to conv.
  - conv. to reduced
- Time-constant spray control
- PI control for ML (60X surf temp gains)

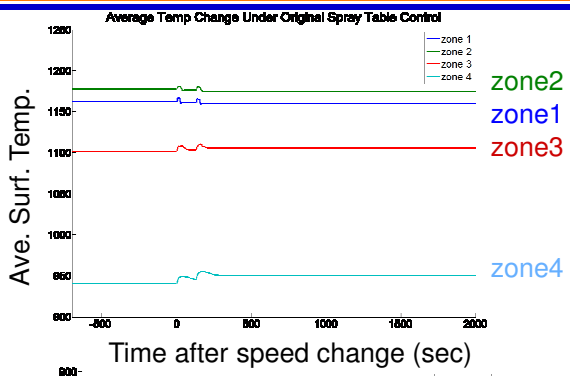
Spray Table Control (conv. to conv.) -ML

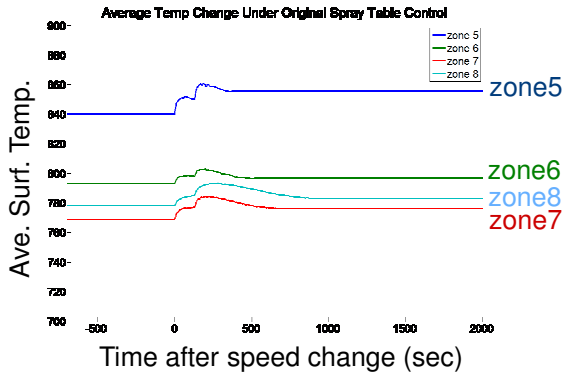
- Spray pattern:
  conventional (1.7m/min) to conventional (1.5 m/min)
- ML drop = 2.31 m
  = ML change (defined as maximum change in ML)

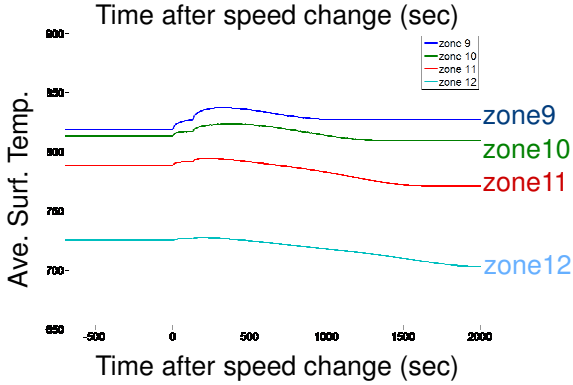


Spray Sable Control (conv. to conv.)
-Surface Temperature

- Spray pattern = conventiona to conventional

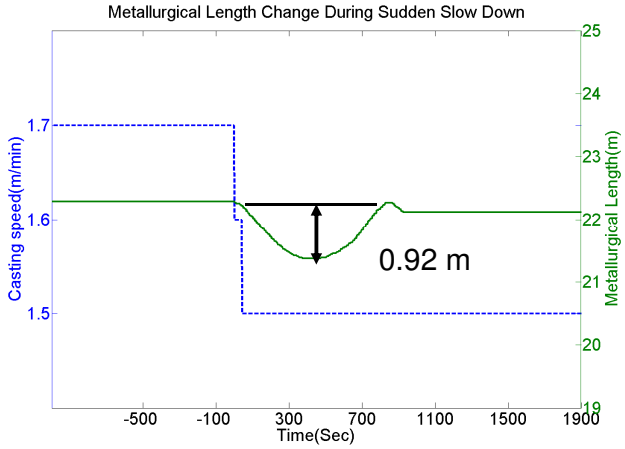






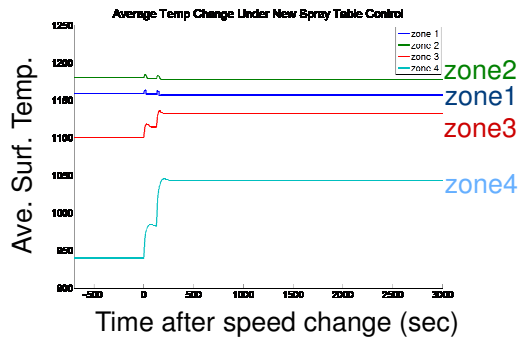
Spray Table Control (conv. to reduced)
-ML

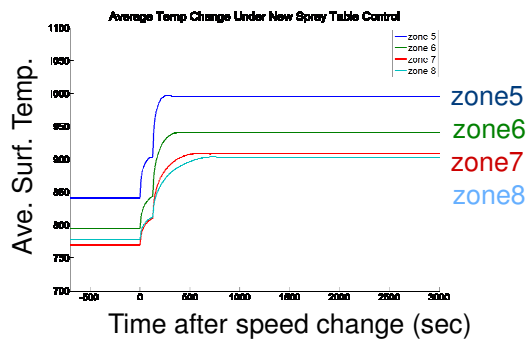
- Spray pattern = conventional to reduced
- ML change = 0.92 m

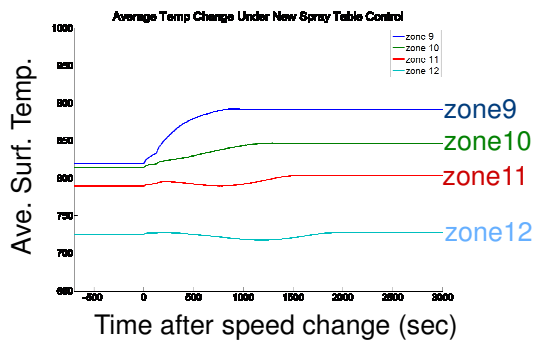


Spray Table Control (conv. to reduced)
-Surface Temperature

- Spray pattern = conventional to reduced







"Time-constant" Spray Control
(conv. to reduced spray pattern)

- Spray table control: spray water rate changes immediately when speed changes.
- Intuitive idea: spray water rate changes gradually as speed changes, (i.e. spray water rate changes according to time instead of velocity).
- For a typical caster, the relation between spray water rate and casting speed is assumed to be:

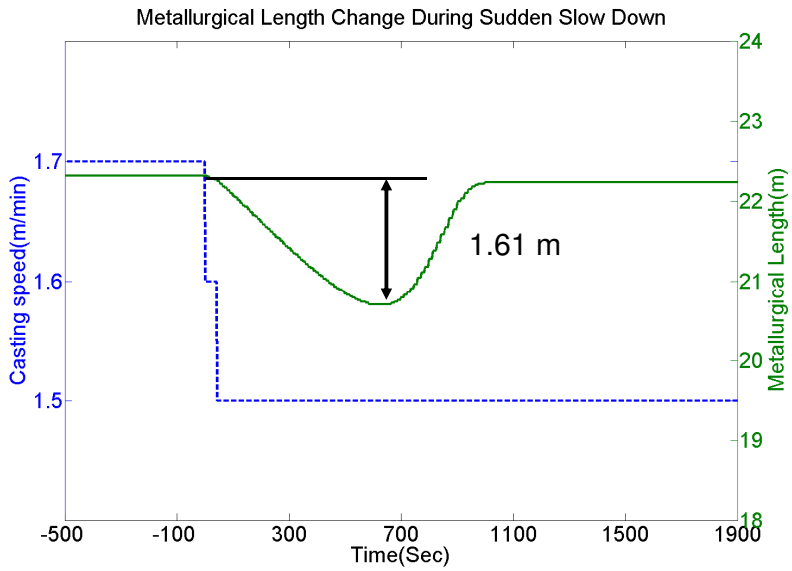
$$SW_{spray}\left[l/m/row\right] = A + Bv_c\left[m/\min\right]$$

- Above equation can be transferred to:

$$SW_{spray}\left[l/m/row\right] = A + B\frac{z}{\tau(z)}\left[m/\min\right]$$

- Can be found solving the inverse of equation: $\int_{t-\tau(Z)}^{t} v(s)\,ds = z$

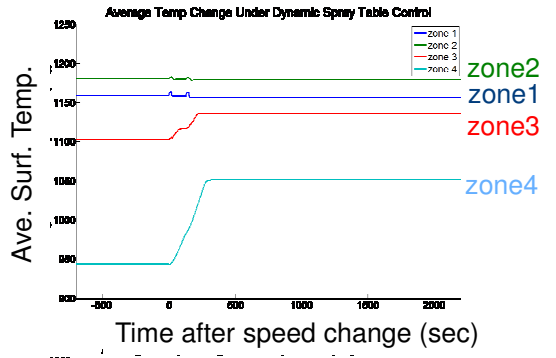
"Time-constant" Spray Control - ML (conv. to reduced spray pattern)

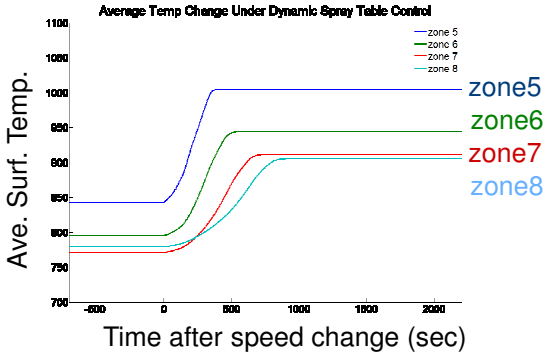


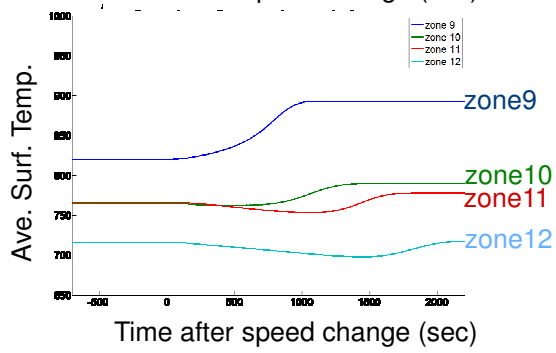
- ML change = 1.61 m

"Time-constant" Spray Control – Surface temperature (conv. to reduced spray pattern)

- The transition between two steady state is more smooth than conv. to reduced spray table control







PI Control based on Shell Thickness Setpoints

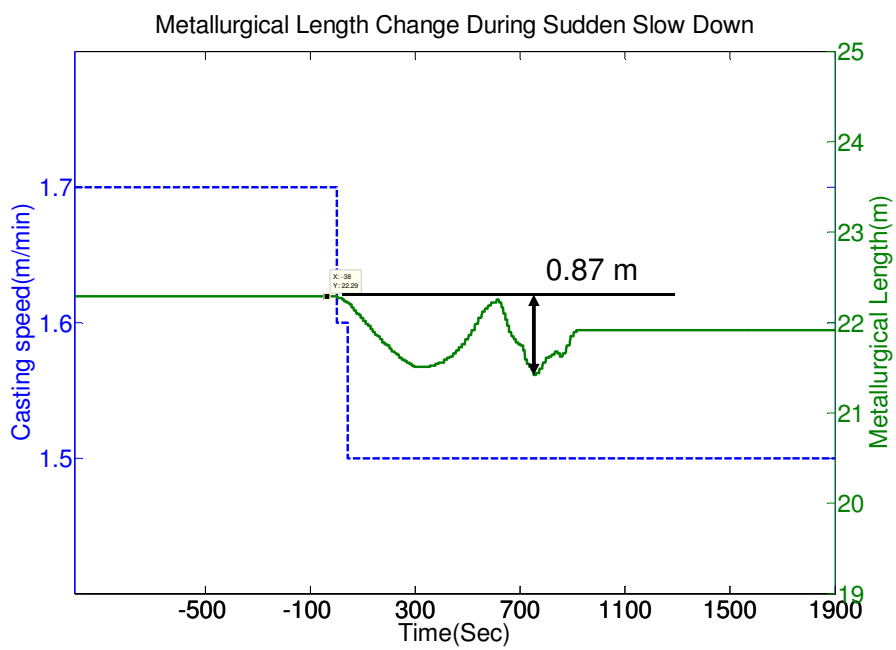
- **Control setpoints:** Controller setpoints is generated based on the CONONLINE result of steady state at 1.7 m/min.

Zone #	Setpoint (mm)
3	23.65
4	33.45
5	44.32
6	58.80
7	76.20
8	91.25
9	105.01
10	110.5
11	110.5
12	110.5

Zone #	Water flow rate upper bound (l/min/row)
3	180
4	70
5	70
6	63
7	63
8	42
9	26
10	48
11	36
12	36

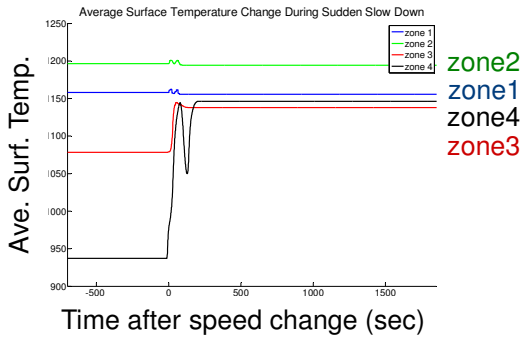
Zone #	Water flow rate lower bound (l/min/row)
3	36
4	10
5	10
6	4.5
7	4.5
8	3
9	1.53
10	1.5
11	1.5
12	1.5

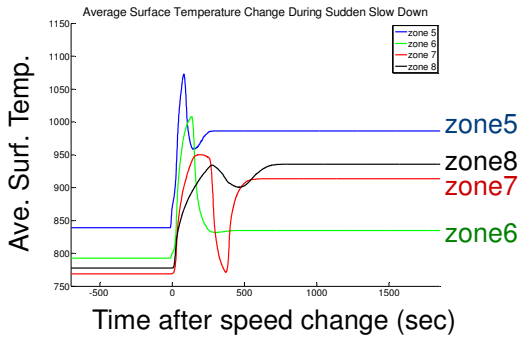
PI control based on Shell Thickness Setpoints-ML

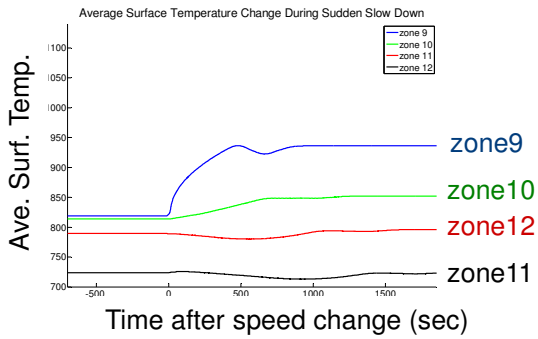


- ML change = 0.87 m, **BEST**

PI Control based on Shell Thickness Setpoints - Ave. Surface Temp.







- Change of water flow rate have immediate response on average surface temperature.

Conclusions: Conoffline

- Has been calibrated to match steady casting conditions at a commercial thick-slab caster
- Using PI controller, surface temperature can successfully be controlled during a speed drop at this caster.
- Has been applied to investigate potential for ML control during speed drop from 1.7 to 1.5 m/min:
  - Conventional spray table control causes metallurgical length drop of 2.31 m (fs=0.7).
  - Spray table control with conv. to reduced water flow rates at low speed causes metallurgical length (ML) drop of 0.92 m (fs=0.7).
  - "Time constant" spray control (based on conv. to reduced spray table control) causes ML change of 1.61 m (fs=0.7)
  - **PI control based on shell thickness causes ML change of 0.87 m.**

Future work

- Improve control methods to maintain ML during speed change.
- Tune the PI controller gains for shell thickness feed back control method.
- Find better (fundamental) methods for ML control
- Investigate other scenarios?

- Any other suggestions?

Acknowledgments

- Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, SSAB, ANSYS/ Fluent)
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- Dr. Petrus, (former grad student, currently at Nucor) for helping with Cononline program development and advice.
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References

- [1] Petrus, B., K. Zheng, X. Zhou, B.G. Thomas, and J. Bentsman, “Real-Time Model-Based Spray-Cooling Control System for Steel Continuous Casting”, *Metallurgical and Materials Transactions B*, Vol. 42B:2, 87- 103, 2011
- [2] P. Duvvuri, B. Petrus, B.G. Thomas, *“Correlation for Mold Heat Flux Measured In A Thin Slab Casting Mold,”* AISTech 2014, Indianapolis, IN, 2014
- [3] T. Nozaki: *Iron Steel Inst. Jpn. Trans.*, vol. 18, pp. 330-38, 1978.
- [4] Petrus, Bryan, Danny Hammon, Megan Miller, Bob Williams, Adam Zewe, Zhelin Chen, Joseph Bentsman, Brian G. Thomas, “New Method to Measure Metallurgical Length and Application to Improve Computational Models”, AISTech 2015, Cleveland, OH, May 4-6, 2015, Assoc. Iron Steel Technology, Warrendale, PA, pp. 3238-3248.
- [5] Gregurich, N., Flick, G., Moravec, R., and Blazek, B. “In-Depth Analysis of Continuous Caster Machine Behavior During Casting With Different Roll Gap Taper Profiles”, *Iron & Steel Technology*, Dec. 2012