MechSE

CCC Annual Report

UIUC, August 20, 2014

Investigating Dynamic Thermal Behavior with Conoffline

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Outline

- Brief introduction to Cononline and Conoffline
- Validating transient behavior of model
  – Advection versus conduction in the casting
  – Compare CON1D with analytical result
  – Compare Conoffline with published strain gauge measurements
- Conoffline parametric study: effect of casting speed changes on metallurgical length

CON1D: heat transfer and solidification model [2]

- In the casting direction, heat is transferred by:
  - Conduction
  - Advection
- Peclet number describes the ratio o these two effects

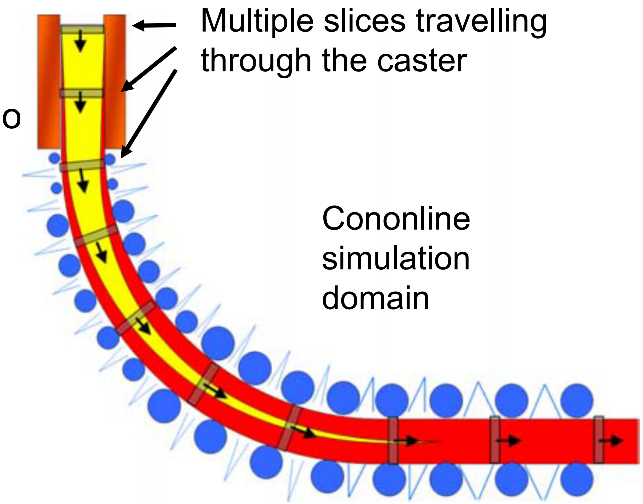
$$\mathrm{Pe} = \frac{L v_c}{\alpha} = \frac{\text{advection rate}}{\text{conduction rate}}$$

$L =$ characteristic length

$v_c =$ casting speed

$\alpha =$ thermal diffusivity

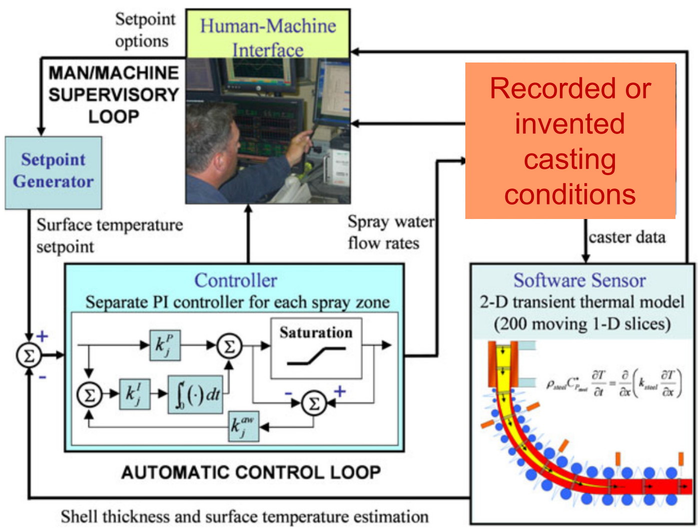
- For a typical caster, Pe is on the order of 10^3. Suggest conduction can be neglected.
- **Governing equation:** (LaGrange frame of reference)



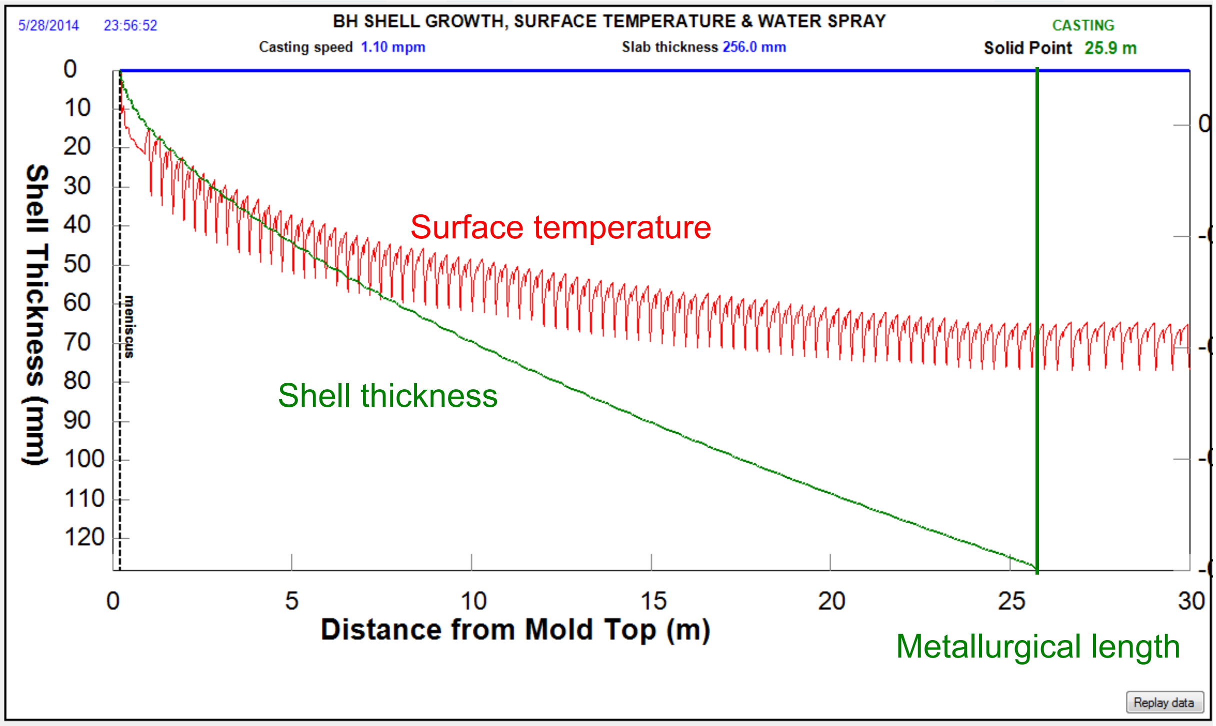
$$\rho c_p \frac{\partial T'}{\partial t} = k \frac{\partial^2 T'}{\partial x^2}$$

Conoffline [3]

- Consensor can run offline using recorded or invented casting data.
- Conoffline requires two Linux servers to run.
- Conoffline has been used to :
  - Calibrate the model
  - Tune the controller
- We would also like to use this to investigate the behavior of casters, particularly things like shell growth that cannot be easily measured.



Conoffline Monitor

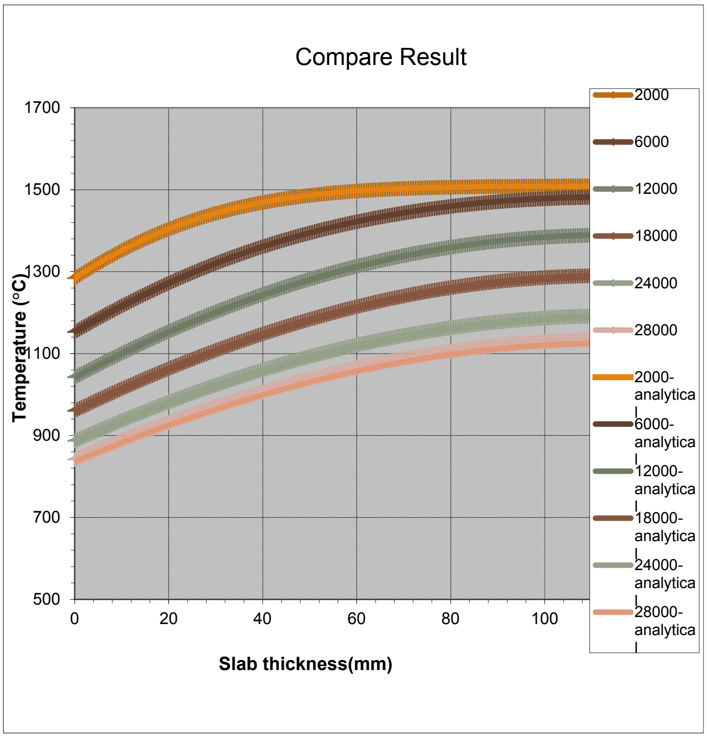


Comparison of CON1D result with analytical result: temperature

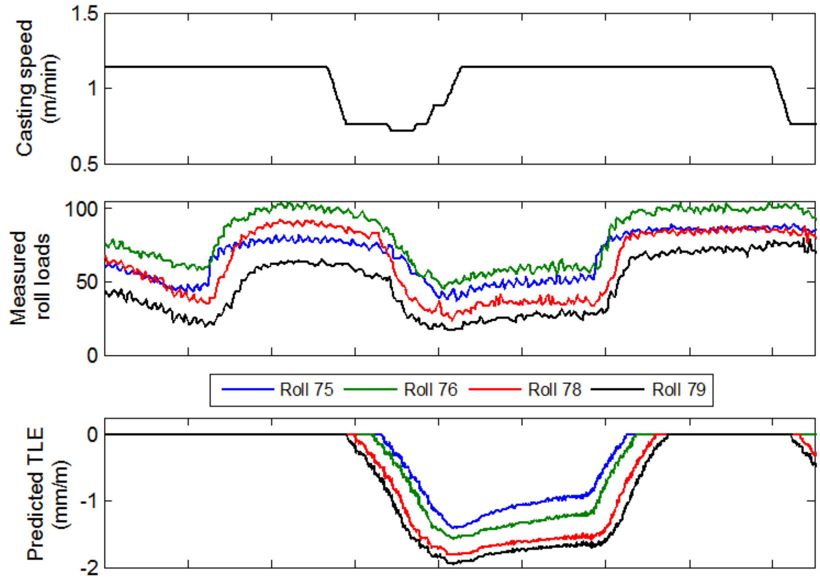
- Analytical result from Dantzig, J. A., & Tucker, C. L. (2001):

$$\theta = 2\sum_{n=1}^{\infty} \frac{\sin(u_n)}{u_n + \sin(u_n)\cos(u_n)} \bullet \exp(-u_n^2 t^*)\cos(u_n x^*)$$

- By equation $Z = vt$ we can transfer time into location.
- The error is 0.36%. Model is varified



Comparison of Cononline with strain gauges: thermal shrinking [5]



- Predicted thermal linear expansion and measured roll loads for Burns Harbor caster are qualitatively match after the slow down.
- Cononline model is verified.

Parametric simulation study

- Conoffline is used to investigate the transient behavior of continuous casters.
- In this presentation, we focus on the effect of casting speed changes on metallurgical length on a thick-slab caster.
- And the performance of 3 different control algorithm (no control, speed table control, dynamic spray control) on surface temperature during speed changes.
- Based on standard conditions at Burns Harbor: 230 mm thickness slab, low-carbon steel.

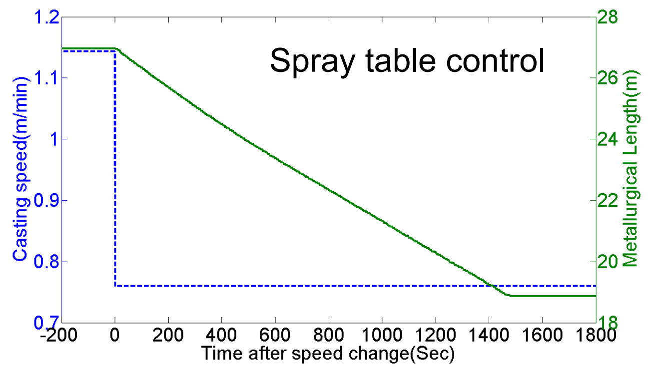
Casting condition

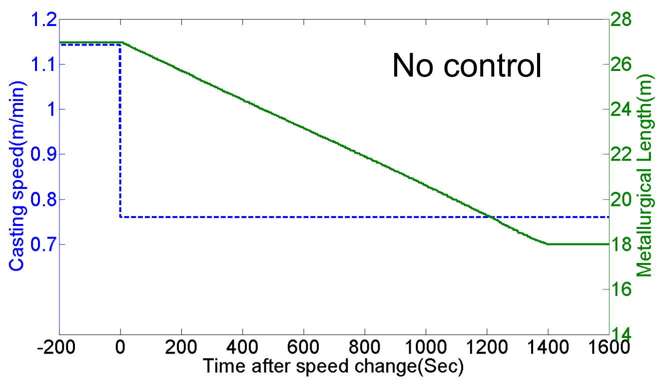
- Simulations are based on Burns Harbor caster.
- Thickness: 260 mm
- Grade: Low-carbon (0.05%) steel
- Speed: sudden speed drop, speed change size varies
- Mold heat flux: varies with casting speed, based on an empirical correlation for a thin slab caster in [6]

$$\bar{q}_{\mathrm{m}}\left[\mathrm{MW/m^2}\right] = 0.9535\left(v_c\left[\mathrm{m/min}\right]\right)^{0.5}$$

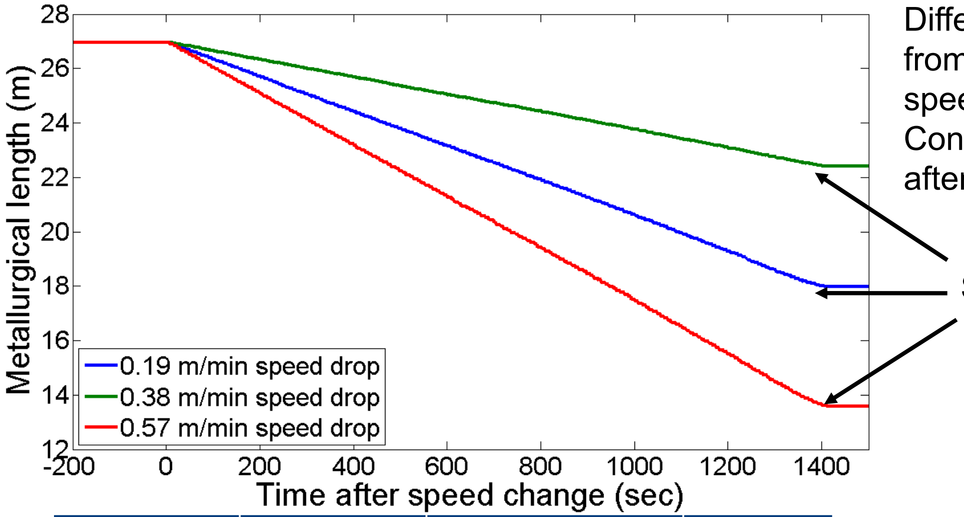
Examine effect of control method

- Both control method lead to similar metallurgical length response during speed change:
- Initial decrease is mostly response to speed, continuous decrease gradualy





Effect of casting speed



Different speed drop from initial casting speed 1.14m/min. Constant water spray after speed drop

Final casting speed (m/min)	Casting speed drop (m/min)	Slope of metallurgical length (m/min)	Settling time (s)
0.95	0.19	-0.193	1400
0.76	0.38	-0.382	1406
0.57	0.57	-0.567	1417

Settling time for the metallurgical length:

– The time after which the metallurgical length is within 25 mm of its final value

K-factor estimate for ML settling time

- The shell thickness can be estimated by equation

$$s(t) = K\sqrt{t}$$

- Then the settling time for ML during speed change can be estimated by:

$$\tau = \frac{L^2}{4K^2}$$

- Where L is slab thickness, τ is settling time.
- For all speed drop simulation the initial casting speed is 1.14m/min, and the spray water rate is constant after speed drop. The steady state K-factor for 1.14 m/min is

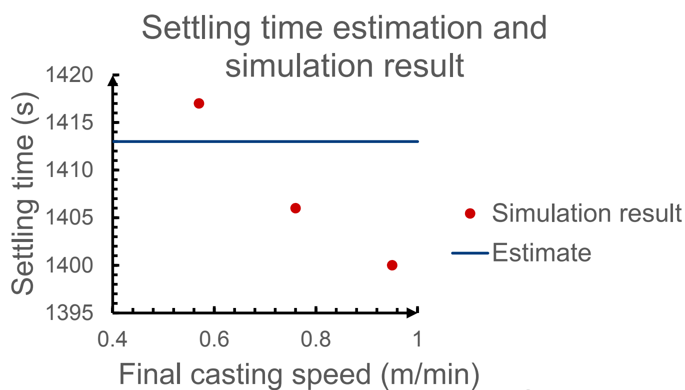
$$K_{BH} = 1.05\, inch / \min^{0.5}$$

K-factor model

$$z_{\mathrm{ML}}(t)=\begin{cases} \dfrac{L^2}{4K^2}v_{c1}, & t<0 \\ \dfrac{L^2}{4K^2}v_{c1}+t\left(v_{c1}-v_{c2}\right), & 0<t<\dfrac{L^2}{4K^2} \\ \dfrac{L^2}{4K^2}v_{c2}, & \dfrac{L^2}{4K^2}<t \end{cases}$$

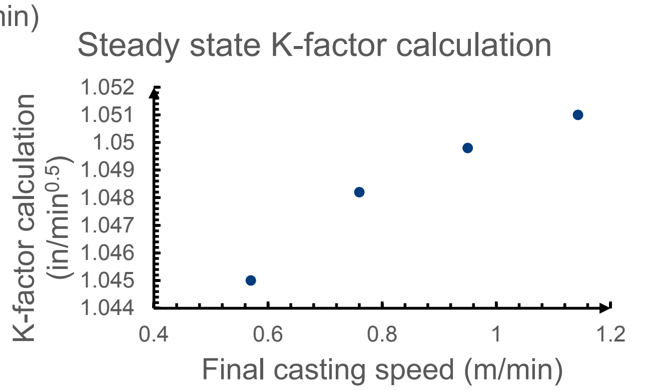
- The k-factor models would predict two things:
  - 1. the metallurgical length moves at exactly the difference between the two casting speeds after a sudden speed change.
  - 2. the transient in metallurgical length always takes exactly the same time

Settling time estimate for metallurgical length during speed drop



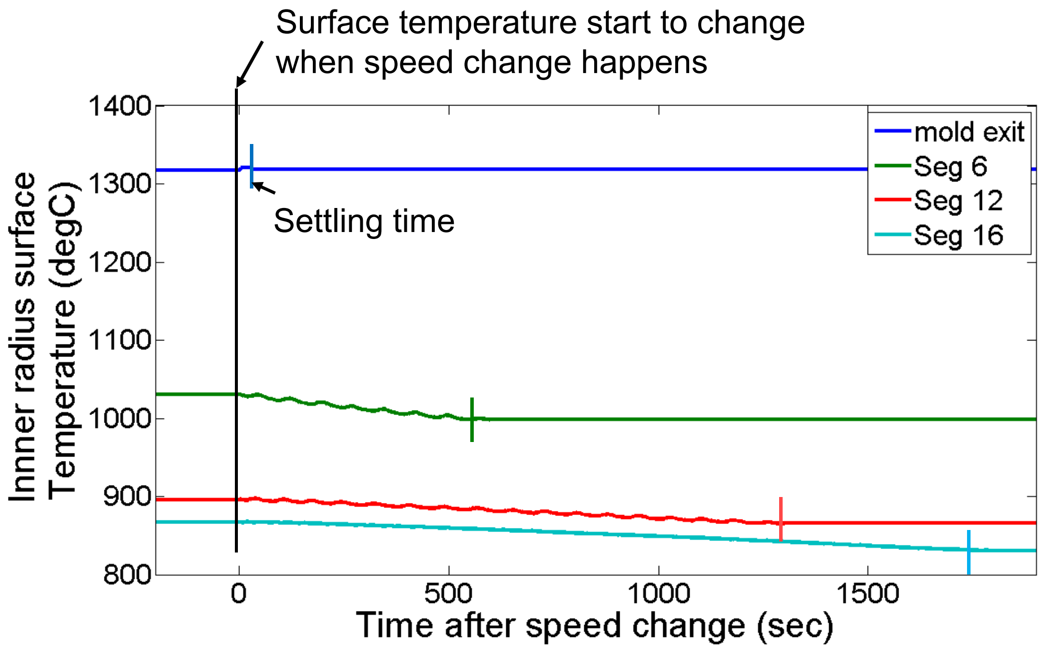
$$\tau=\frac{L^2}{4K^2}=1413\,\mathrm{sec}$$

The k-factor for all speed is very close regardless of final casting speed



Sudden slow down in casting speed with constant spray

Following simulation is run under constant spray rate with speed drop from 1.14 m/min to 0.95 m/min



Estimate for surface temperature settling time

- Settling time for surface temperature: the time after which the temperature stays within 10 ° C of its final value.
- The settling time for surface temperature during speed drop can be estimated by equation:

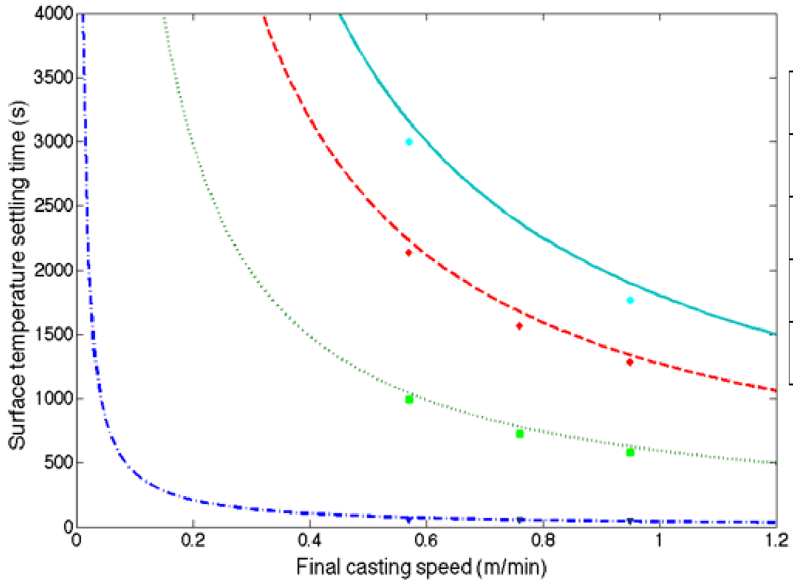
$$\tau(z) = \frac{z}{v_c}$$

$\tau(z)-$ settling time for surface temp at location z

$v_c -$ casting speed after speed change

- When the liquid steel with new casting speed reaches location z, the surface temperature at location z reach steady-state.

Settling time estimate for surface temperature during speed drop



Legend	estimation	simulation
Mold exit		
Seg 6		
Seg 12		
Seg 16		

Dynamic spray control

- 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 Burns Harbor caster, the relation between spray water rate and casting speed is assumed to be:

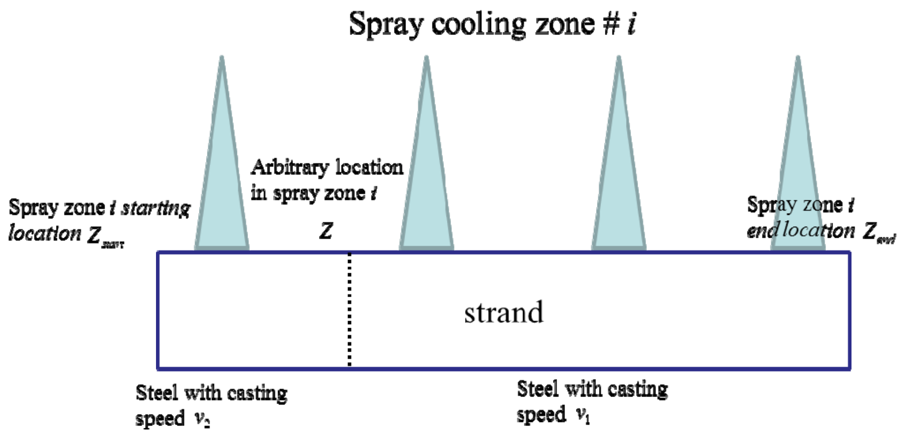
$$SW_{spray}\left[l/m/row\right] = -8 + 30v_c\left[m/\min\right]$$

- Above equation can be transferred to:

$$SW_{spray}\left[l/m/row\right] = -8 + 30\frac{z}{\tau(z)}\left[m/\min\right]$$

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

Dynamic spray control-simple case



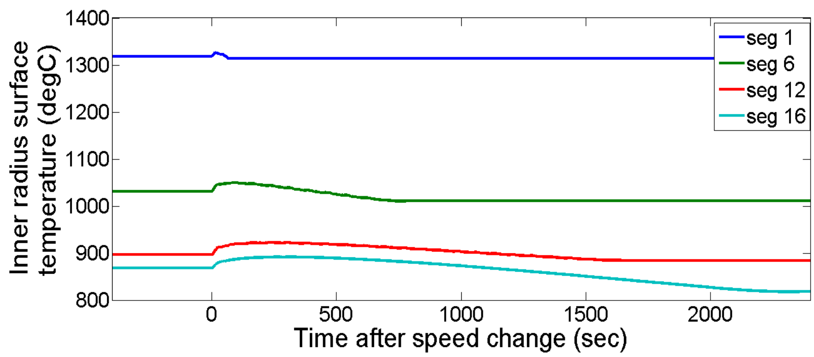
- Dwell time calculation:

$$\tau(Z)=\begin{cases} \dfrac{Z-Z_{start}}{v_1}, t<0 \\ \dfrac{(Z-Z_{start})+(v_1-v_2)t}{v_1}, 0<t<\dfrac{Z-Z_{start}}{v_2} \\ \dfrac{Z-Z_{start}}{v_2}, t>\dfrac{Z-Z_{start}}{v_2} \end{cases}$$

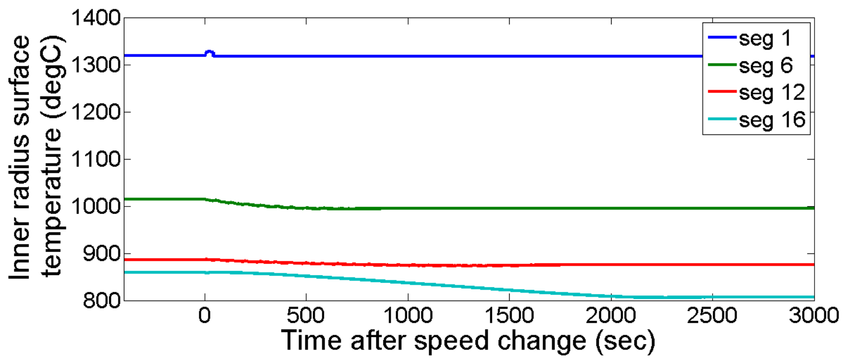
For each spray zone, we can only have one flow rate, therefore, we select endlocation of each zone to calculate dwell time.

Comparison of Dynamic spray control and Spray table control

Spray table control

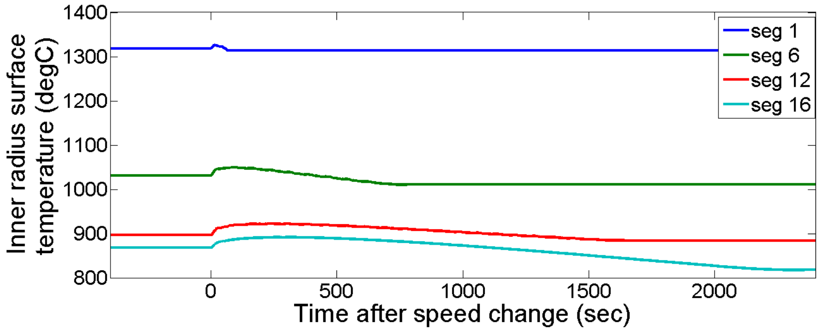


Dynamic spray control

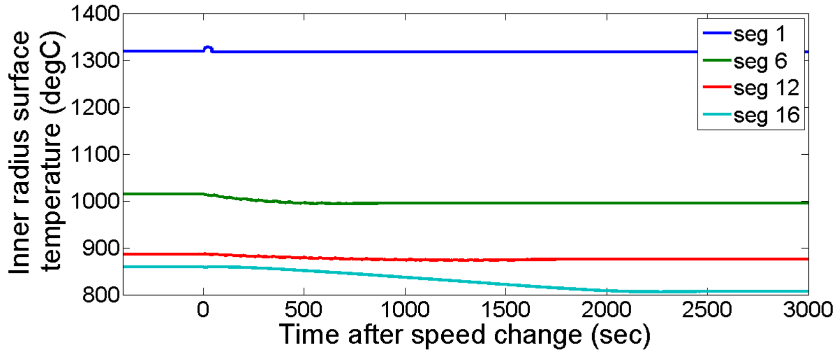


Comparison of spray table control and dynamic spray control

Spray table control



Dynamic spray control



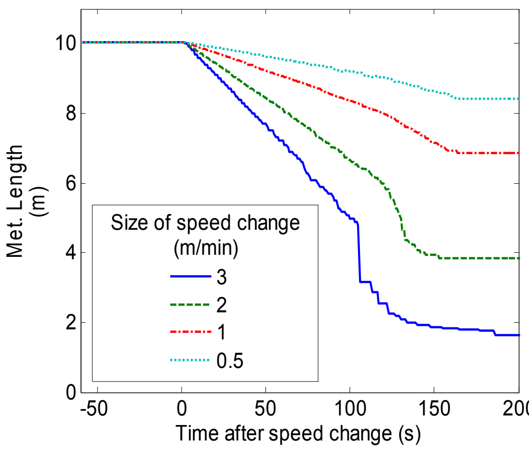
Casting condition for thin slab caster [5]

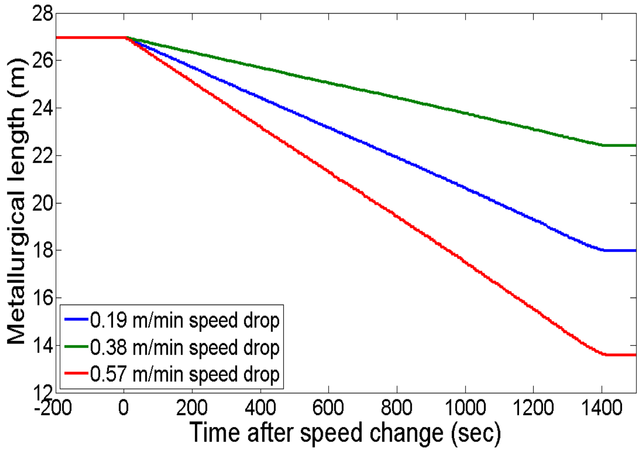
- Simulations are based on Nucor Decatur steel mill.
- Thickness: 90 mm
- Grade: Low-carbon (0.05%) steel
- Speed: sudden speed drop, speed change size varies
- Mold heat flux: varies with casting speed, based on an empirical correlation in [6]

$$\bar{q}_{\mathrm{m}}\left[\mathrm{MW/m^2}\right]=1.197\left(v_{\mathrm{c}}\left[\mathrm{m/min}\right]\right)^{0.544}$$

- Following simulation result is from [5]

Effect of shell thickness

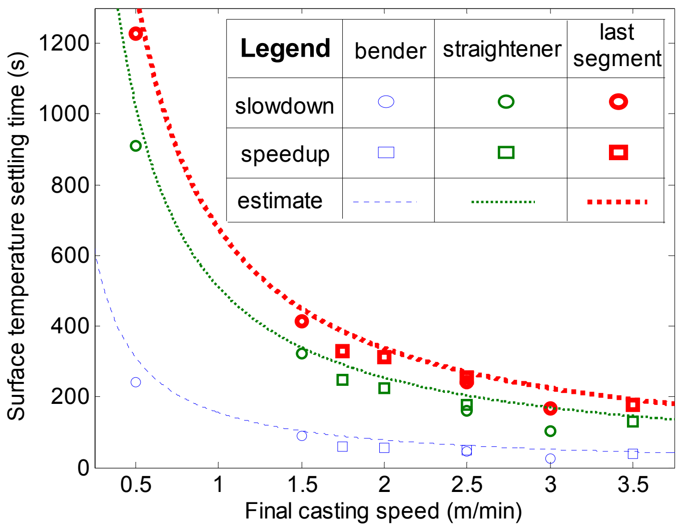




Thin-slab caster

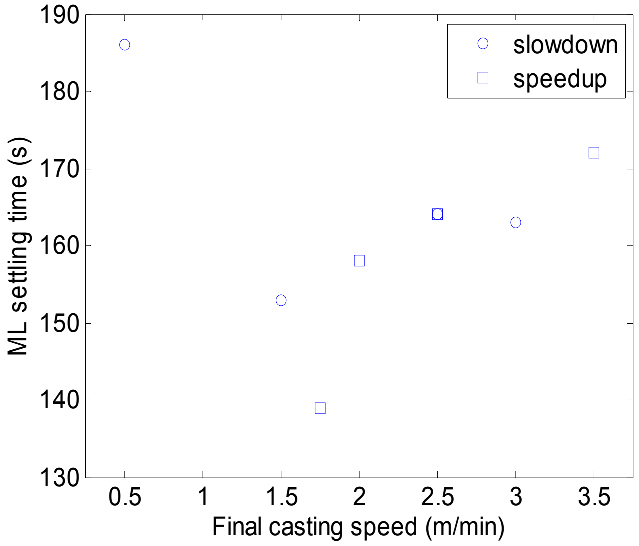
Thick-slab caster

Settling time for surface temperature



- The model for thick-slab caster also suits for thin-slab caster.

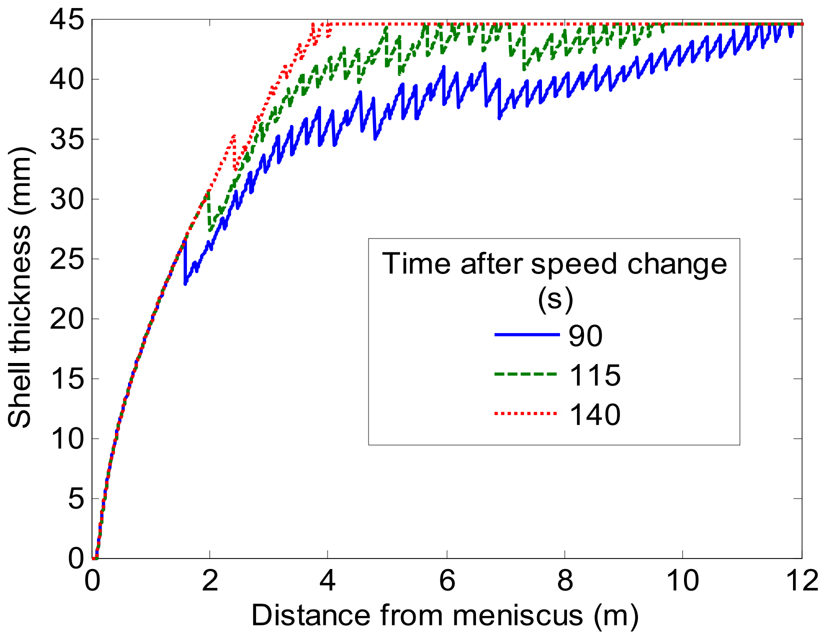
Settling time for Metallurgical length



- Here, settling time is the time after which the metallurgical length is within 25 mm of its final value

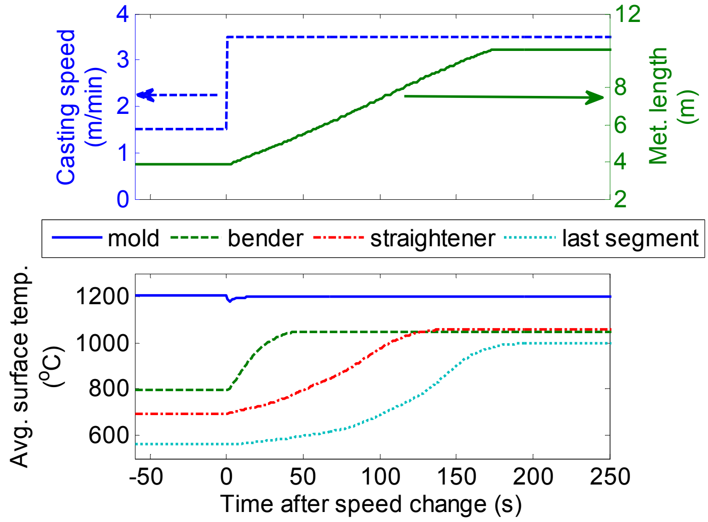
- K-factor models would expect these all to be equal, But there are small difference here

Pinch-off



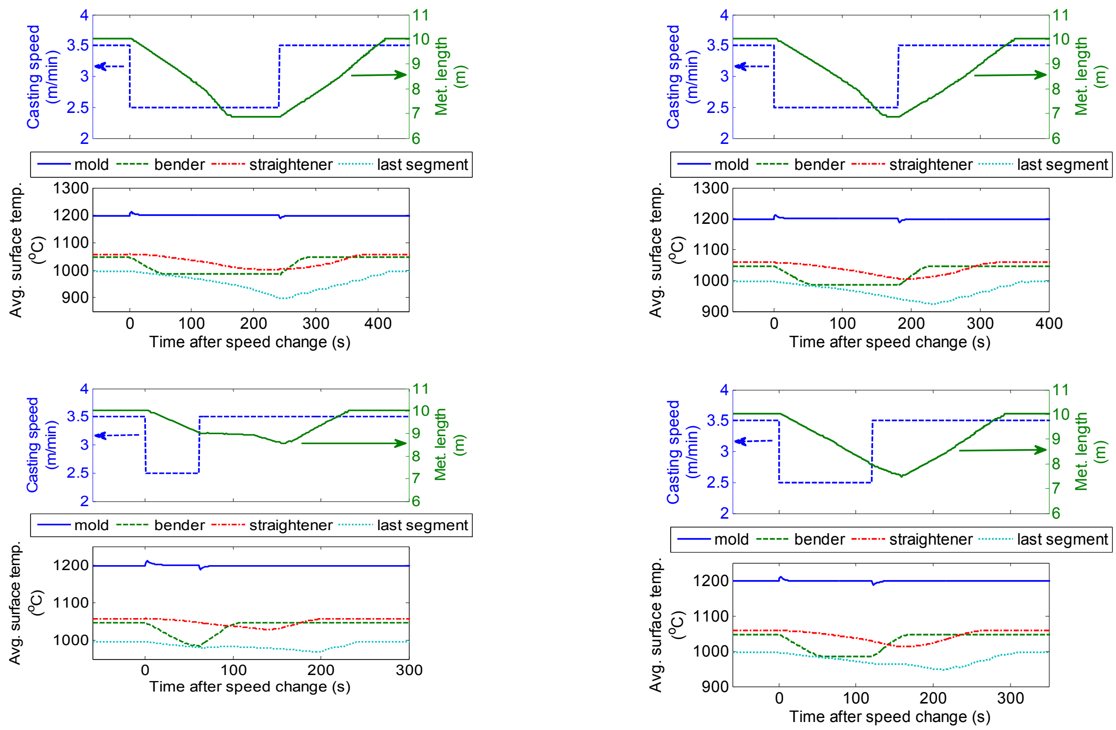
snapshots of the shell thickness

No "Pinch off" effect during speed up

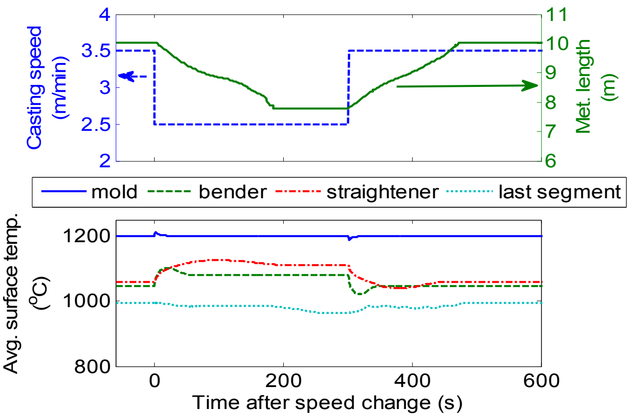


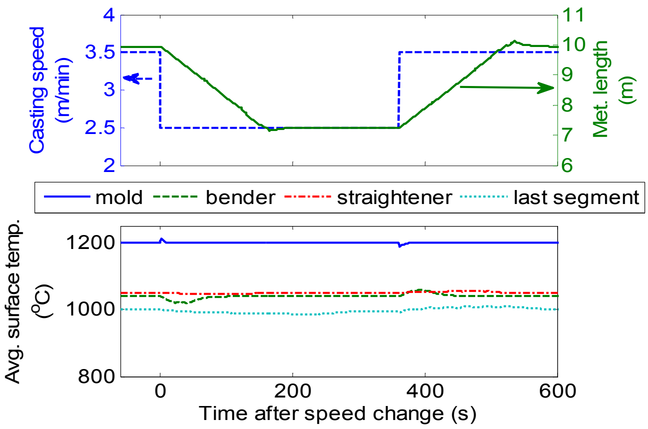
no "pinching off," and the rate of increase of the metallurgical length remains fairly constant

Sequential speed changes



Effect of control method





Spray table control

PI control

Conclusion

- The response time for metallurgical length can be estimated by formula: $\tau = \frac{L^2}{4K^2}$
- The response time for surface temperature at location z can be estimated by formula: $\tau = \frac{z}{v_c}$
- Dynamic spray control have better performance during sudden speed drop than spray table control.
- For thin slab caster during big speed drop there are "pinch-off" phenomenon.
- During sequence speed change, PI control have better performance

Future work

- Extend the parametric study for different thickness slab and different steel grade.
- Continue study pinch off problem
- Any other suggestions?
- Does anyone want us to include their caster in the study?

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
- Bryan Petrus, Prathiba Duvvuri and other students from Metals Processing Simulation Lab

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