MechSE

CCC Annual Report

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Investigating Dynamic Thermal Behavior with Conoffline

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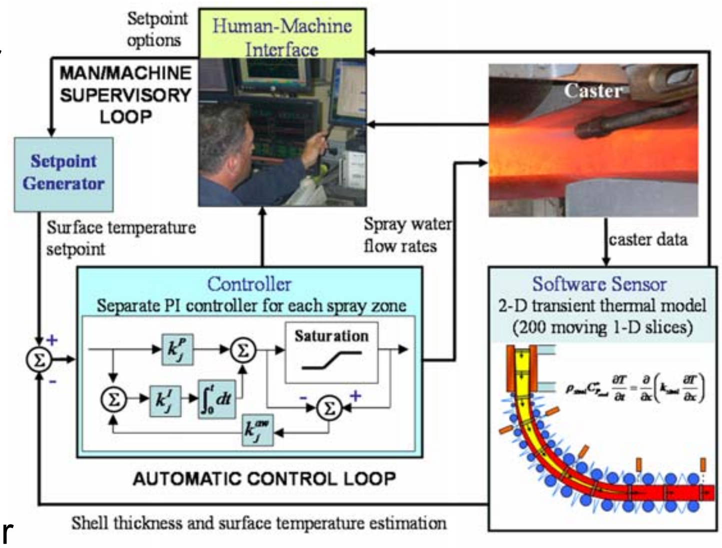
Outline

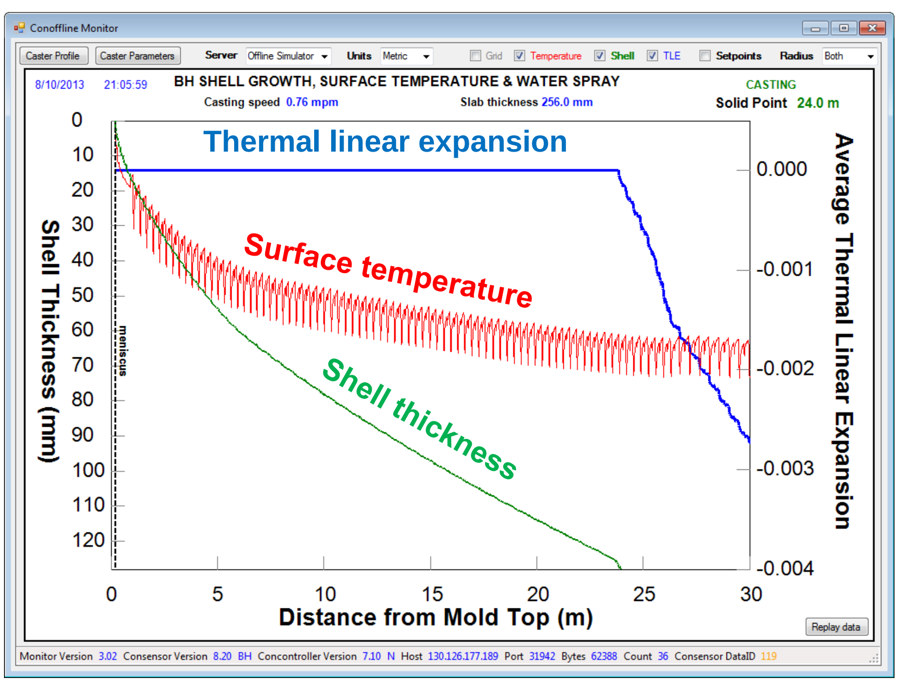
- Brief introduction to Cononline and Conoffline
- Validating transient behavior of model
  - Advection versus conduction in the casting direction (inherent in slice model assumption)
  - Compare Conoffline with published strain gauge measurements
- Conoffline parametric study: effect of casting speed changes on metallurgical length

Cononline [1]

- 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") tries to keep the Consensor prediction constant



CON1D: heat transfer and solidification model

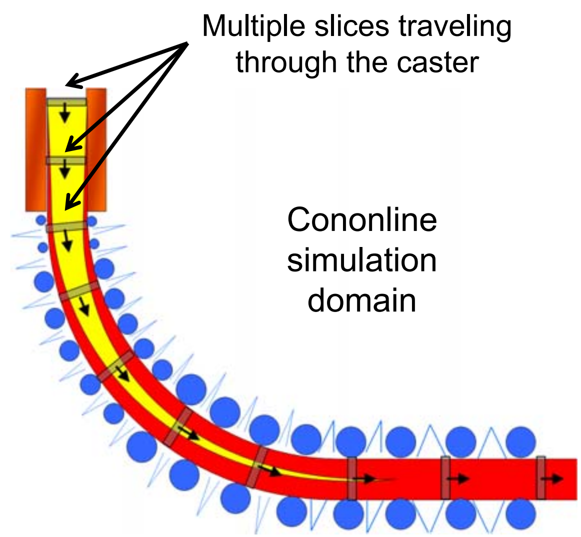


CON1D model [2]

- In the axial (casting) direction, heat is transferred by:
  - Conduction
  - Material moving through the caster at the casting speed (advection)
- The ratio of these two effects is described by the Peclet number:

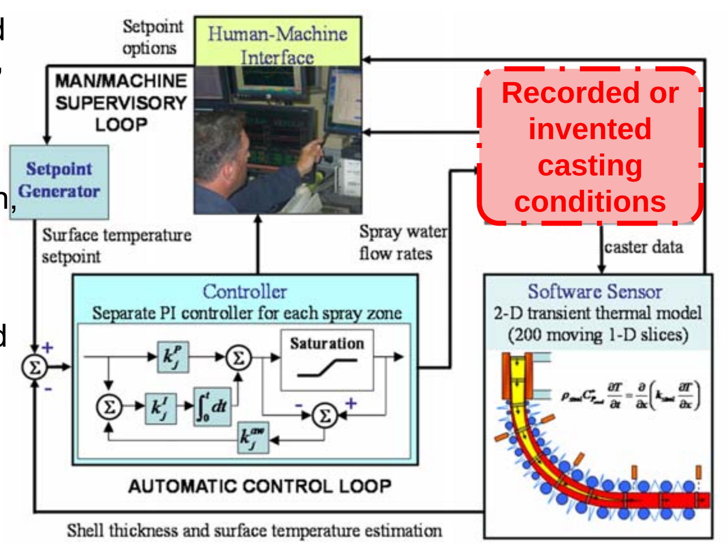
$$\mathrm{Pe} = \frac{L v_c}{\alpha} = \frac{\text{advection rate}}{\text{conduction rate}}$$

  - L = characteristic length
  - v_c = casting speed
  - α = thermal diffusivity
- For a typical continuous caster, this is on the order of 10^3, which suggests advection dominates
- Neglecting axial conduction allows CON1D to run significantly faster



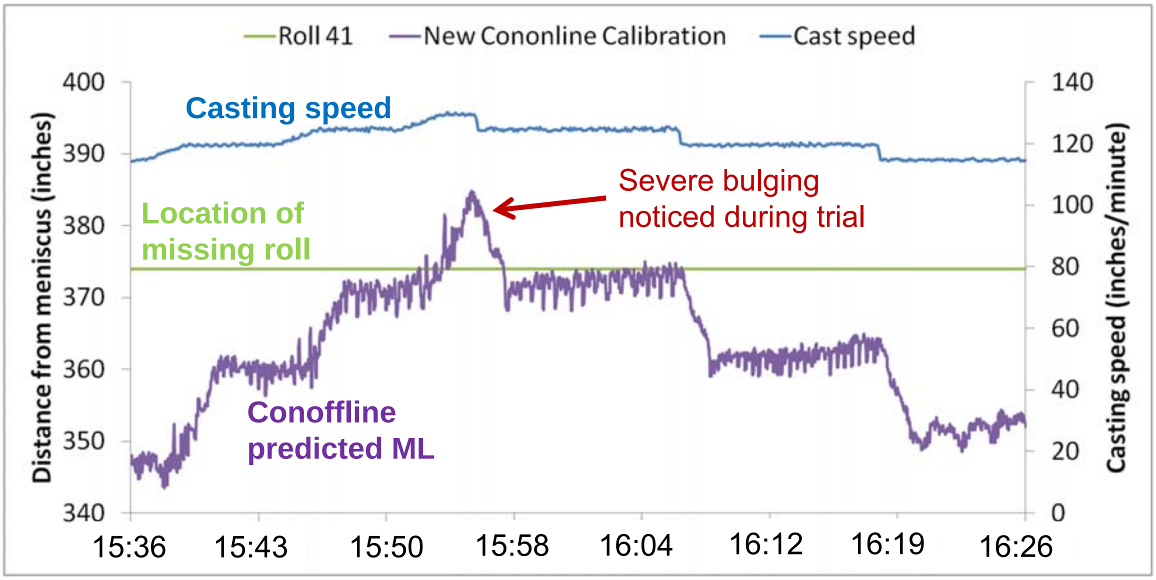
Conoffline

- However, we can also run Consensor offline, using casting conditions recorded from actual measurements, or fully made up
- For now, this still requires the two Linux servers to run, but we are working on a single-PC version
- This version has been used to:
  - Calibrate the model
  - Tune the controllers
- We would also like to use this to investigate the behavior of casters, particularly things like shell growth that cannot be easily measured

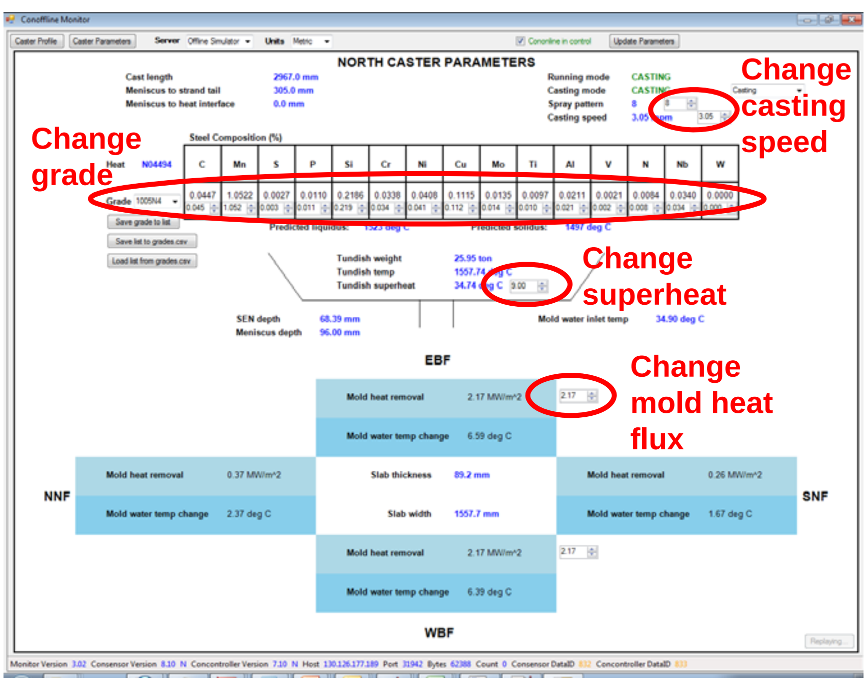


Example application of Conoffline [3]

Offline “replay” capability was used to compare re-calibrated Cononline model predictions to a previously performed trial. See 2012 CCC presentation for more details.



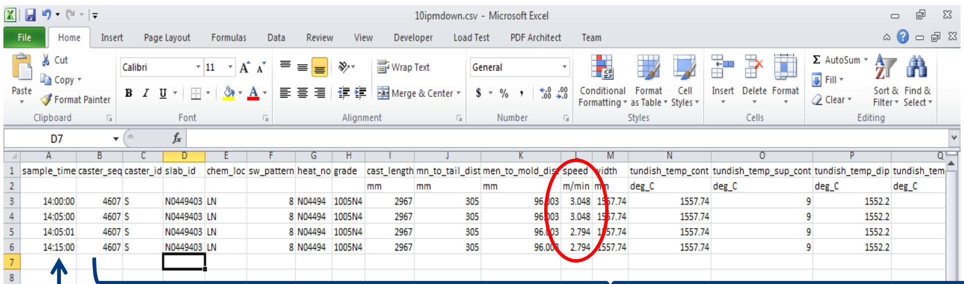
Conoffline Monitor



- Some options are available in a special version of the monitor program for changing simulated casting conditions on the fly
- More complicated scenarios with time-varying conditions require pre-written files

Example of Conoffline “replay” file

- The current way to generate scenarios for Conoffline replays is by editing a comma-separated value (CSV) file in Excel where each row contains all (83) CON1D casting conditions at that time
- This particular file is for a sudden drop in casting speed



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	sample_time	caster_seq	caster_id	slab_id	chem_loc	sw_pattern	heat_no	grade	cast_length	mn_to_tail_dist	men_to_mold_dist	speed	width	tundish_temp_cont	tundish_temp_sup_cont	tundish_temp_dip	tundish_tem
2									mm	mm	mm	m/min	mm	deg_C	deg_C	deg_C	deg_C
3	14:00:00	4607	S	N0449403	LN	8	N04494	1005N4	2967	305	96.003	3.048	1557.74	1557.74	9	1552.2	
4	14:05:00	4607	S	N0449403	LN	8	N04494	1005N4	2967	305	96.003	3.048	1557.74	1557.74	9	1552.2	
5	14:05:01	4607	S	N0449403	LN	8	N04494	1005N4	2967	305	96.003	2.794	1557.74	1557.74	9	1552.2	
6	14:15:00	4607	S	N0449403	LN	8	N04494	1005N4	2967	305	96.003	2.794	1557.74	1557.74	9	1552.2	

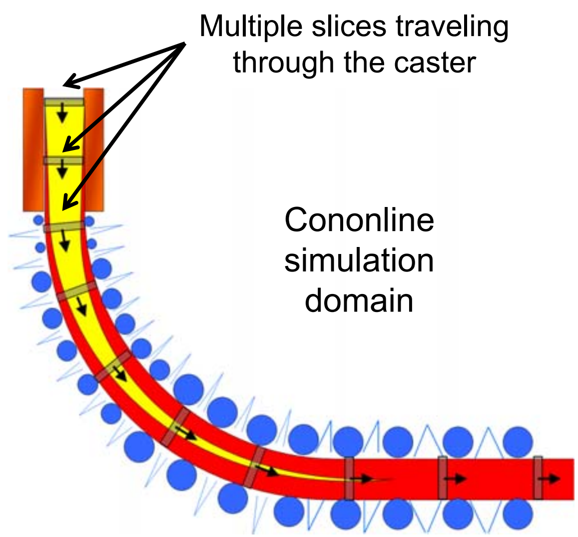
• • •

Time **Casting conditions**

Transient model [1]

- Cononline works by tracking multiple CON1D runs, and interpolating between them to get full transient behavior of the caster
- An implicit assumption in this is that each slice is independent of the other slices

- Questions:
  - Is this assumption valid for transient case? (CON1D is steady)
  - If so, does the assumption hold for conventional casters? (Cononline has so far been used for thin slabs)



Strain gauge measurements from Gregurich et al [4]

- Plant measurements were taken at Burns Harbor Caster #1 using strain gauges attached to support rolls
- Roll loads were recorded during changes in casting speed
- Change in speed leads to change in liquid core position, which causes change in measured roll loads

- This is a quick step change in speed, on a conventional caster (thick slab, low speed). These are the conditions where conduction should matter the most. This makes it a good test case for Cononline

High strain – liquid core
- Ferrostatic pressure pushes shell into roll

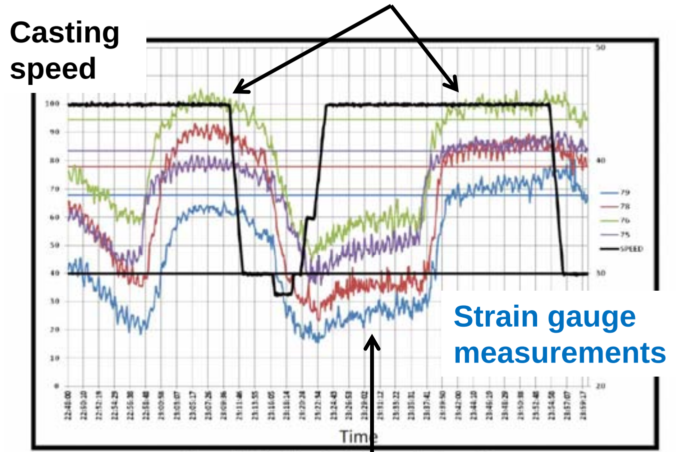


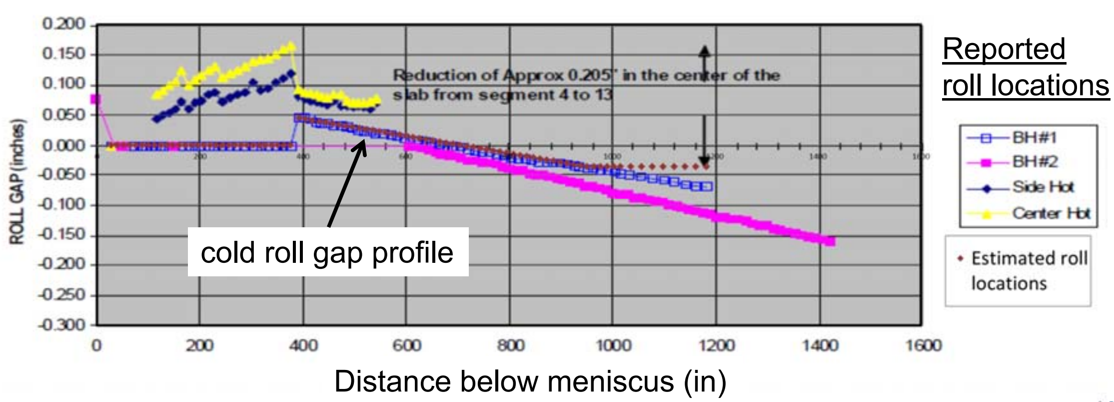
Figure 18. Roll loads during unsteady casting

Low strain – solid core
- No ferrostatic pressure
- Thermal shrinkage pulls away from roll

CON1D model calibration: caster dimensions

- The goal is to
  1. Calibrate CON1D using steady state measurements in the paper
  2. Re-create the speed change in Conoffline
  3. Compare the results

- Roll locations and roll gaps: Figure 3 in [4], shown below
  (BH1 line with adjusted roll gaps beyond 1000 in)



CON1D model calibration with steady-state measurements

- A plain low-carbon (0.05%) steel was assumed
- CON1D was calibrated to match two steady state metallurgical lengths (ML) reported in the paper
  - Secondary cooling sprays were assumed to be proportional to casting speed, v_c
  - Mold heat flux was assumed to be proportional to $v_c^{0.7}$ (see Prathiba's work [5])
  - The constants of proportionality for both were chosen to match reported MLs under steady conditions in the paper

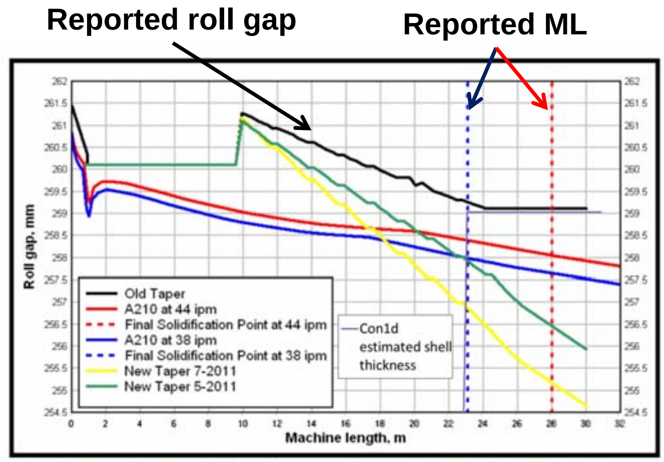


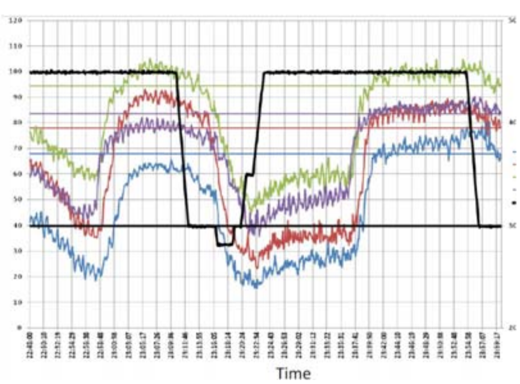
Figure 3. Calculated shrinkage for two casting speeds plotted with machine taper

Speed	0.9 m/min	1.1 m/min
Reported ML	23 m	28 m
CON1D predicted ML	23.2	28.1 m

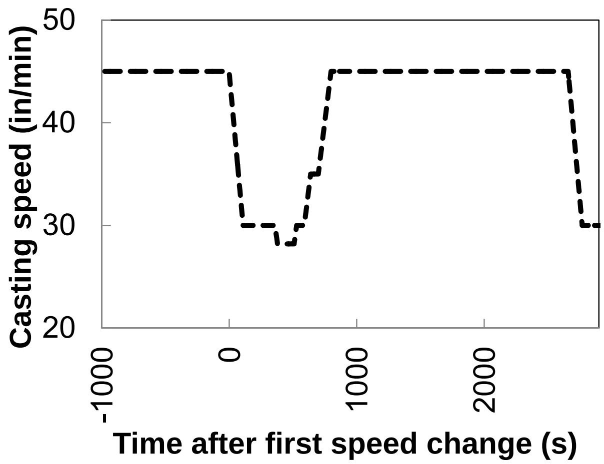
Recreating trial conditions

Casting speed history during the trial was re-created from Fig 18 in [4]

Figure 18 from [4]

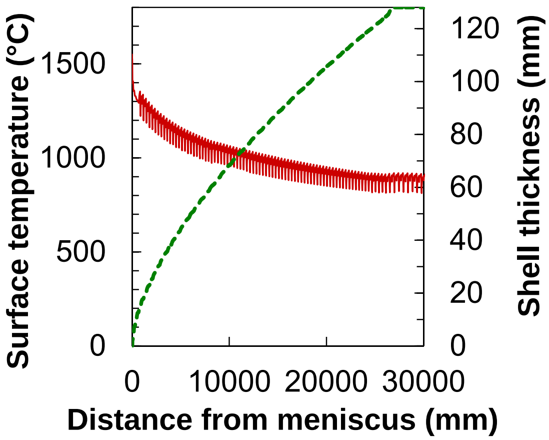


Recreated casting speed history

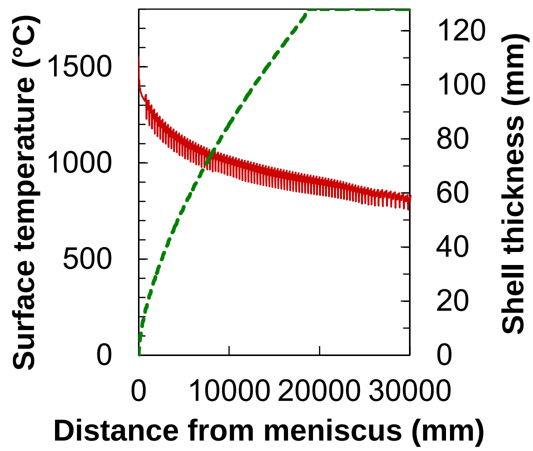


Steady-state results

Fast speed
45 ipm (1.14 m/min)
ML = 26.6 m



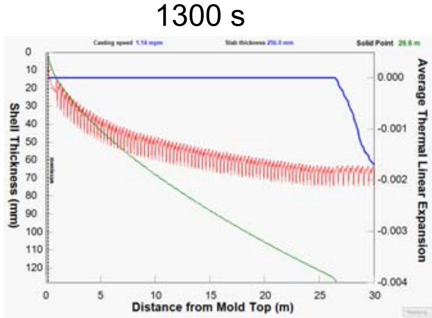
Slow speed
30 ipm (0.762 m/min)
ML = 18.6 m



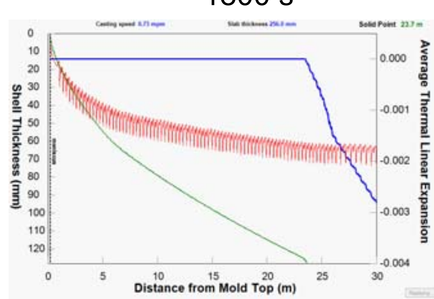
Legend	Surface temperature	Shell thickness

Conoffline replay of trial

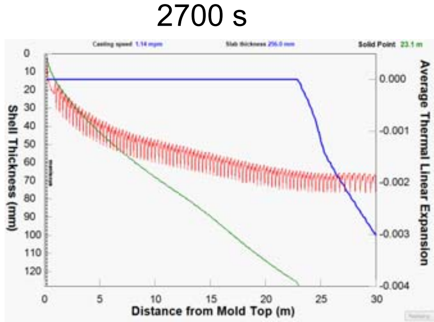
1300 s



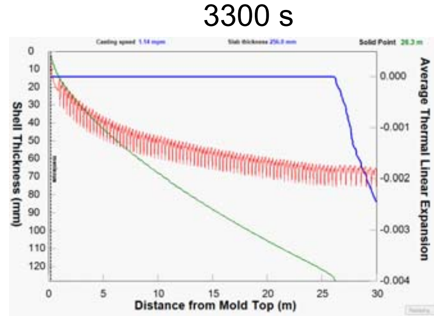
1800 s



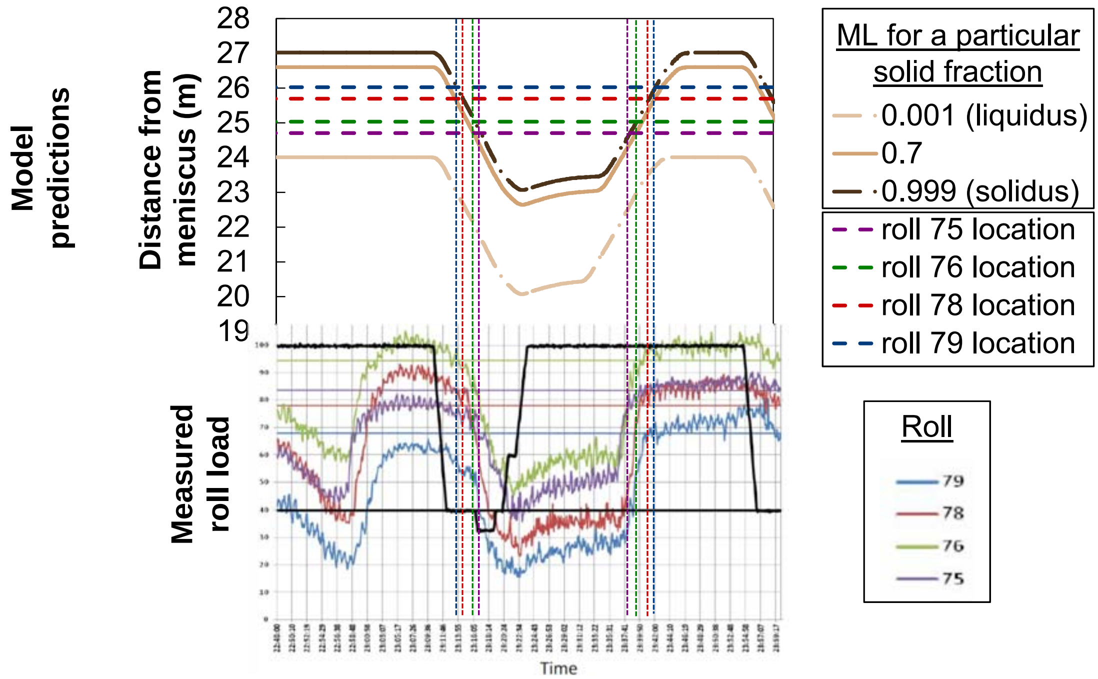
2700 s



3300 s

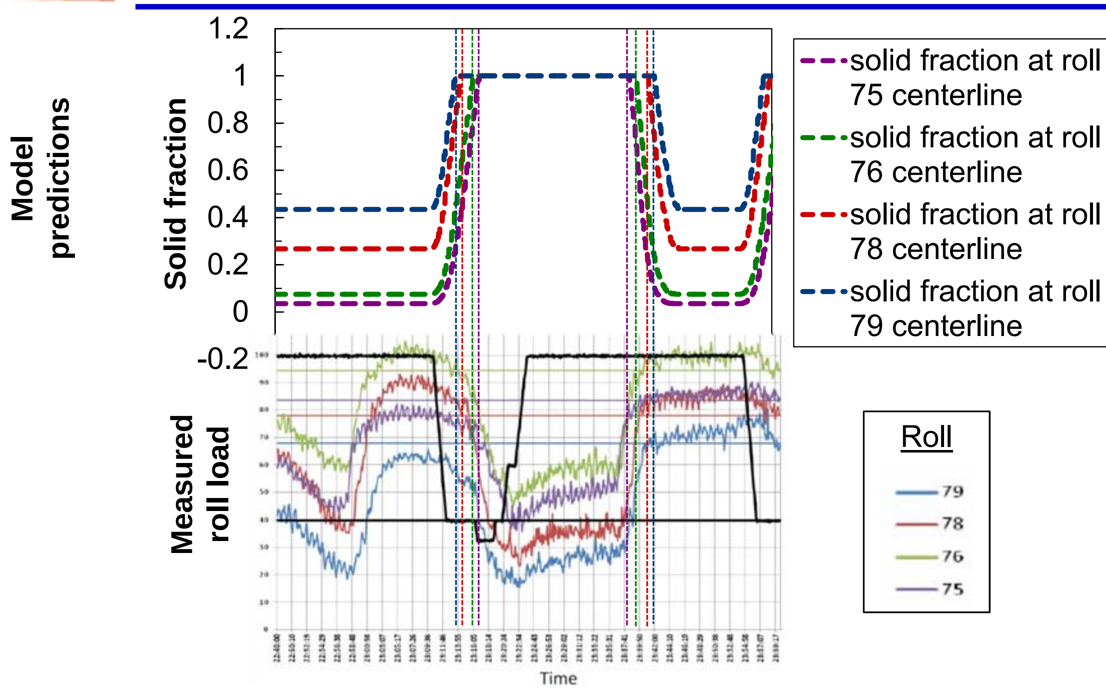


Comparison of Conoffline with measurements: ML



Changes in roll loads match best with Cononline predicted *solidus location*

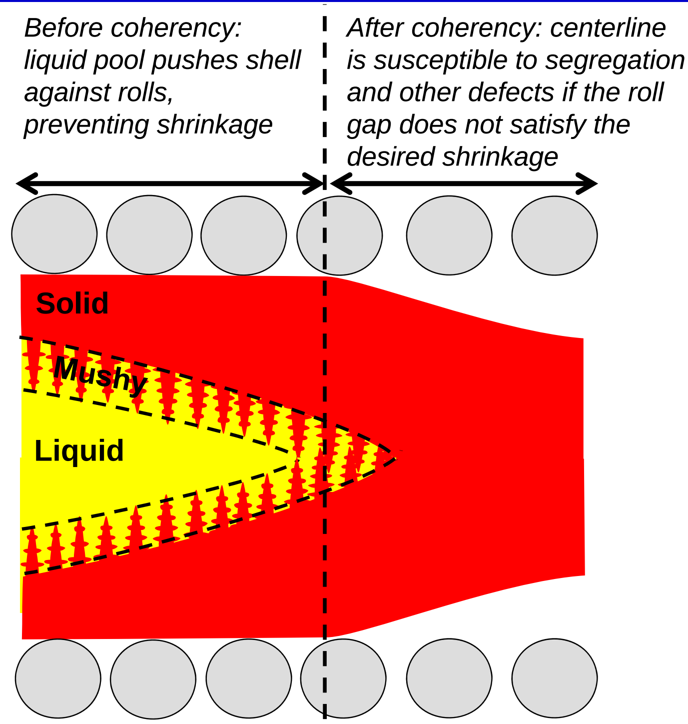
Comparison of Conoffline with measurements: solid fraction



Changes in roll loads match best with Cononline predicted *solidus location*

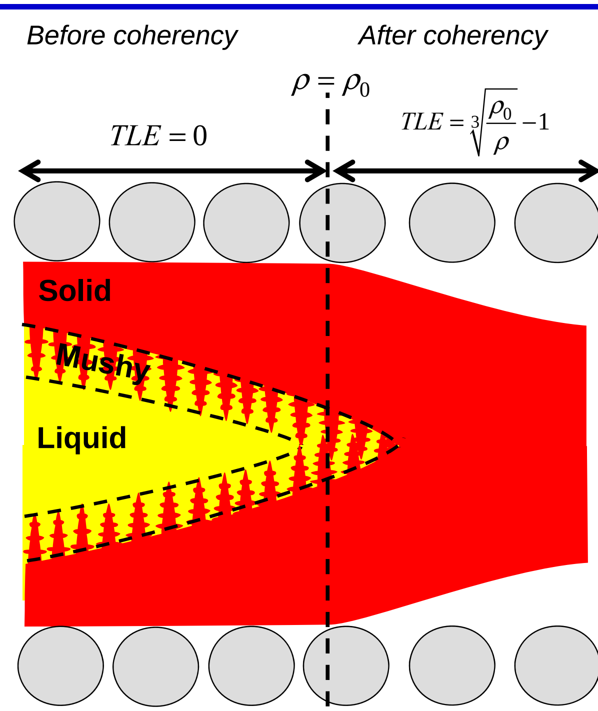
Cononline thermal shrinkage calculation

- Phase fraction at centerline only predicts the
- For further investigation, we modified Cononline to estimate the thermal linear expansion (TLE) of the material
- Intuitive idea: shrinkage occurs after solid fraction in the entire strand is below a value chosen to represent coherency

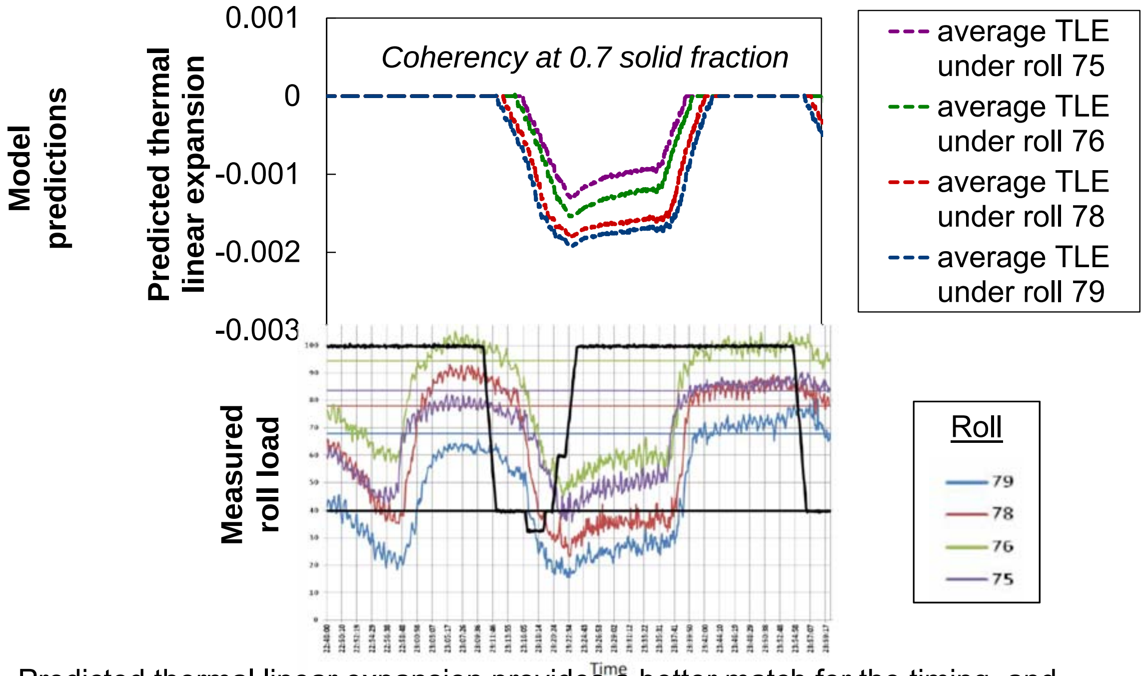


Cononline thermal shrinkage calculation

- Detailed method for Conline shrinkage estimation
  1. At every location, calculate density of present phases according to relationships from Harste, Jablonka, and Jimbo [7]
  2. Before coherency, total TLE is set to 0
  3. After coherency total TLE is based on the change in density (ρ) from the point of coherency (ρ_0)
- Open question: what solid fraction represents coherency?



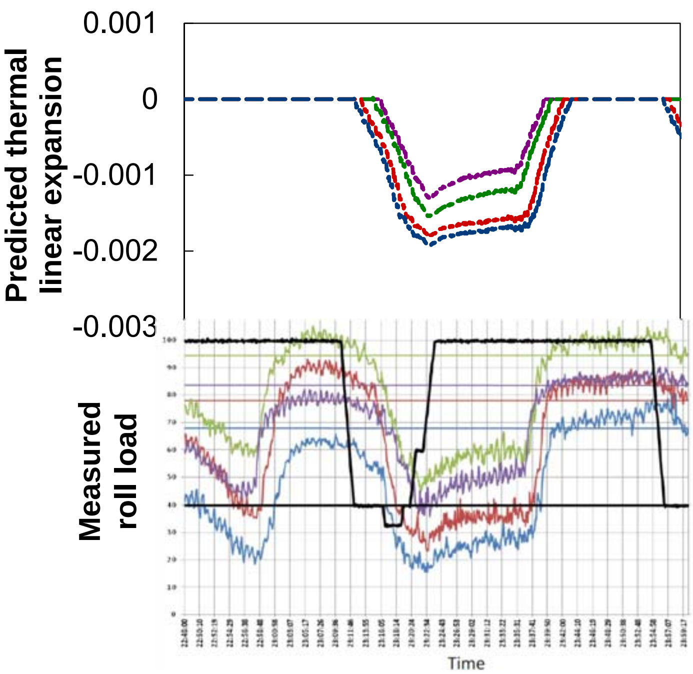
Comparison of Cononline with strain gauges: thermal shrinking



Predicted thermal linear expansion provides a better match for the timing, and qualitatively predicts the undershoot and rebound in strain after the slowdown

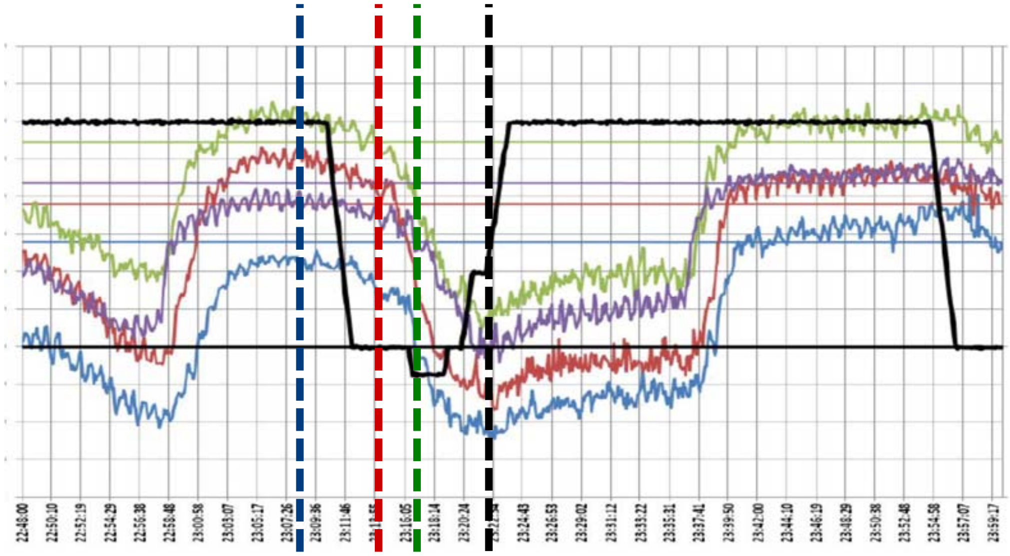
Model is verified

- If inter-slice effects were important, the time to reach steady state after the slowdown would be significantly longer, according to [6]
- This assumption about transient behavior is therefore valid for this caster



Evolution of strain during slow down

The next slide shows snapshots of the strand while the caster was slowing down

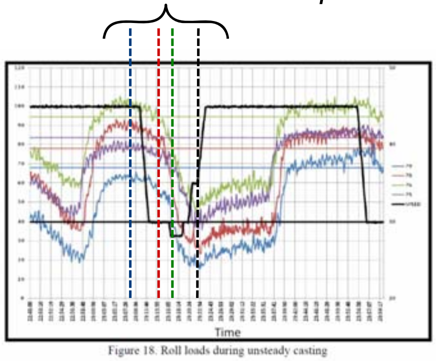


Time after start of slow down: -140 220 400 730 (s)

Snapshots of TLE and phase fraction profiles during slow down

Legend

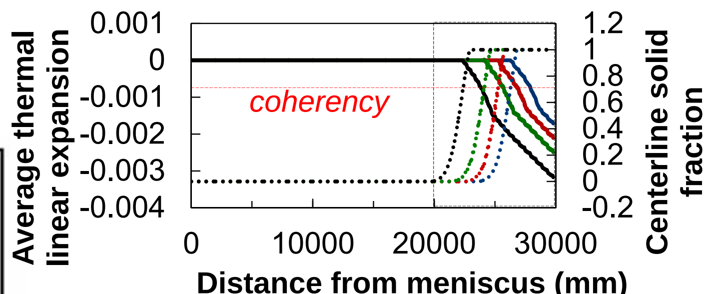
Colors indicate time of profile

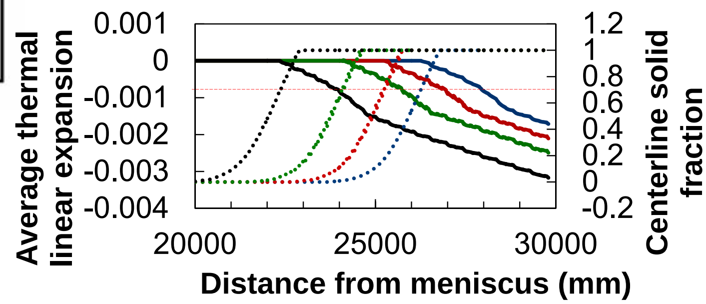


Time related to start of slowdown

TLE

Solid fraction



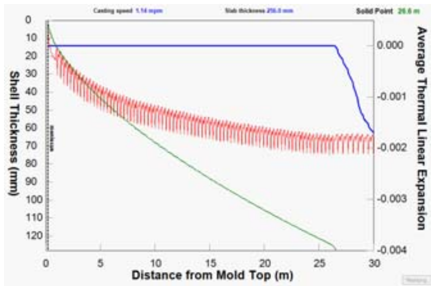


Note that TLE profile has same slope throughout speed-up.

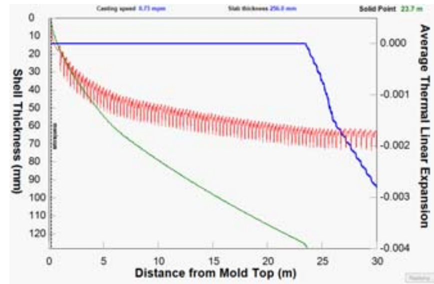
Continuous Casting Consortium

Conoffline replay of trial

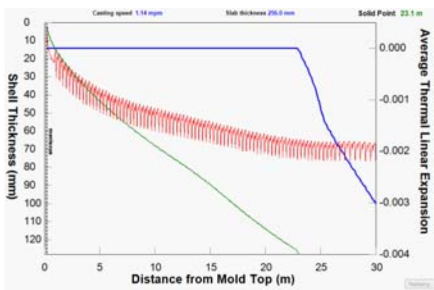
1300 s



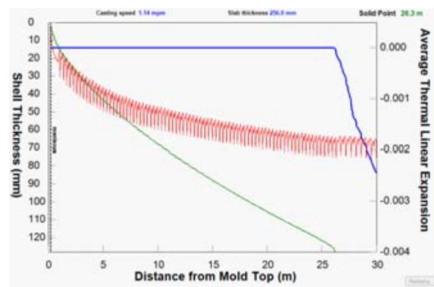
1800 s



2700 s



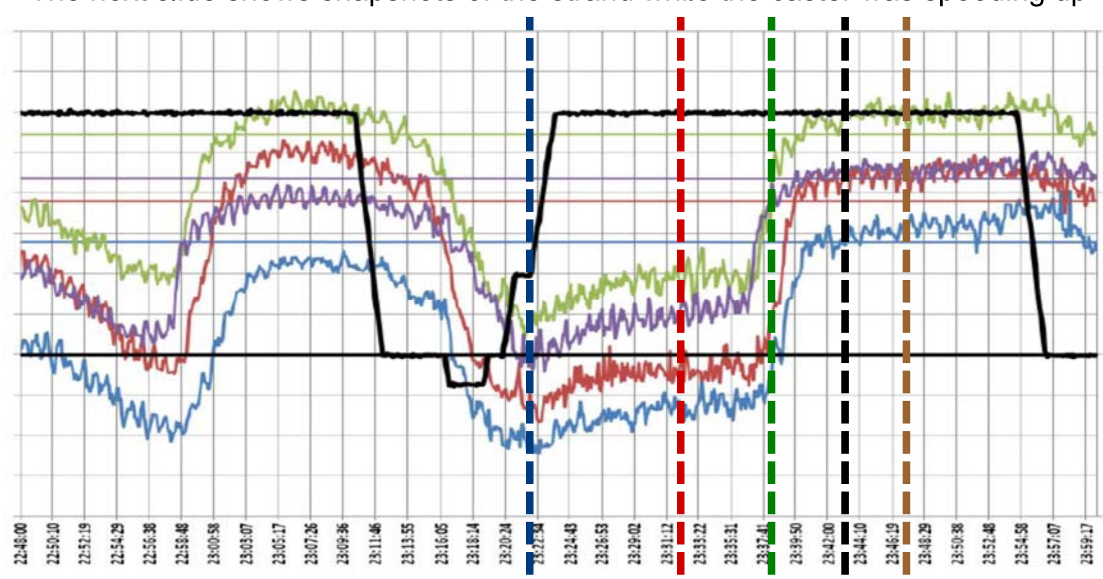
3300 s



Continuous Casting Consortium

Evolution of strain during speed up

The next slide shows snapshots of the strand while the caster was speeding up



Time after start of speed up: 220 790 1150 1450 1690 (s)

Snapshots of TLE and phase fraction profiles during speed up

Legend

Colors indicate time of profile

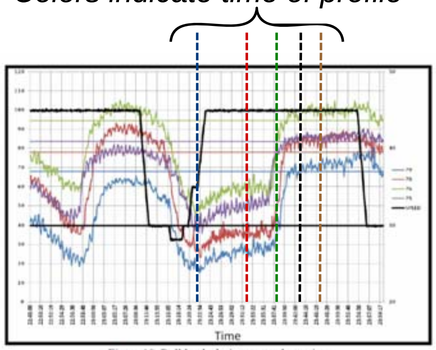
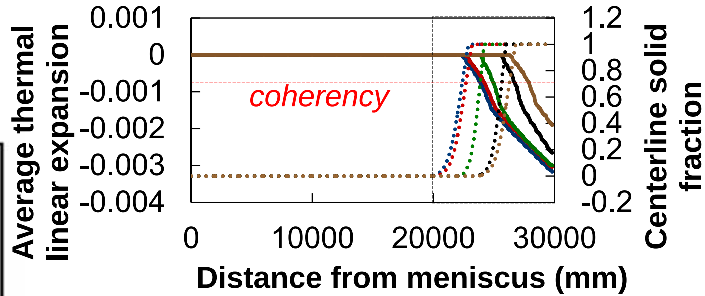
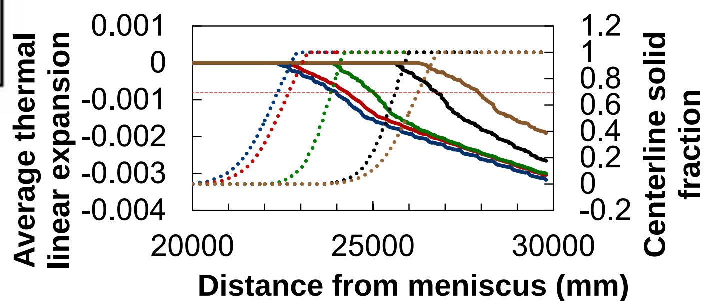


Figure 18. Roll loads during unsteady casting



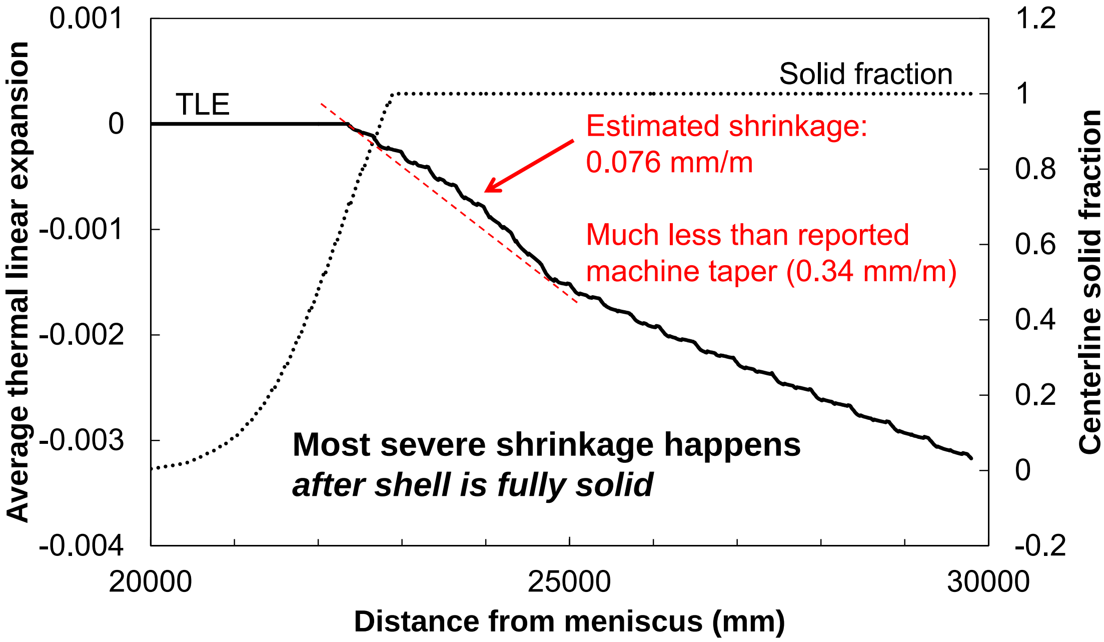


TLE

Solid fraction

Note that TLE profile is steeper during slow-down than the speed-up. This is because the transient from the speed-up did not complete.

Snapshot: 2070 seconds after start of speed change

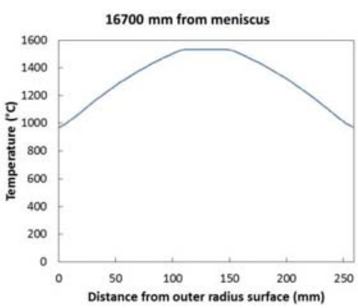


Thermal shrinkage

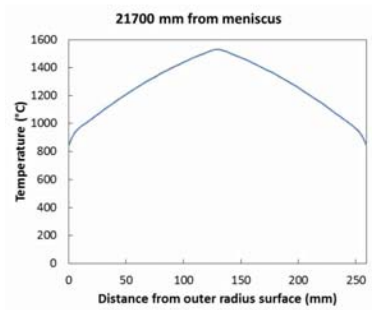
Conoffline predicts highest rate of shrinkage occurs *after* final solidification, because there is a sudden drop in temperature at that time.

- Before final solidification: latent heat is being removed, creating large temperature gradients in the material
- After final solidification: temperature quickly drops towards the average

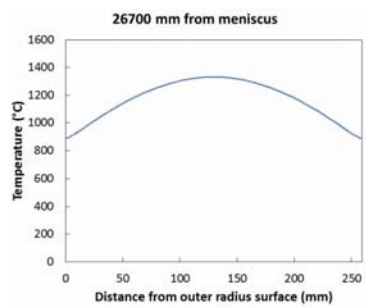
5 m before final solidification



Final solidification

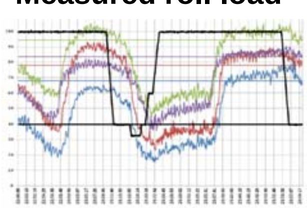


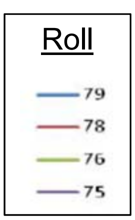
5 m after final solidification

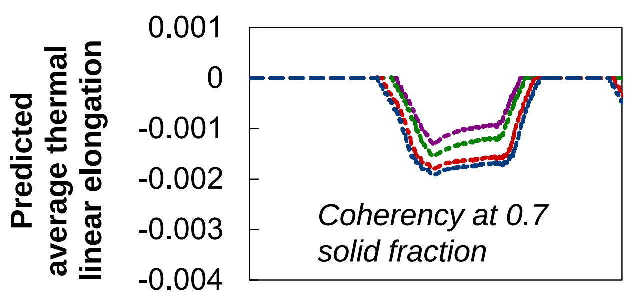


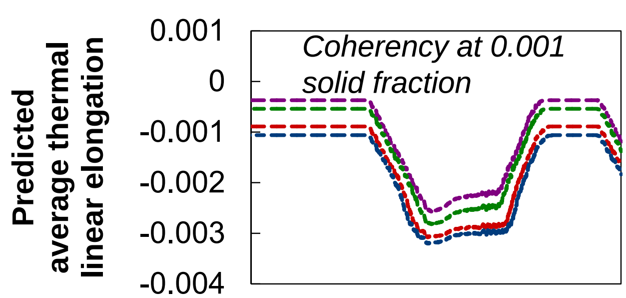
Effect of coherency choice: comparison with measurements

Measured roll load



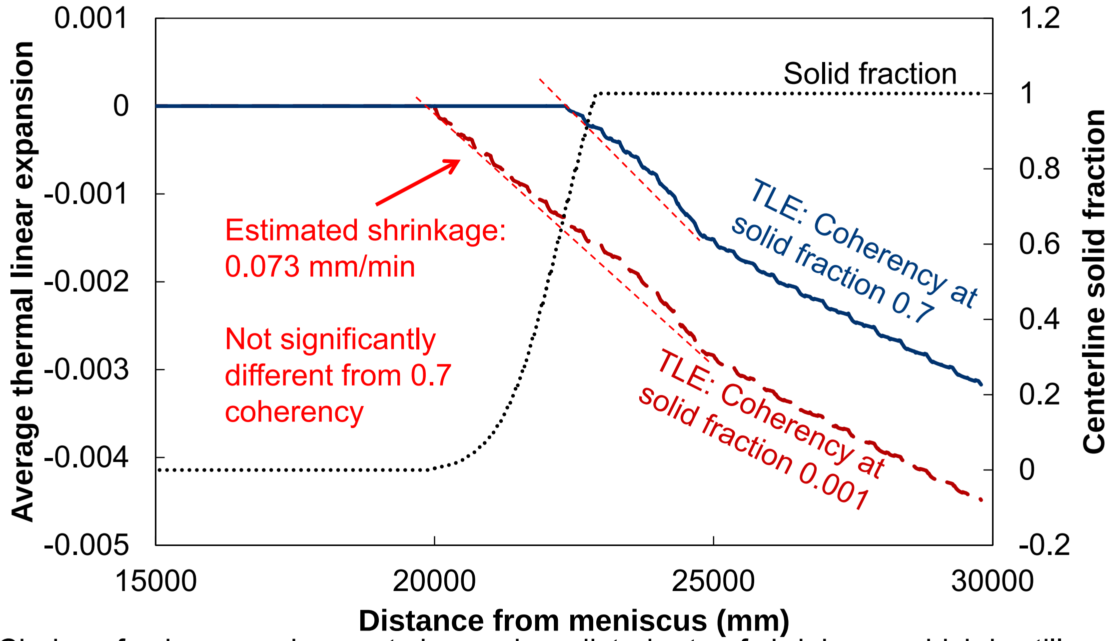






Coherency choice changes where Conoffline predicts thermal shrinkage to start

Effect of coherency choice: snapshot of strand profile



Choice of coherency does not changed predicted rate of shrinkage, which is still smaller than reported machine taper (0.34 mm/m)

Parametric Simulation Study

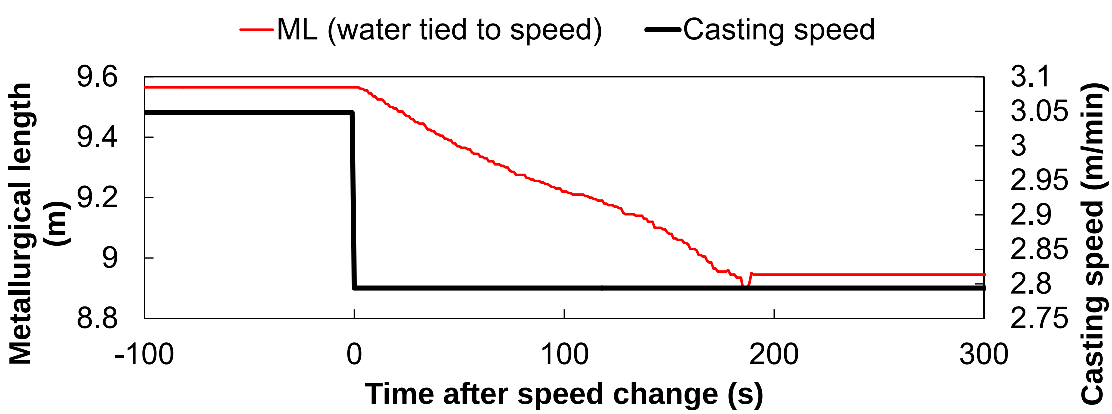
- We would like to use Conoffline to investigate the transient behavior of continuous casters
- In this presentation, we focus on the effect of casting speed changes on metallurgical length, on a thin-slab caster
- Based on standard conditions at Nucor Decatur: 90 mm thickness slab, low-carbon steel
- Future work will investigate additional conditions

Casting conditions

- Simulations are based on Nucor Decatur steel mill

- Thickness: 90 mm
- Grade: Low-carbon (0.045%) steel
- Speed: varies, depending on simulation
  - 3.05 → 2.92 → 2.79 → 2.54 m/min
- Mold heat flux: varies with casting speed, based on average measured values
  - 2.17 → 2.09 → 2.00 → 1.82 MW/m^2

Sudden slowdown in casting speed

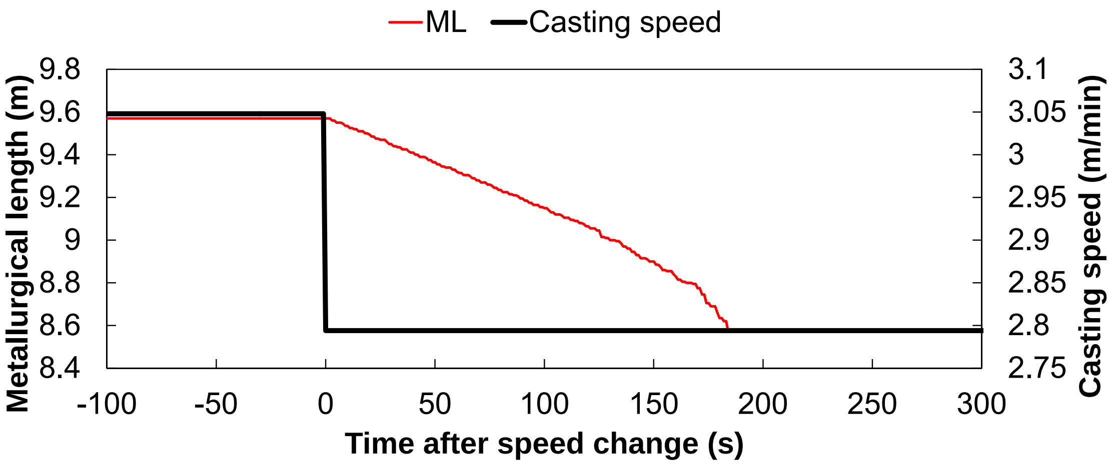


A problem with these simulations is that other conditions are strongly related to casting speed. In this simulation, when the casting speed dropped, two other conditions changed:

- Secondary cooling spray rates: changed according to current Nucor Decatur practice
- Mold heat removal rate: changed according to average of measured values at each speed at Nucor Decatur

Effect of change in casting speed only

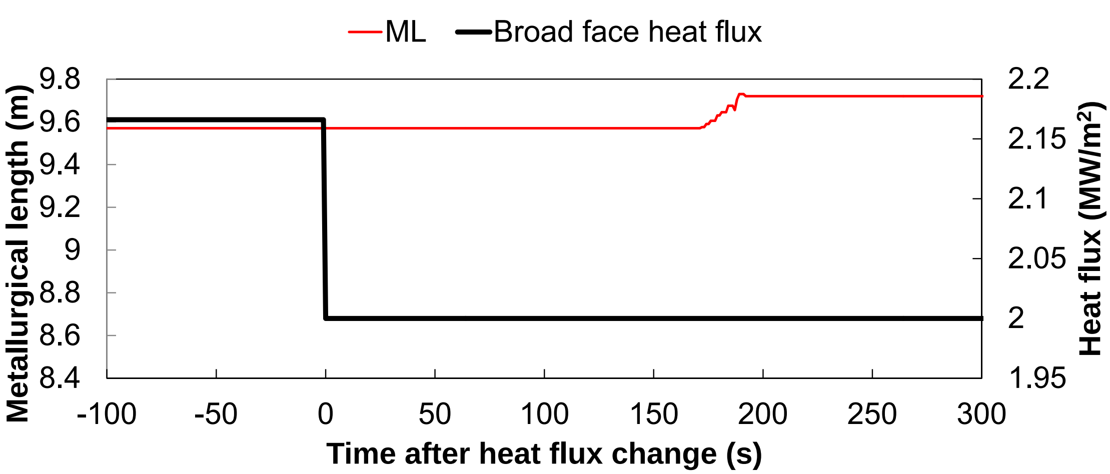
In this simulation, the casting speed is changed the same as during the slowdown, but heat flux and secondary cooling are constant.



The change in metallurgical length is gradual, begins roughly linear, and speeds up at the end.

Effect of change in heat flux only

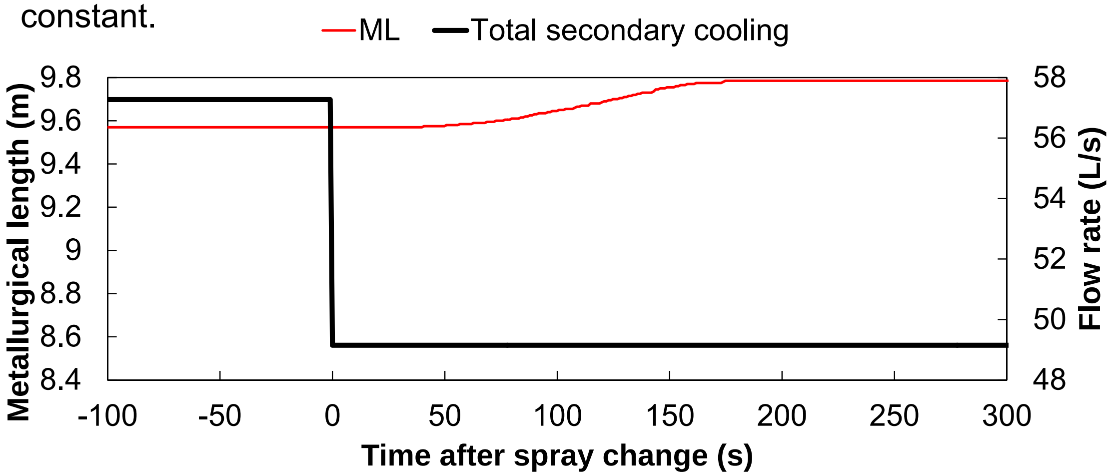
In this simulation, the heat flux is changed the same as during the slowdown, but casting speed and secondary cooling are constant.



The change in metallurgical length is small, sudden, and happens after the speed change according to the dwell time of the material.

Effect of change in secondary cooling

In this simulation, the secondary cooling water is changed the same as during the slowdown, but casting speed and mold heat flux are constant.



The change in metallurgical length is gradual, and relatively small compared to the other effects.

Comparison of the three cases: steady state effects

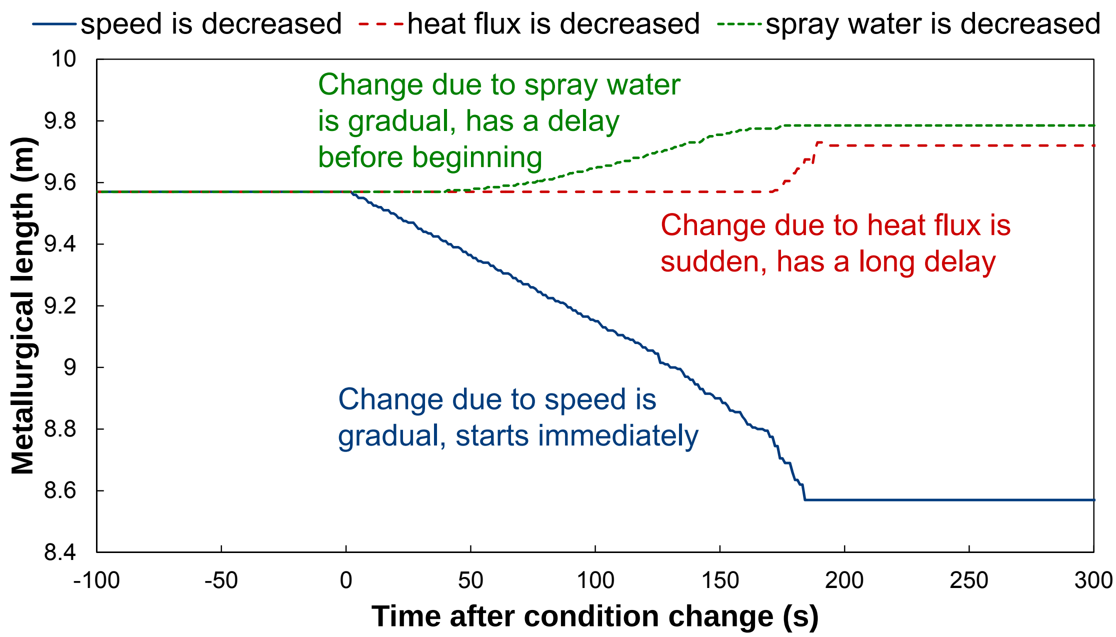
	Casting speed		**Metallurgical length**	
	(m)	**(%)**	**(m)**	**(%)**
Before change	3.05		9.57	
After change	2.79	91.7	8.57	89.6
Difference	0.25	**8.3**	1.00	**10.4**
	Mold heat flux		**Metallurgical length**	
	(MW/m²)	**(%)**	**(m)**	**(%)**
Before change	2.17		9.57	
After change	2.00	92.4	8.72	101.6
Difference	0.17	**7.6**	0.15	**1.6**
	Secondary cooling		**Metallurgical length**	
	(L/s)	**(%)**	**(m)**	**(%)**
Before change	57.3		9.57	
After change	49.2	85.8	9.79	102.2
Difference	8.1	**14.1**	0.21	**2.2**

In terms of proportional effect on steady-state metallurgical length …

… casting speed has more effect than mold heat flux …

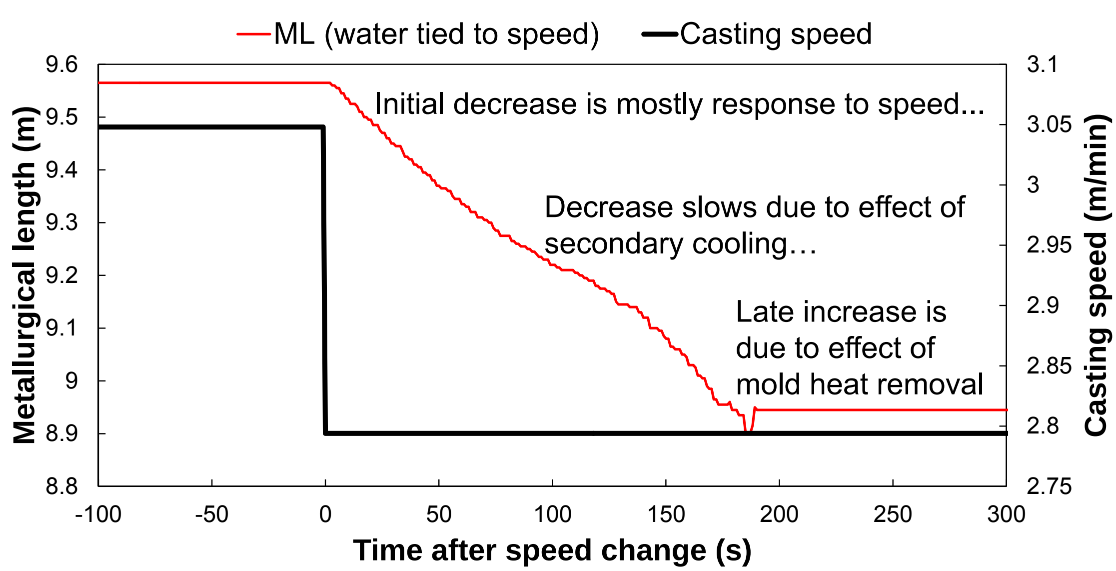
… and mold heat flux has more effect than secondary cooling.

Comparison of the three cases: transient effects

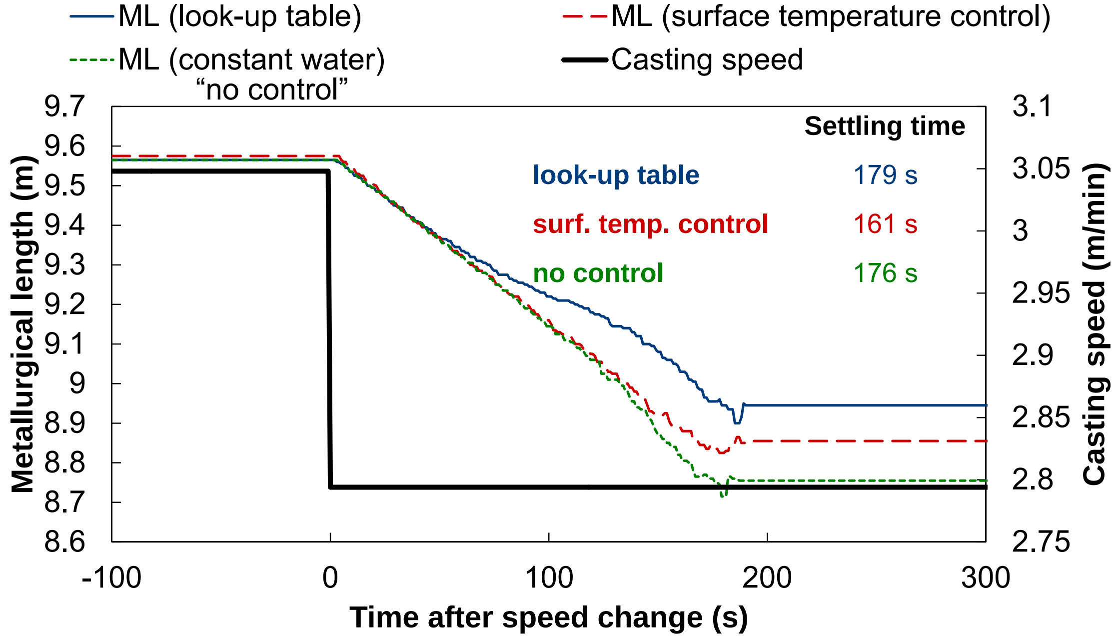


Sudden slowdown in casting speed

Returning to the first (realistic) simulation, with all three effects (decrease speed, spray water, and mold heat flux) happening at once:

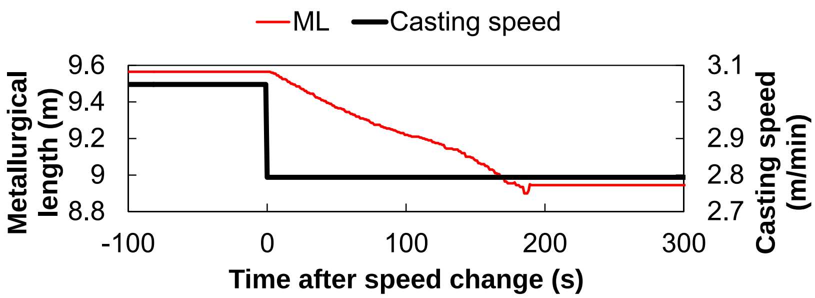


Different spray water control systems

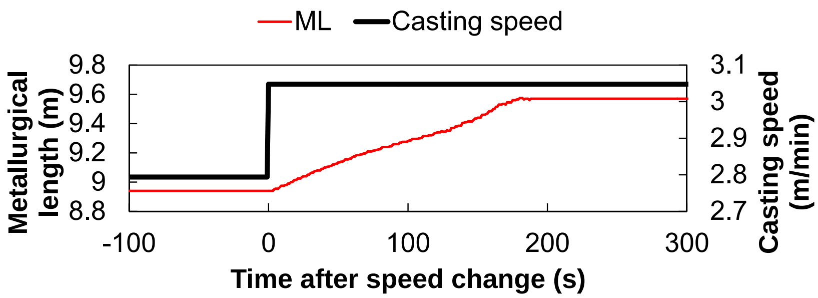


- In all following simulations, the look-up table (speed-tied) method is used to set water sprays

Comparison of slowdown and speed up



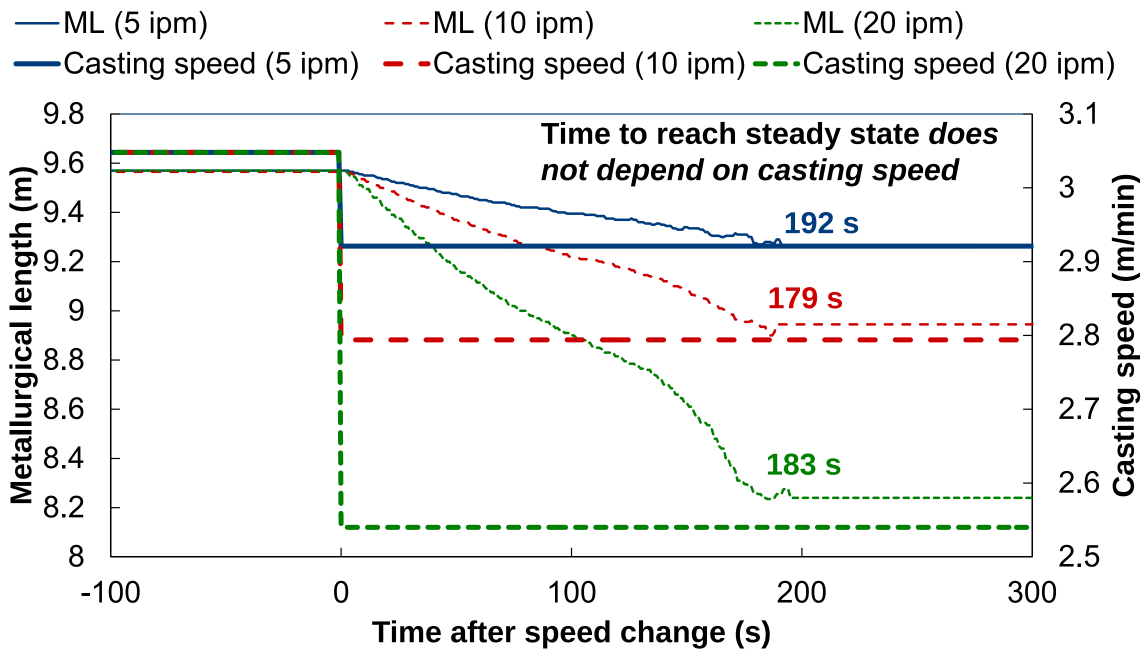
- Final speed: 2.79 m/min
- Final ML: 8.95 m
- Time to reach steady state: 179 s



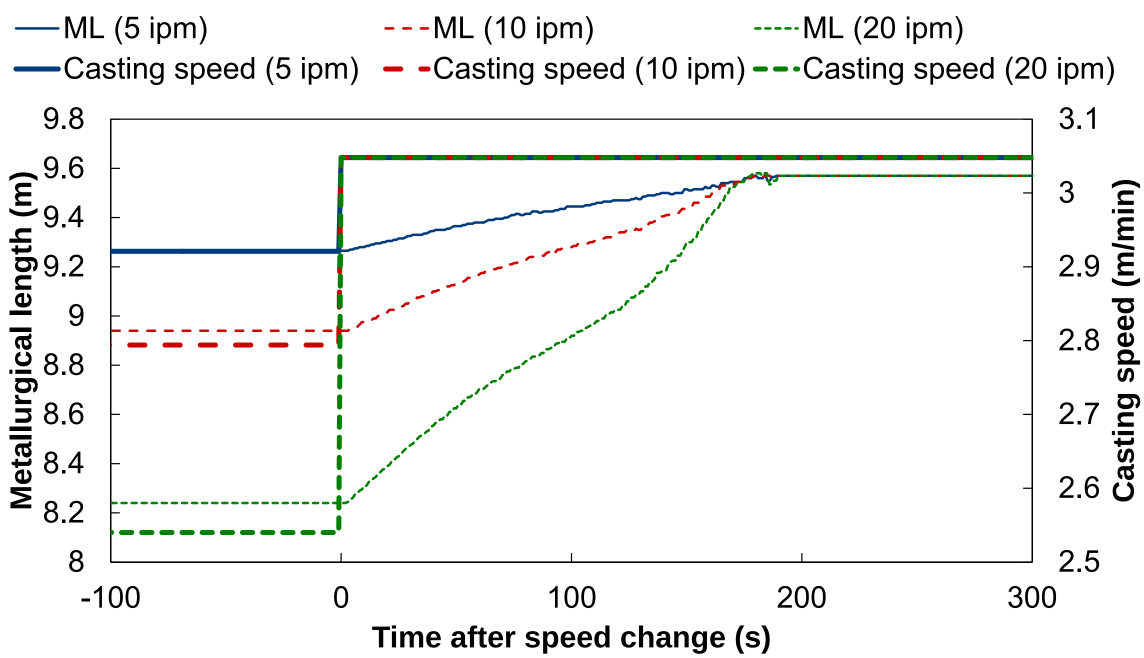
- Final speed: 3.05 m/min
- Final ML: 9.57 m
- Time to reach steady state: 180 s

Time to reach steady state *does not depend on casting speed*

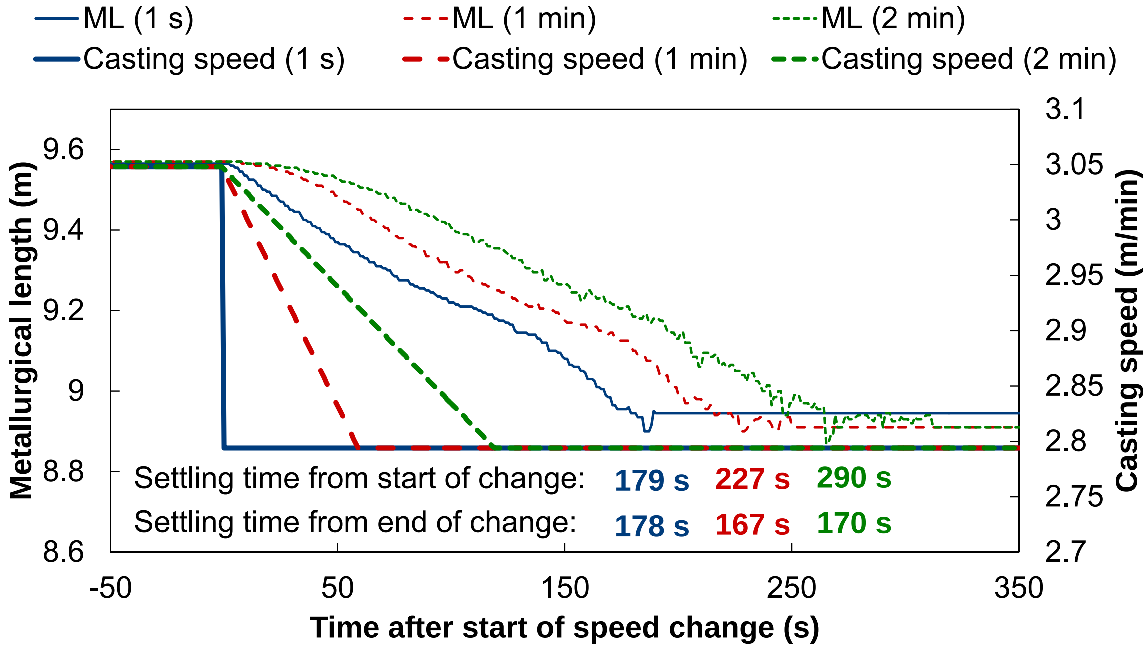
Comparison of different size speed decrease



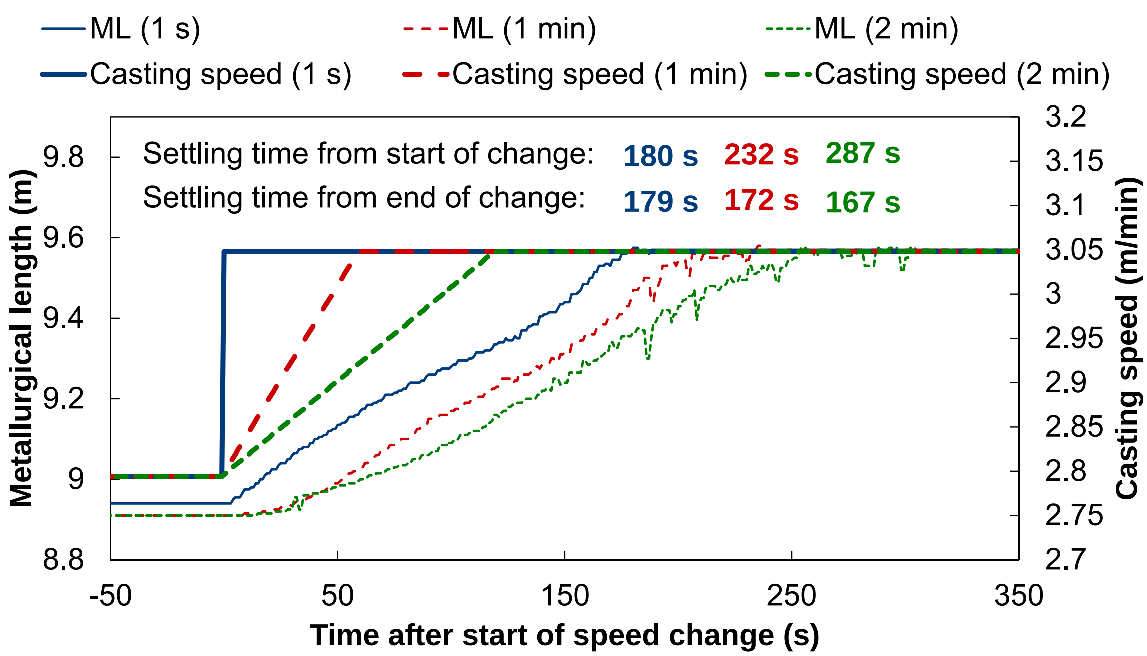
Comparison of different size speed increases



Comparison of different rates of speed decrease



Comparison of different rates of speed increase



Conclusions

- Cononline generalizing CON1D modeling framework to transient cases is valid
- Conoffline predicted thermal shrinkage is a good qualitative match to roll loads
- Cononline should be an accurate tool to adjust *location* of soft reduction during transient conditions
- However, predicted *amount* of thermal shrinkage is an order of magnitude smaller than typical soft reduction amounts – soft reduction cannot be explained by centerline shrinkage alone

- For typical variations of casting speed, the settling time of metallurgical length does not vary much
- This may not be true for more severe changes in casting speed

Future Work

- Extend CON1D/Cononline to investigate and predict ideal machine taper

- We want to complete a full parametric study (in coordination with Prathiba's work)
- *Study the effect of changing …*
  - casting speed
  - spray rate
- *… on …*
  - metallurgical length
  - shell thickness
  - thermal shrinkage
- *… for different …*
  - thicknesses
  - grades
- Any other suggestions?
- Does anyone want us to include their caster in the study?

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