CCC Annual Report

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Spray cooling optimization using CON1D

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Optimizing Secondary Cooling: Feasible operating windows

- Controlling metallurgical length is important for[1]
  - Optimizing casting speed and equipment usage
  - Avoiding excessive bulging
  - Preventing whale formation
- Regulating surface temperature profile is important for[2]
  - Avoiding defects such as transverse cracks
  - Maximizing energy efficiency for further rolling operations
- Secondary cooling plays an important role in determining these two factors of steel quality[3]
- Determining feasible ranges of operating conditions is an essential **first step** to optimize casting for quality without defects or whales

Objectives

Determine feasible operating conditions for a continuous steel caster, using the thin (90 mm) slab caster at Nucor Decatur as an example.

- **Constraint 1:** Maintain metallurgical length (ML) between straightener and end of containment
- **Constraints 2:** Maintain ML (satisfy constraint 1) and also keep surface temperature (T_s) outside the ductility trough (T_s < 900 °C)

1. Find maximum range of casting speeds where given constraint(s) can be met by changing water spray rates
   Repeat for low (0.03% C), peritectic (0.1011% C) and high (0.24% C) carbon steel grades

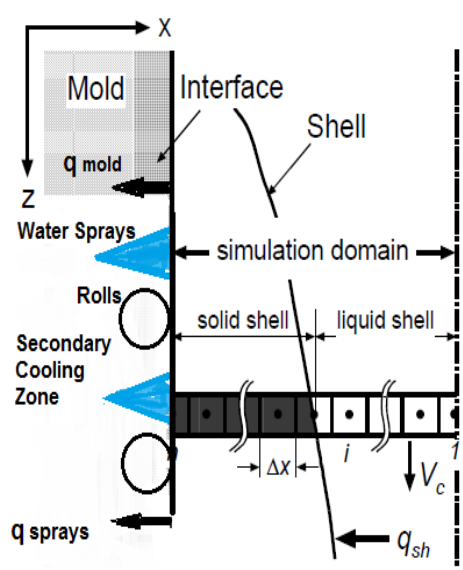
2. Investigate feasibility of meeting constraint(s) by changing only secondary cooling water flow rates for a given set of conditions (speed, grade, superheat)

CON1D

- A Fortran program modeling heat transfer and solidification based on 1-D transient heat conduction equation
- Lagrangian model

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \frac{\partial k}{\partial T}\left(\frac{\partial T}{\partial x}\right)^2 + \rho H_f \frac{\partial f_s}{\partial t}$$

- Employs explicit finite difference discretization
- Modified Clyne-Kurz microsegregation model for calculation of phase fractions



CON1D Manual Version 10.10.01

Boundary heat flux

Mold:

Boundary heat flux in the mold, $-k\frac{\partial T}{\partial z} = h_{int}(T_s - T_{int})$

Average heat transfer in the mold is calculated as[4]

$Q = 0.949 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.728} * W^{0.090}$

where μ = 0.08 pa-s; T_{melt} = 1129°C ; W = 1400 mm ; V_c (m/min)

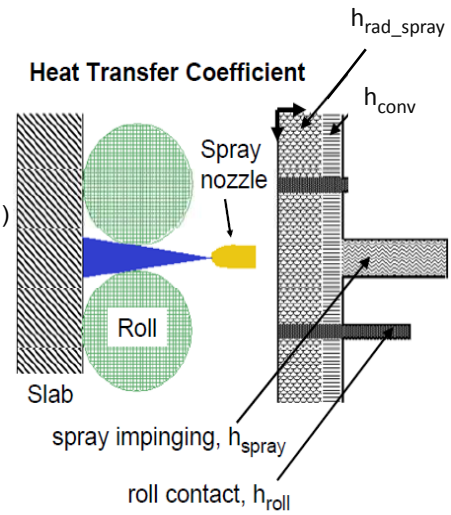
Secondary Cooling Zone:

$q_{sprays} = (h_{spray} + h_{radspray} + h_{conv} + h_{roll})\ (T_s - T_{amb})$

$h_{spray} = A * Q^c_{water} * (1 - b * T_{spray})$ - Nozaki et al[5]

$h_{rad_spray} = \sigma \cdot \varepsilon_{steel}(T_{sK} + T_{ambK})(T^2{}_{sK} + T^2{}_{ambK})$

$h_{conv} = 8.7\ W/m^2K$



$$\mathbf{h_{roll}} = \left(\frac{(\mathbf{h_{rad_spray}} + \mathbf{h_{conv}} + \mathbf{h_{spray}}) \cdot \mathbf{L_{spray}} + (\mathbf{h_{rad_spray}} + \mathbf{h_{conv}}) \cdot (\mathbf{L_{spray\ pitch}} - \mathbf{L_{spray}} - \mathbf{L_{roll\ contact}})}{\mathbf{L_{roll\ contact}} \cdot (\mathbf{1} - \mathbf{f_{roll}})}\right) \cdot \mathbf{f_{roll}}$$

CON1D Manual Version 10.10.01

Validation with analytical solution: Input parameters

Property		Units
T_m	1535.6	°C
T_o	683.7125	°C
T_∞/T_{pour}	1550	°C
V_c	2	m/min
$T_{surface}$	1000.08	°C
$k_{s,l}$	34.5	W/mK
$\rho_{s,l}$	7400	kg/m³
$Cp_{s,l}$	0.76	kJ/kgK
k_m	315	W/mK
ρ_m	8960	kg/m³
Cp_m	0.386	kJ/kgK
L_f	243	kJ/kg

- Shell thickness from analytical solution[6] is

  $\boldsymbol{\delta(t) = 2\emptyset\sqrt{\alpha_s t}}$

  where $\delta(t)$ = shell thickness(mm)

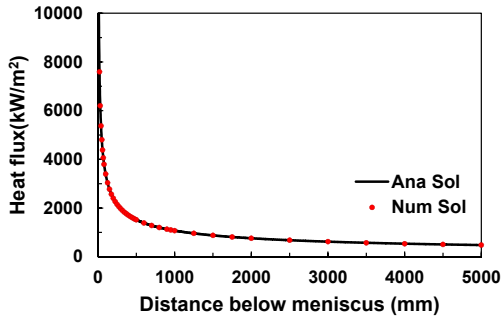
  $\emptyset$ = parameter obtained while solving analytical solution

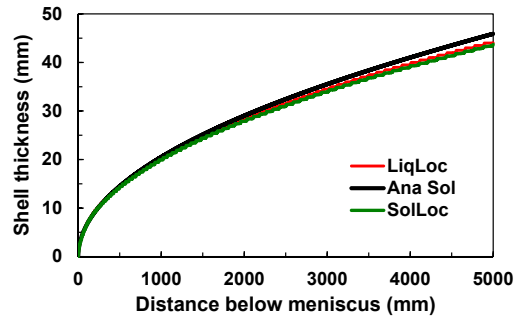
  α_s = thermal diffusivity (m²/s)

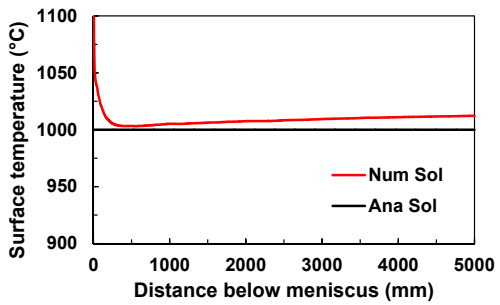
  T = time (s)

- Mold length of 5000mm
- 100 mm thick slab
- Pure material, simulated in Con1d as low (0.005 %) carbon
- Constant shell surface temperature of 1000°C
- Constant density, thermal conductivity, specific heat etc

Validation with analytical solution: Results







For CON1D, heat flux (matching with that of analytical solution) is given as input

For a simulation thickness of 50 mm,
RMS Error = 0.95 mm

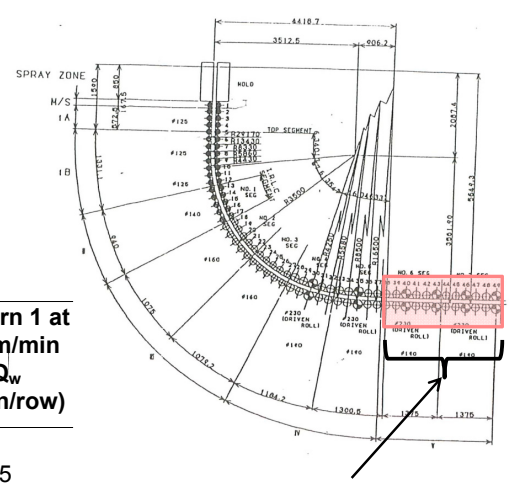
Numerical solution for shell thickness matches well with the analytical solution

Nucor Decatur Caster

- Thickness: 90 mm
- Mold length: 0.95 m
- End of straightener 8.6m
- End of containment: 11.25 m

- Slab width: 1400 mm for this study

Plant Zone Name	Zone Number	Zone Starts at	Max. Q_w (l/min/row)	Min. Q_w (l/min/row)	Pattern 1 at 3.3 m/min Q_w (l/min/row)
MS	1	850	120	50	90.84
Z1A	2	1017.5	400	50	172.75
Z1B	3	1590	250	30	127.93
ZII	4	2921.1	100	15	48.98
ZIII	5	3861.1	60	9	45.27
ZIV	6	6015.3	40	6	38.68
ZV	7	8500	24	6	47.31
		11250			



Desired range of Metallurgical Length (8.6 < ML < 11.25)

Nucor Decatur caster [7]

Explanation of Constraints

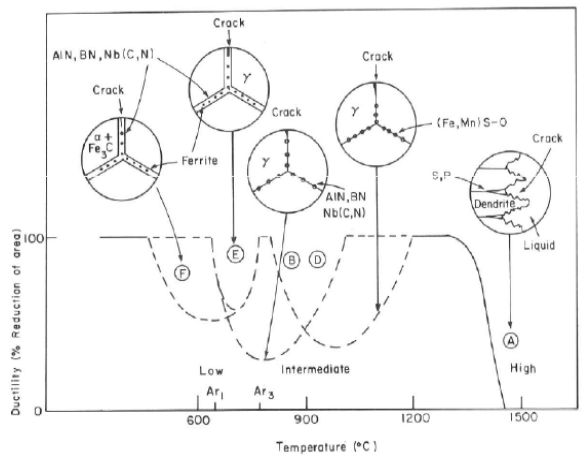
- **Constraint 1:**
  - Metallurgical length between the unbender and the last roll

a. ML > 8.6m
   - Difficult to unbend completely solid strand
   - More prone to stresses and transverse cracks

b. ML < 11.25m
   - To avoid whales

- **Constraints 2:**

  Surface temperature of the strand above ductility trough T_s > 900°C



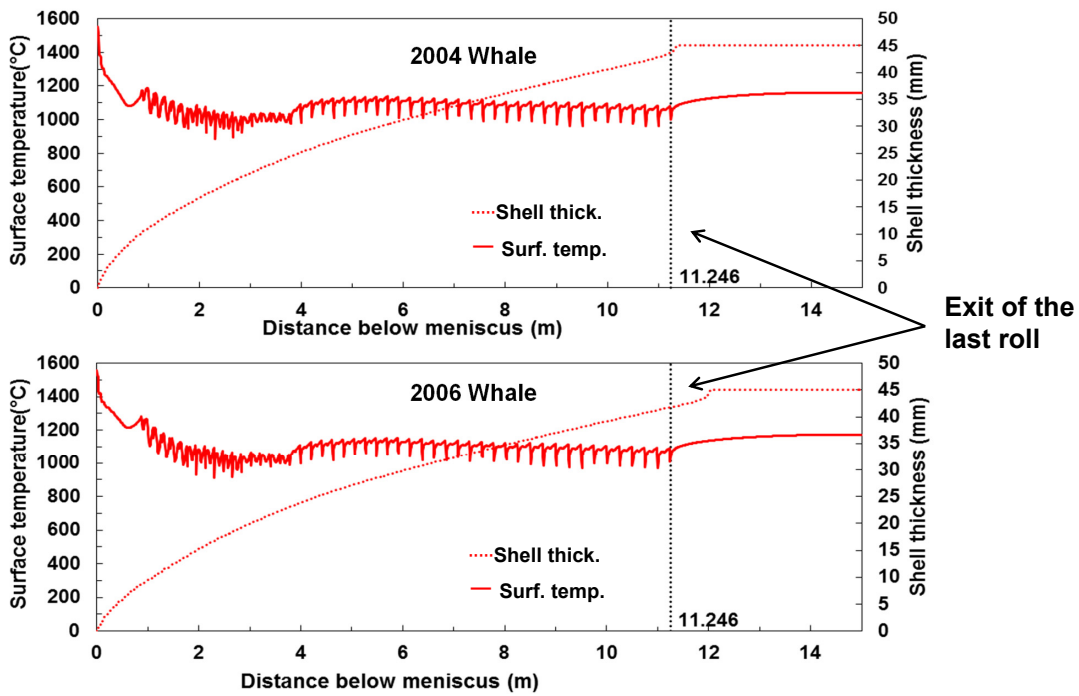
B.G.Thomas, *ISS Transactions*, 1986, pp.7.

Validation of CON1D with whale cases: Input conditions

	2004 Whale case							
Composition	% C	0.0600	% Mn	1.1500	% S	0.0020	% P	0.0100
	% Si	0.1880	% Cr	0.0400	% Ni	0.0400	% Cu	0.1200
	% Mo	0.0100	% Ti	0.0020	% Al	0.0200	% V	0.0010
	% N	0.0080	% Nb	0.0350	% W	0.0000	% Co	0.0000
Dimensions of the strand	90 mm thk x 1396 mm wide							
Casting Speed (m/min)	3.701							
Pour Temperature (°C)	1553							
Average Mold Heat Flux (From empirical relation)(MW/m2)	2.4258							
Flow rates in the secondary cooling Zone (L/min/row)	MS - 89.9; ZIA -172; ZIB-107.8;ZII -31.2;ZIII -11;ZIV 15.5 and ZV-19.7							

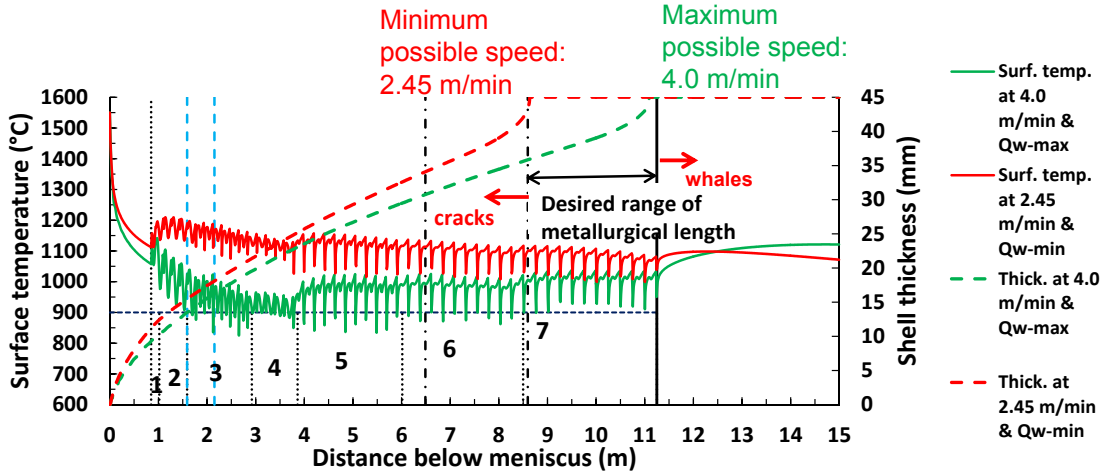
	2006 Whale case							
Composition	% C	0.0400	% Mn	0.2000	% S	0.0020	% P	0.0100
	% Si	0.0300	% Cr	0.0400	% Ni	0.0400	% Cu	0.0800
	% Mo	0.0100	% Ti	0.0020	% Al	0.0200	% V	0.0010
	% N	0.0080	% Nb	0.0000	% W	0.0000	% Co	0.0000
Dimensions of the strand	90 mm thk x 1553 mm wide							
Casting Speed (m/min)	3.701							
Pour Temperature (°C)	1560							
Average Mold Heat Flux (From empirical relation)(MW/m2)	2.4258							
Flow rates in the secondary cooling Zone (L/min/row)	MS - 89.9; ZIA -172; ZIB-107.8;ZII -31.2;ZIII -11;ZIV 15.5 and ZV-19.7							

CON1D ML validation: correctly predicts 2004 and 2006 whale cases



Max. range of casting speeds: Criterion 1 (ML only)

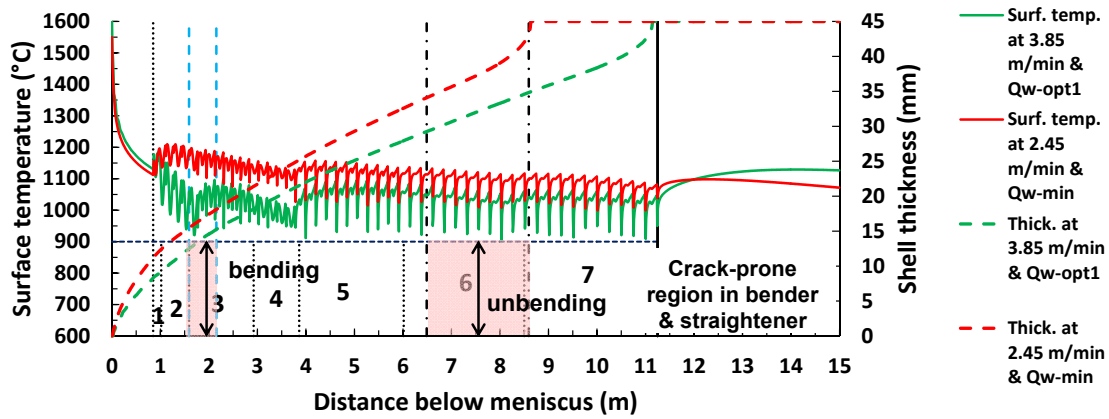
High Carbon (0.24%), super heat (T_{Sh}) = 41.5 °C
Max. and min. water spray rates at max. and min. casting speed respectively



For the given caster and casting parameters, casting speed can be varied from **4.0 to 2.45 m/min** with metallurgical length in the desired range

Max. range of casting speeds: Constraints 2 (ML and T_s> 900°C)

- High Carbon (0.24%),super heat (T_{Sh}) = 41.5 °C
- Spray rates are chosen to satisfy both constraints, while that for min. casting speed remain the same

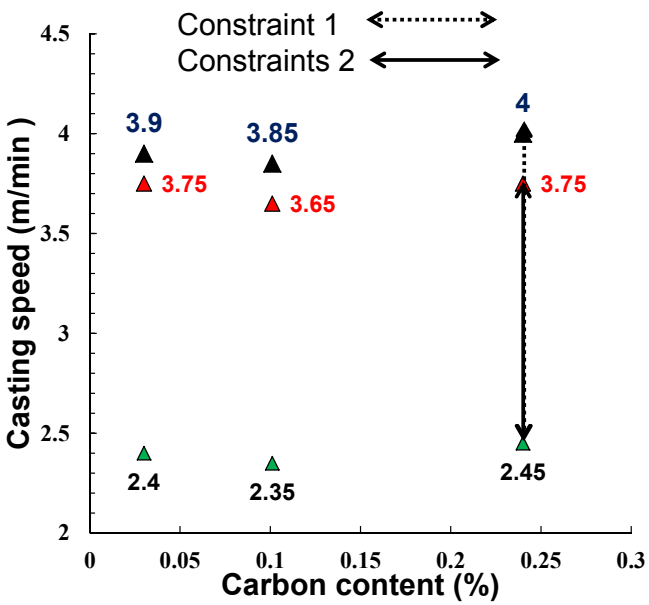


Besides ML constraint, to regulate surface temperature above 900 °C for no crack zone, range of casting speed decreases to **3.75 to 2.45 m/min**

3 grades of steel

Grade	Liquidus Temperature (°C)	Solidus Temperature (°C)
Low Carbon Steel (0.03%)	1531.5	1509.7
0.03%C, 0.08%Mn, 0.01%S, 0.015%P, 0.005%Si, 0.01%Cr, 0.01%Ni, 0.01%Cu, 0.00%Mo, 0.05%Ti, 0.04%Al, 0.000%V, 0.00%N, 0.00%Nb)		
Peritectic (0.1011%)	1515.5	1474.7
(0.1011%C, 2.0666%Mn, 0.0027%S, 0.0102%P, 0.0722%Si, 0.0096%Cr, 0.00%Ni, 0.00%Cu, 0.2985%Mo, 0.0046%Ti, 0.644%Al, 0.000%V, 0.0058%N, 0.00%Nb)		
High Carbon Steel (0.24%)	1508.5	1453.5
0.24%C, 1.09%Mn, 0.0019%S, 0.014%P, 0.175%Si, 0.04%Cr, 0.04%Ni, 0.087%Cu, 0.01%Mo, 0.002%Ti, 0.039%Al, 0.001%V, 0.0076%N, 0.035%Nb		

Range of max. casting speeds: low, peritectic & high carbon steels



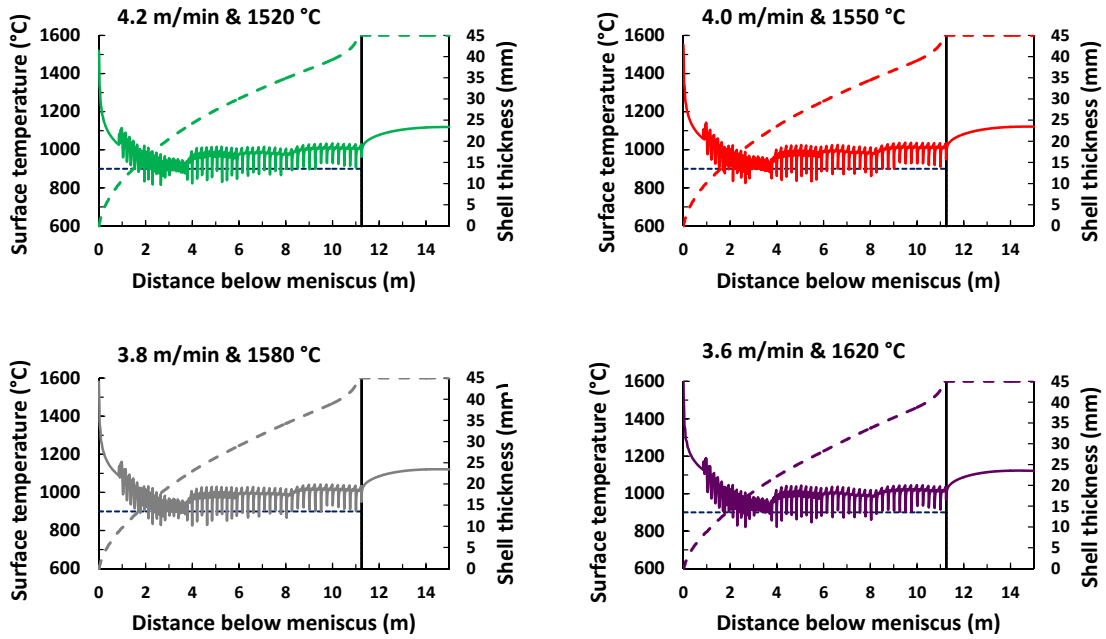
The results show how the safe operating window of casting speeds changes with grade (for a given set of casting conditions)

This high carbon steel can be cast at faster casting speeds than the low or peritectic grades

This result was for 41.5 °C superheat.

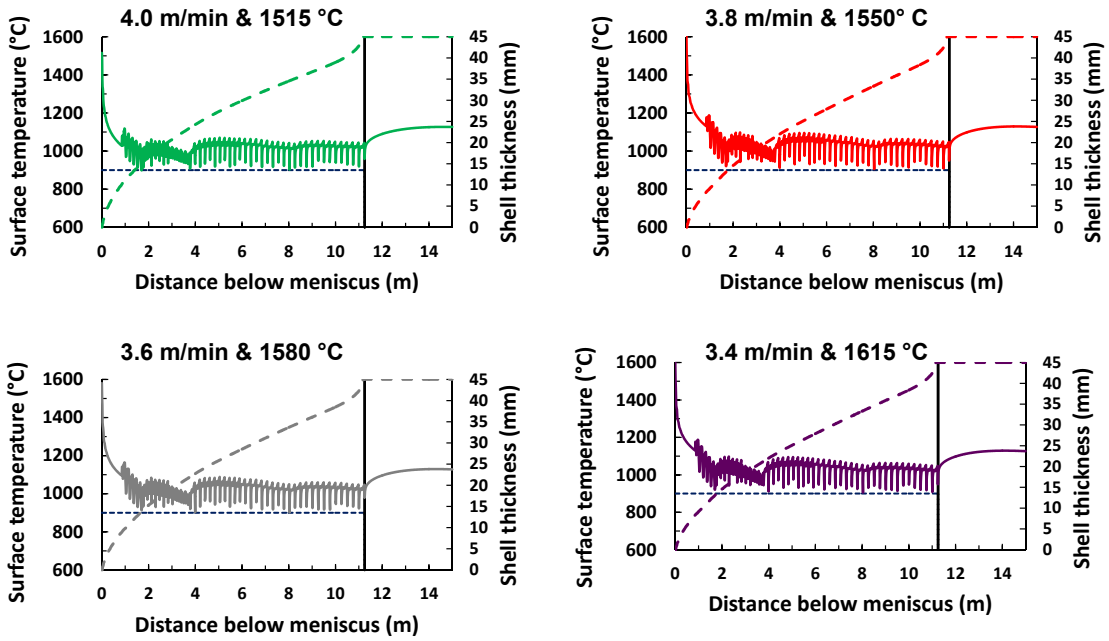
Max. casting speed for different super heats: constraint 1 (ML only)

High Carbon (0.24%); Max. water spray rates at max. casting speed



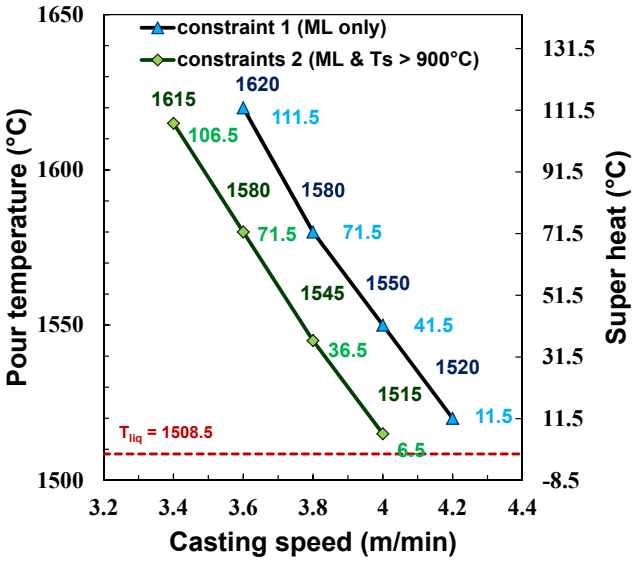
Max. casting speed for different super heats: constraints 2 (ML & T_s > 900°C)

High Carbon (0.24%) ; spray rates are chosen to satisfy both constraints



Max. casting speed for different super heats: constraint 1 & constraints 2

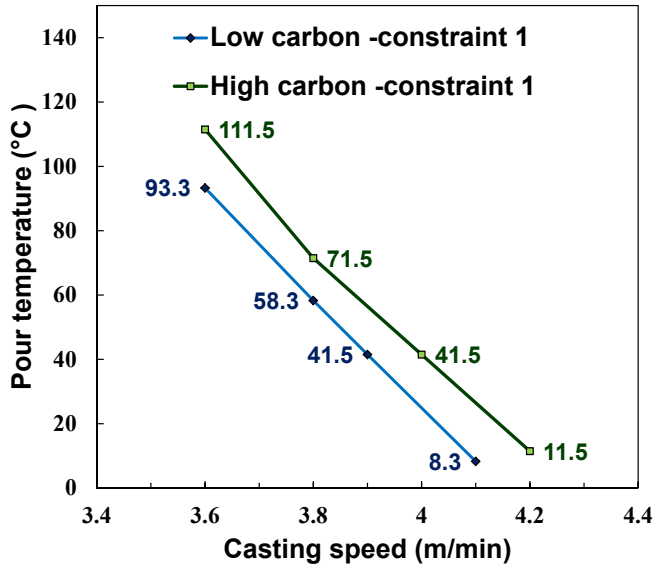
High carbon (0.24%) steel



Maximum cast-able superheat decreases with casting speed

For constraints 2, max. casting speeds further decrease, because less water is used to keep temperatures above ductility trough.

Max. casting speed for different super heats: Low and high carbon



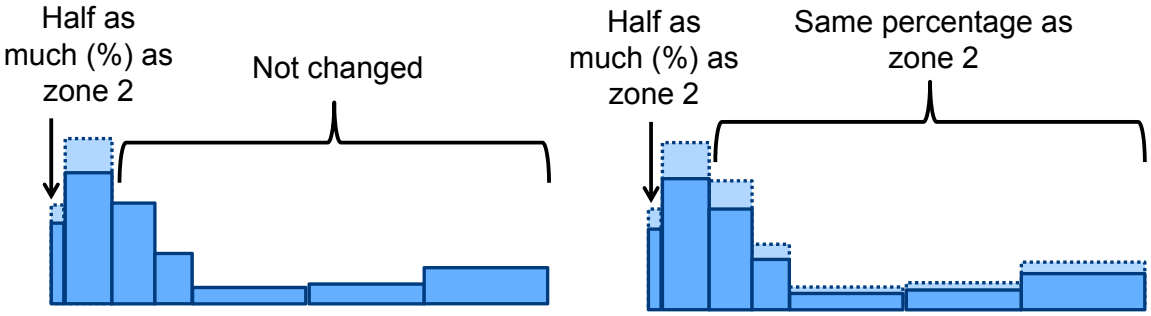
For both low and high carbon, max. casting speeds increase with drop in super heat

For a given super heat, the high carbon steel can be cast at greater speeds compared to the low carbon

Investigating feasible secondary cooling water flow rates

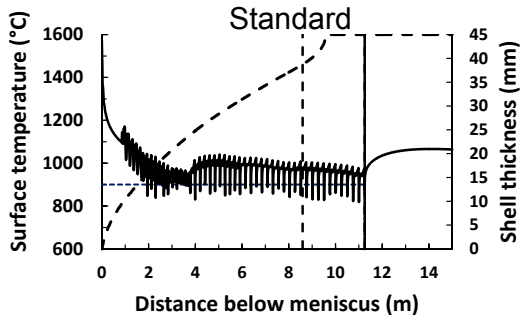
High Carbon (0.24%), thin slab (90mm), casting speed = 3.3 m/min, super heat = 61.5 °C
Starting from usual water flow rates for that speed in pattern 1 in all zones

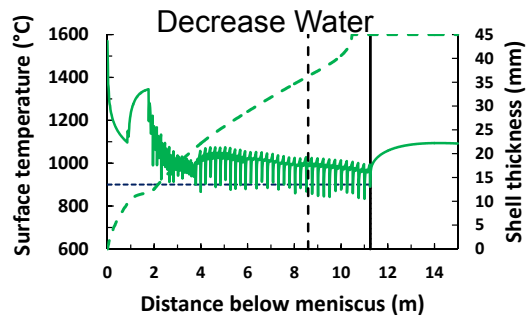
- Method 1: Q_w in Z2 is changed; Z1 by half as much percent change as Z2; Other zones constant
- Method 2: Q_w in Z2 is changed; Z1 by half as much percent as Z2; Other zones by the same percent as Z2

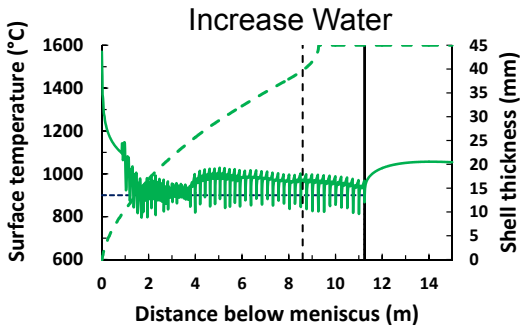


Maintain Constraint 1 (Keep bender < ML < containment)

Investigating feasible secondary cooling water flow rates: Method 1



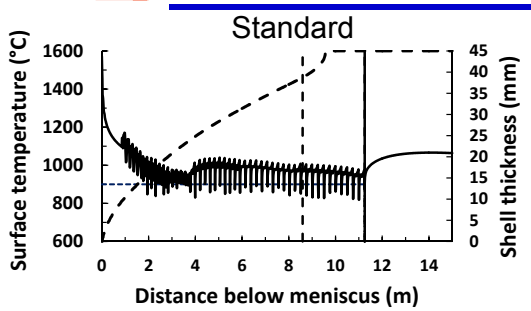


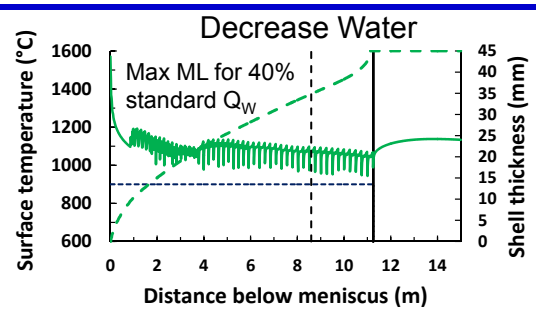


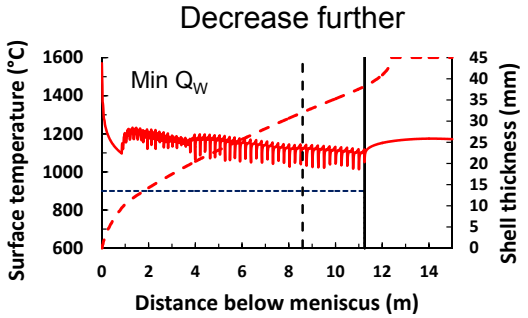
--- Thickness
— Surface temperature

- Water flow rates in Zones 2 and 1 alone can be changed to regulate Metallurgical length and surface temperature
- Changing water in these two zones alone does not move the ML out of the acceptable region

Investigating feasible secondary cooling water flow rates: Method 2 (Decreasing Q_w)



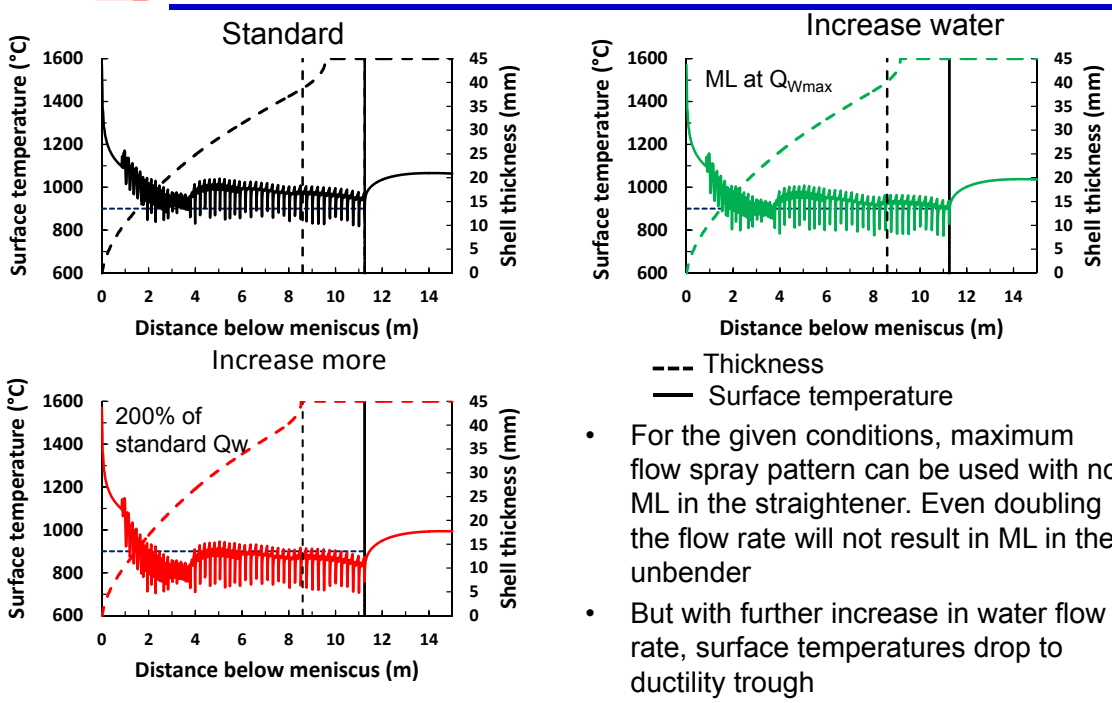




--- Thickness
— Surface temperature

- For the given conditions, spray pattern can be reduced to a maximum of 40 % with out any whales
- Besides preventing cracks, high surface temperatures enhance energy efficiency
- Below 40% of nominal water flow rate, whales will result

Investigating feasible secondary cooling water flow rates: Method 2 (Increasing Q_w)



- For the given conditions, maximum flow spray pattern can be used with no ML in the straightener. Even doubling the flow rate will not result in ML in the unbender
- But with further increase in water flow rate, surface temperatures drop to ductility trough

Conclusions

1. Max. range of casting speeds for a given super heat was determined for three grades.
2. Range of casting speeds is smaller when satisfying 2 constraints simultaneously than only satisfying 1 constraint.
3. Max. feasible casting speed increases with decreasing super heat (because there is less total heat to extract).
4. For a given superheat, max. casting speed was higher for the steel with high carbon content
5. For a given set of conditions, feasibility of changing water flow rates in the secondary cooling zone is explored.

Future Work

- Feasibility study: Find the window of operation for a continuous steel caster
  - Speed
  - Grade
  - Super heat
  - Secondary cooling water
- Optimization: determine best operating conditions for different criteria
  - Production (e.g. constraint 1)
  - Quality (e.g. constraints 2)
  - Energy efficiency
- Extend to additional casters (thicknesses, speeds, secondary cooling)

References

[1] Joydeep Sengupta, Manh-Kha Trinh, David Currey, Brian G. Thomas, " Utilization of CON1D at ArcelorMittal Dofasco's No. 2 Continuous Caster for Crater End Determination",2009

[2] M. M. Wolf: Continuous Casting: Initial Solidification and Strand Surface Quality of Peritectic Steels, vol. 9, Iron and Steel Society, Warrendale, PA, 1997, pp. 1-111

[3] J.K. Brimacombe, P.K. Agarwal, S. Hibbins, B. Prabhaker and L.A. Baptista: "Spray Cooling in Continuous Casting," in Continuous Casting, vol. 2, J. K. Brimacombe, ed., 1984, pp. 105-123

[4] Prediction of Mold heat transfer (Another project* - 2013,D.P)

[5] Nozaki, T., Matsuno, J., Murata, K., Ooi, H., Kodama, M., "A Secondary Cooling Pattern for Preventing Surface Cracks of Continuous Casting Slab", Trans. ISIJ, V. 18, 1978, pp.330-338

[6] J. Dantzig and C. Tucker, Modeling in Materials Processing, Chap. 4.3

[7] Trico Steel L.L.C.: "Spray Nozzle Arrangement," 1995, (Internal Document, Nucor Steel, Decatur AL)

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)

- Nucor Steel Decatur (Ron O'Malley, Bob Williams, and others)

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