ANNUAL REPORT 2007

UIUC, June 12, 2007

Temperature evolution in the spray zones: plant measurements and CON1D prediction

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Objective

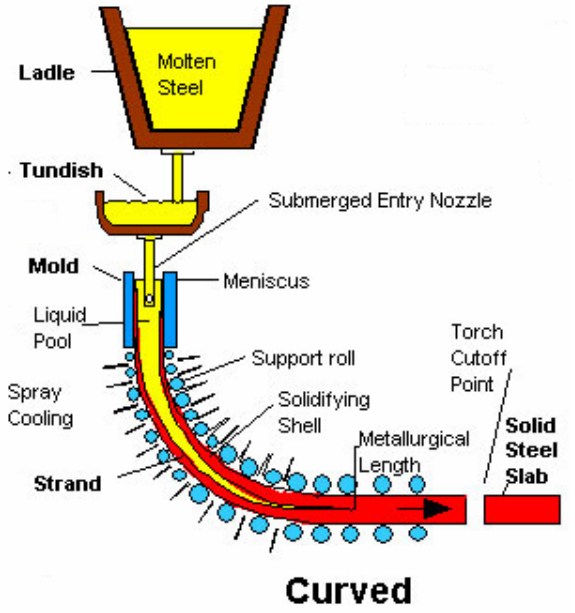
- Develop accurate model of spray cooling (for use in online control, etc.)
  - Incorporate Leidenfrost effect into spray cooling model
  - Test the accuracy of the Goodrich pyrometers at Riverdale caster
  - Compare CON1D model with measurents
- Study transient phenomena during spray water changes

Outline

- CON1D model description
- Plant measurements at Riverdale
- Comparison of original model with Riverdale measurements
- Compare improved model (with Leidenfrost) for Riverdale and Nucor cases
- Nucor experiments: transient case
- Conclusions

CON1D model

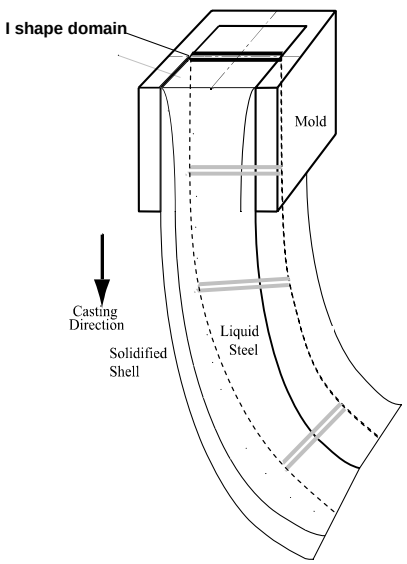
Continuous casting of steel

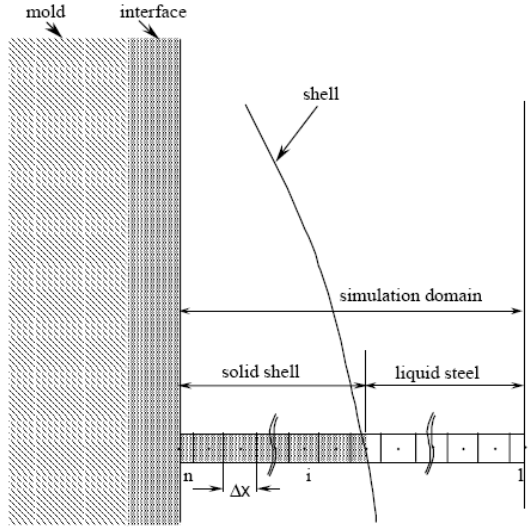


-ccc.me.uiuc.edu

CON1D model

Simulation domain





-K. Zheng, concontroller user's manual

-con1d8.0 user's manual

CON1D model

Heat transfer coefficient in Spray Zones

Spray nozzle cooling $h_{spray} = A \cdot C \cdot Q_{water}{}^{n} \cdot \left(1 - b \cdot T_{spray}\right)$

Radiation $h_{rad\_spray} = \sigma \cdot \varepsilon_{steel} \cdot \left(T_{sK} + T_{amb\,K}\right)\left(T_{sK}{}^{2} + T_{amb\,K}{}^{2}\right)$

Conducton to the roll $h_{roll} = \dfrac{f_{roll}}{L_{roll\,contact} \cdot \left(1 - f_{roll}\right)} \left(\begin{array}{l} \left(h_{rad\_spray} + h_{conv} + h_{spray}\right) \cdot L_{spray} + \\ \left(h_{rad\_spray} + h_{conv}\right) \cdot \left(L_{spray\,pitch} - L_{spray} - L_{roll\,contact}\right) \end{array} \right)$

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

Q_{water} Water Flux

T_{spray} Temperature of spray cooling water

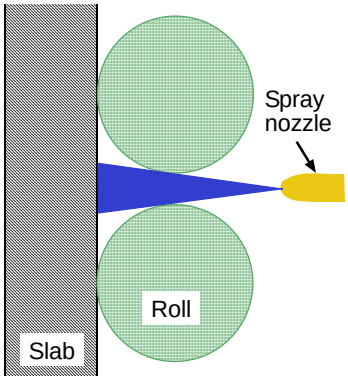
T_{amb} Ambient Temperature

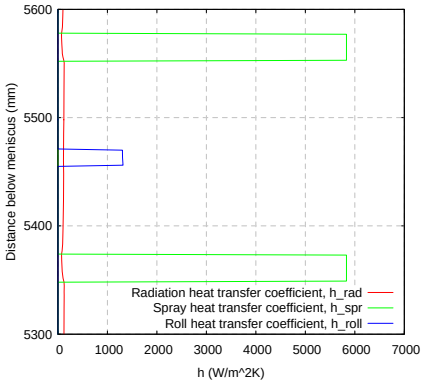
f_{roll} Fraction of heat extraction to rolls

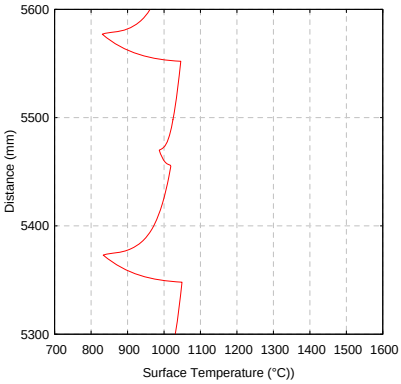
Nozaki – A*C=0.3925, n=0.55, b=0.0075

CON1D model

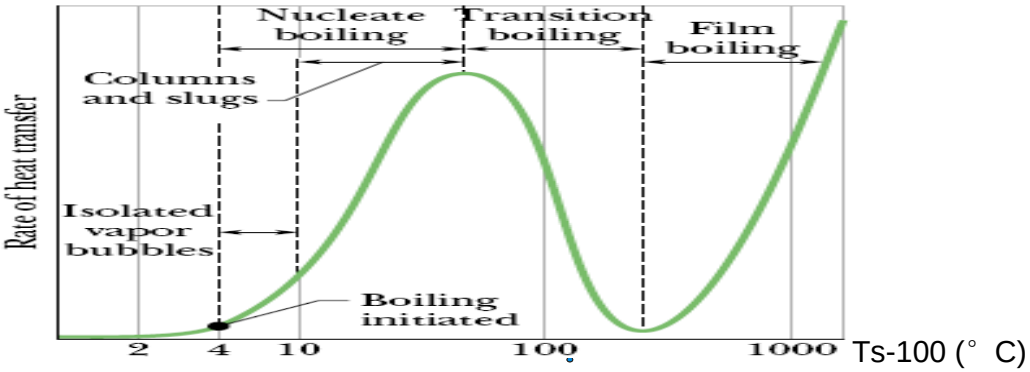
Heat transfer coefficient in Spray Zones

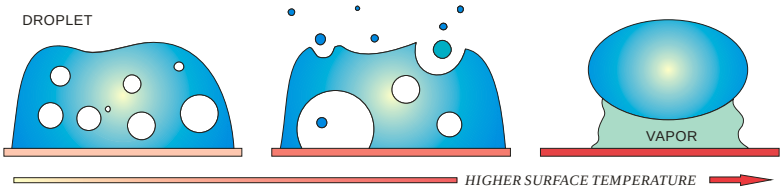






Leidenfrost effect





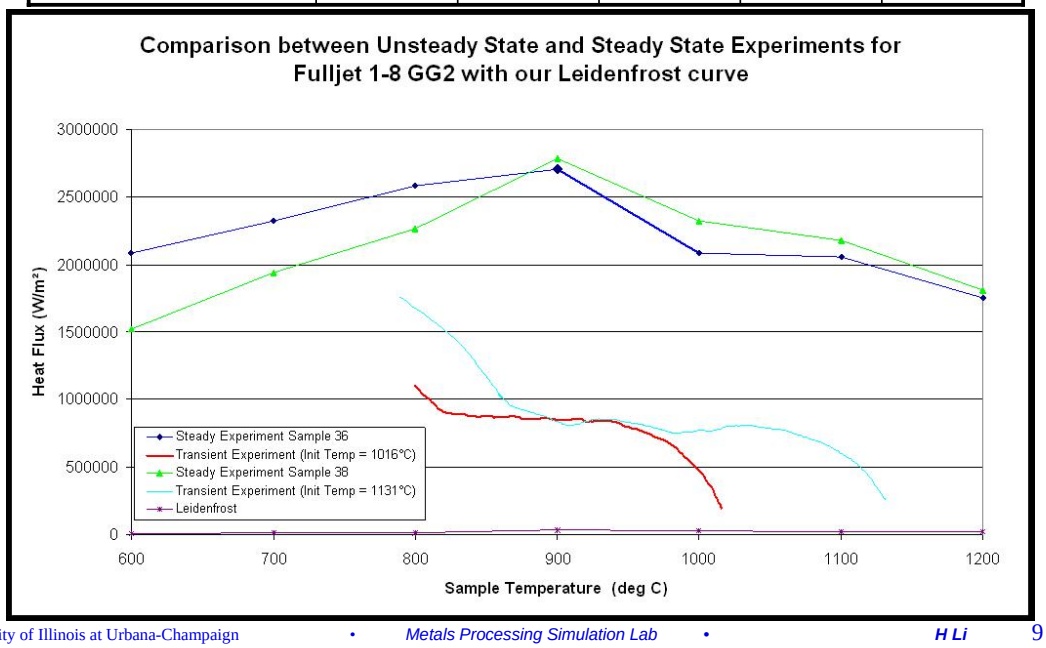
NUCLEATE BOILING
Bubbles form and the droplet evaporates slowly

TRANSITION BOILING
Marked by violent sizzling. Droplet boils away explosively as soon as it hits the surface

FILM BOILING
The droplet floats quietly on a vapor cushion, and evaporates very slowly

Considering Leidenfrost by h-multipliers

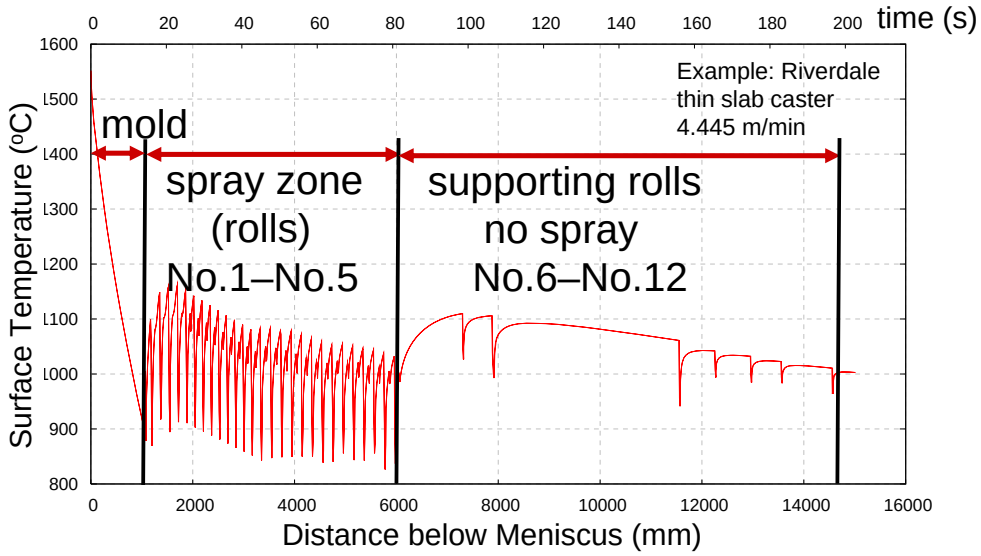
h-multipliers	1.0	1.2	2.2	1.6	1.0
Temperature ° C	700	800	900	1000	1050



Spray coefficient C

zone no.	C (used in Riverdale without Leidenfrost effect)	C (used in Riverdale and Nucor with Leidenfrost)
zone 1	0.25	0.25
zone 2	0.25	0.25
zone 3	0.4	0.25
zone 4	0.4	0.25
zone 5	0.4	0.25

Surface Temperature Down Strand



Zones in CON1D file at Riverdale caster

Zone No.	Zone starts	# of rolls	roll radius(m)
(1)	1040	1	0.02
(2)	1105	4	1
(3)	1800	9	0.06
(4)	3240	7	0.0825
(5)	4647	7	0.0825
(6)	6075	1	0.02
(7)	7300	1	1
(8)	7900	1	0.06
(9)	11562	1	0.0825
(10)	12262	1	0.0825
(11)	12962	1	0.0825
(12)	13562	1	0.0825

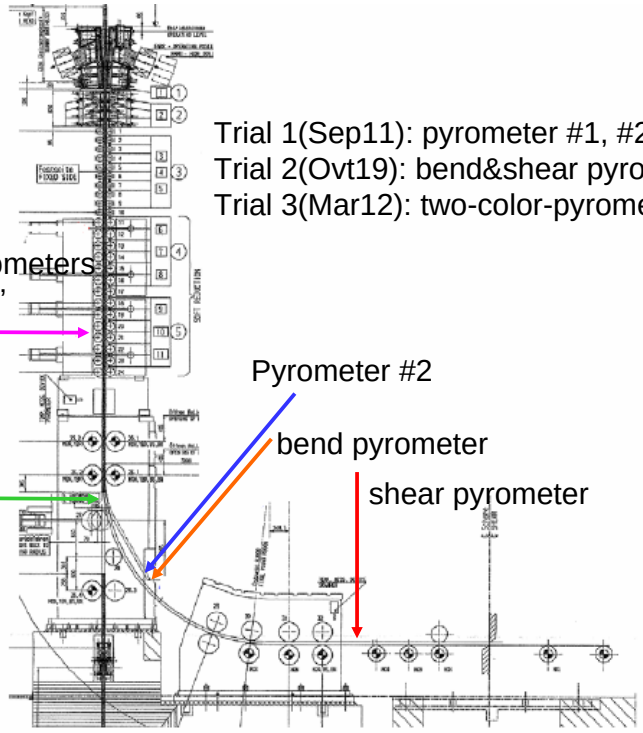
Spray zones

No spray

( ) – CON1D Zone No. 14562.0 End of last spray zone (mm)

Pyrometer locations

Trial 1(Sep11): pyrometer #1, #2&shear pyrometer
Trial 2(Ovt19): bend&shear pyrometer
Trial 3(Mar12): two-color-pyrometers, bend&shear pyro



Casting conditions

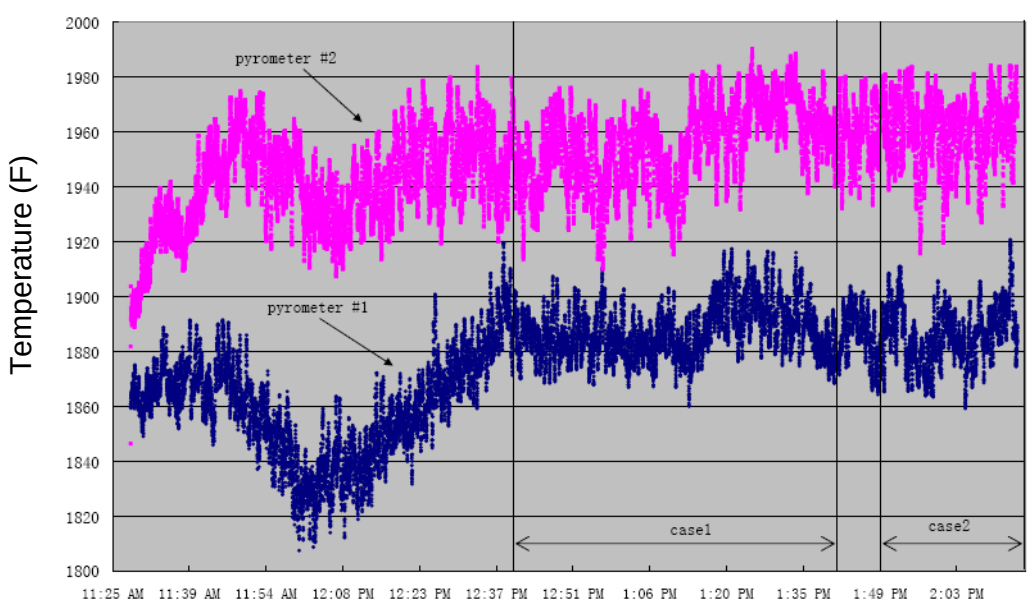
Parameter	case1	case2	case3	case4	case5	Case6
Time	12:07-13:40 Sep11	13:50-14:40 Sep11	9:10-9:38 Oct19	9:45-10:25 Oct19	3:20-5:00 Mar12	6:30-8:00 Mar12
V_{cast} m/min	4.445	4.445	4.47	4.34	4.572	4.699
T_{pour} ° C	1551.7	1555	1554	1551	1540	1549
T_{spray} ° C	21.7	21.7	19.4	19.4	19.4	19.4
Spray water flow rate L/min/row						
Zone1	264.95	21.7	19.4	19.4	276.32	283.89
Zone2	387.98	272.53	257.39	253.61	378.52	448.55
Zone3	84.96	398.39	411.64	368.11	78.65	104.30
Zone4	92.47	87.48	97.57	76.97	90.84	116.26
zone5	70.3	92.47	116.26	91.39	62.19	88.68

Casting conditions

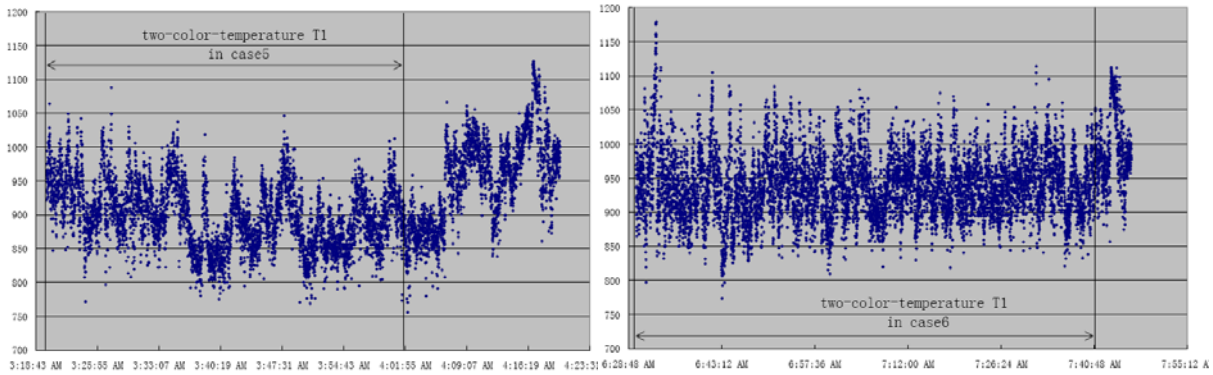
Same conditions for case1~6

Slab thickness (mm)	55
Slab width (mm)	1451
Steel composition (%):	C 0.21, Mn 0.7, S 0.005, P 0.009, Si 0.04, Cr 0.03, Ni 0.03, Cu 0.03, Mo 0.02, Ti 0.002, Al 0.035, V 0.006, N 0.005

Pyrometer measurement: case 1 and 2

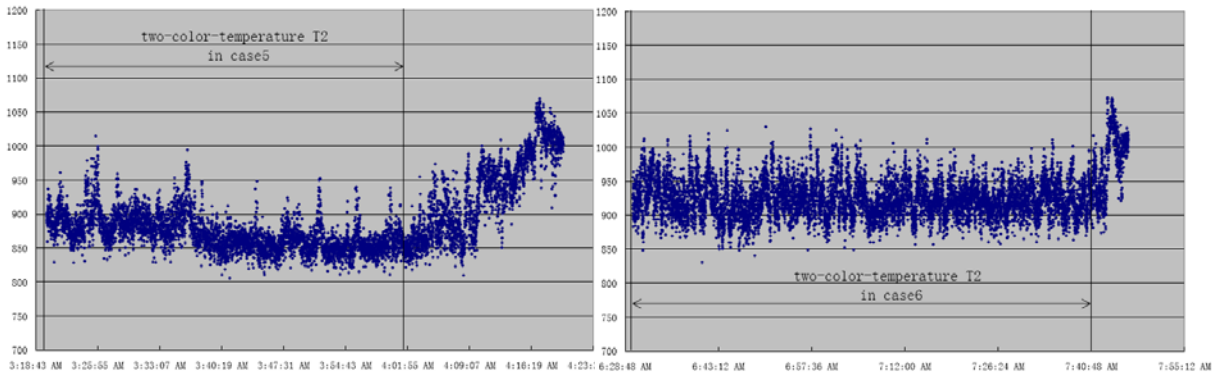


Pyrometer measurement: case 5 and 6



Two-color-temperature T1: calculated by #1'&#2'

Pyrometer measurement: case 5 and 6

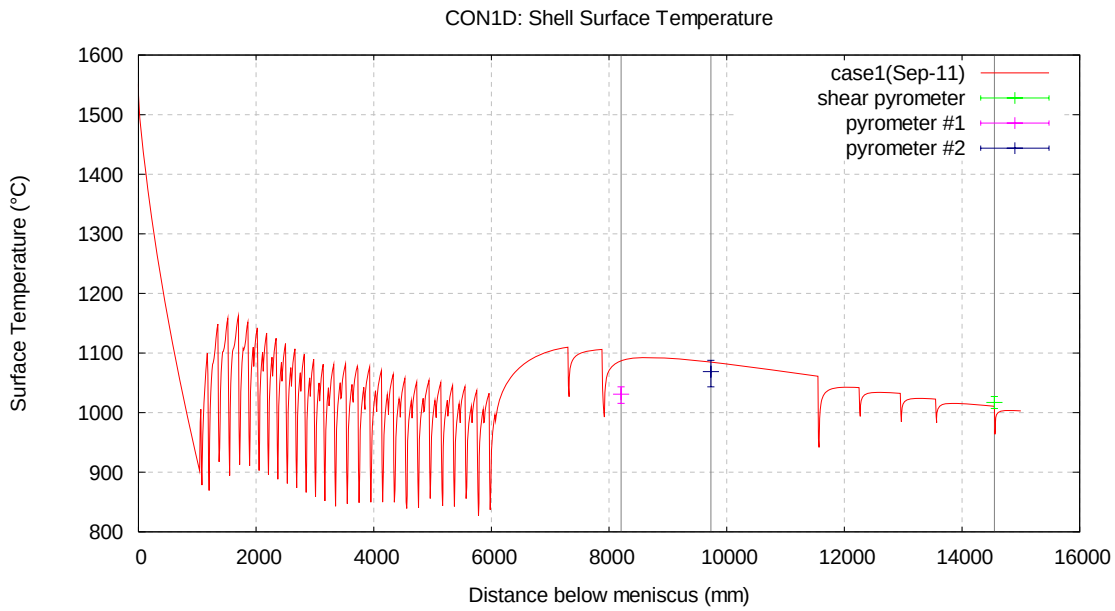


Two-color-temperature T2: calculated by #2'&#3'

Measured temperature goes up from case5 to case6

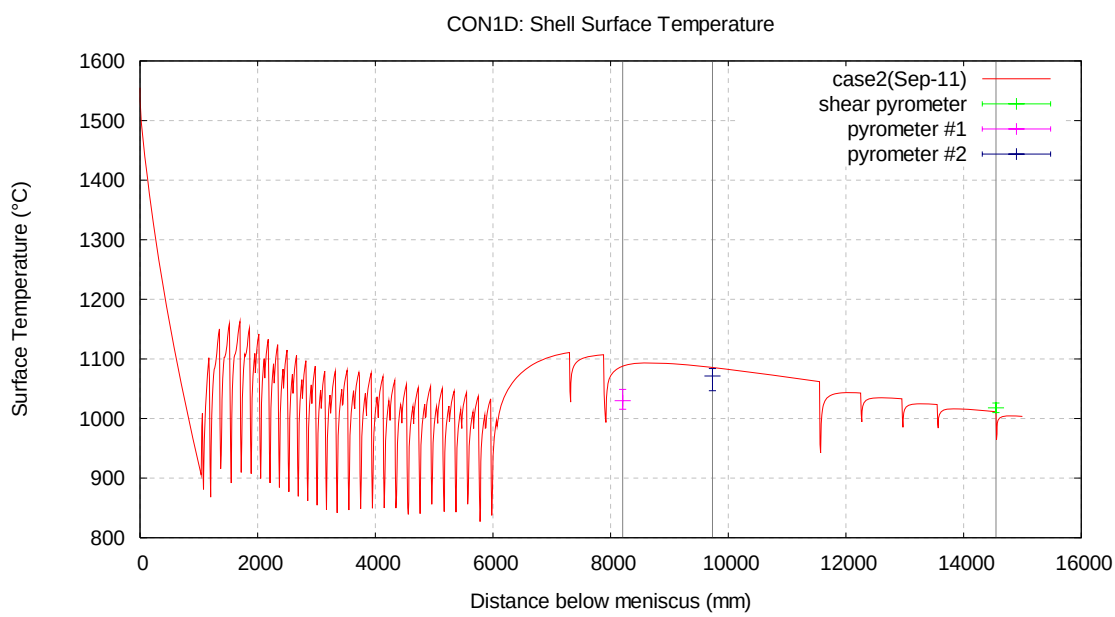
Simulation and comparison

- case 1



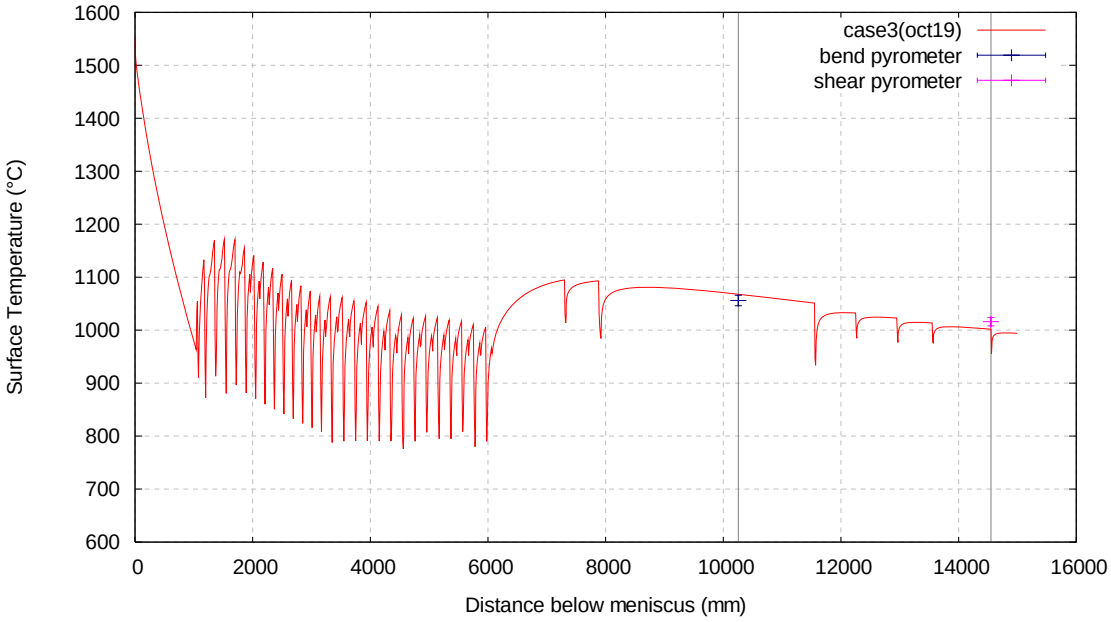
Simulation and comparison

- case 2



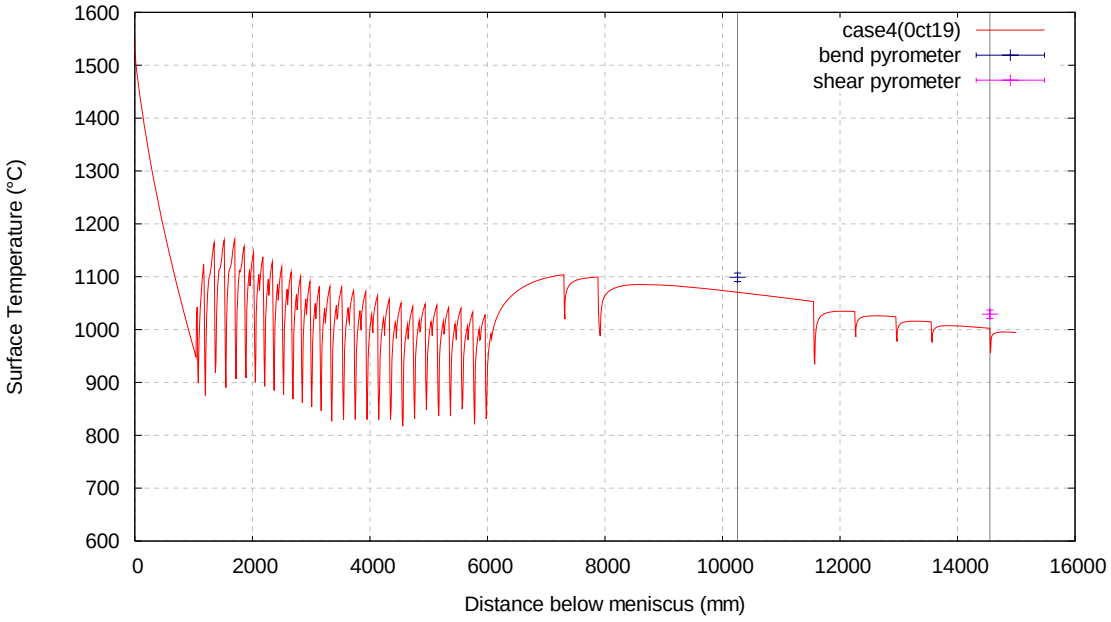
Simulation and comparison

- case 3



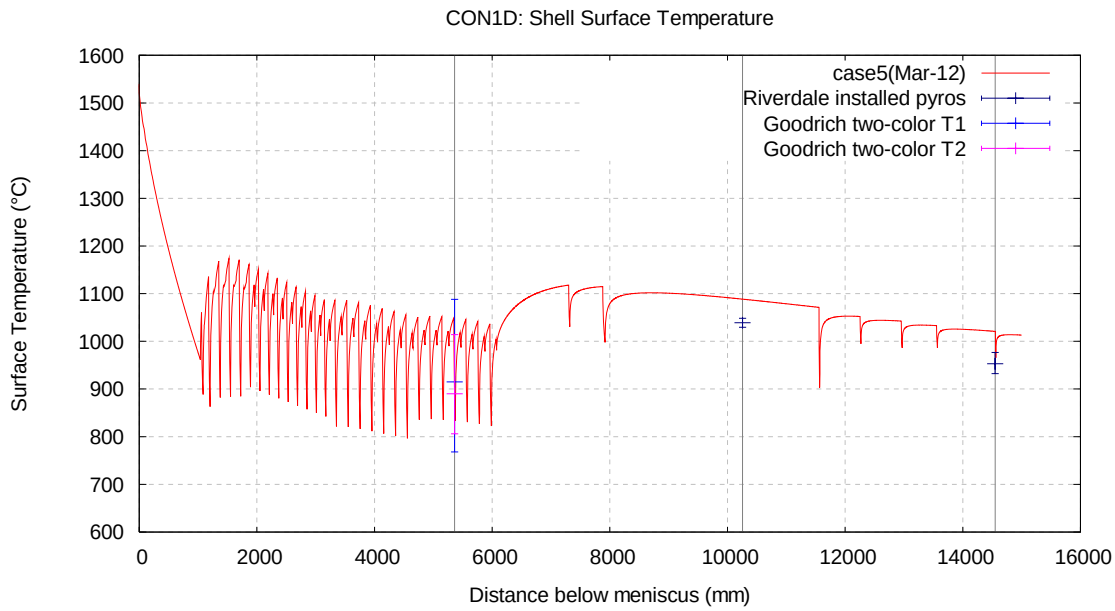
Simulation and comparison

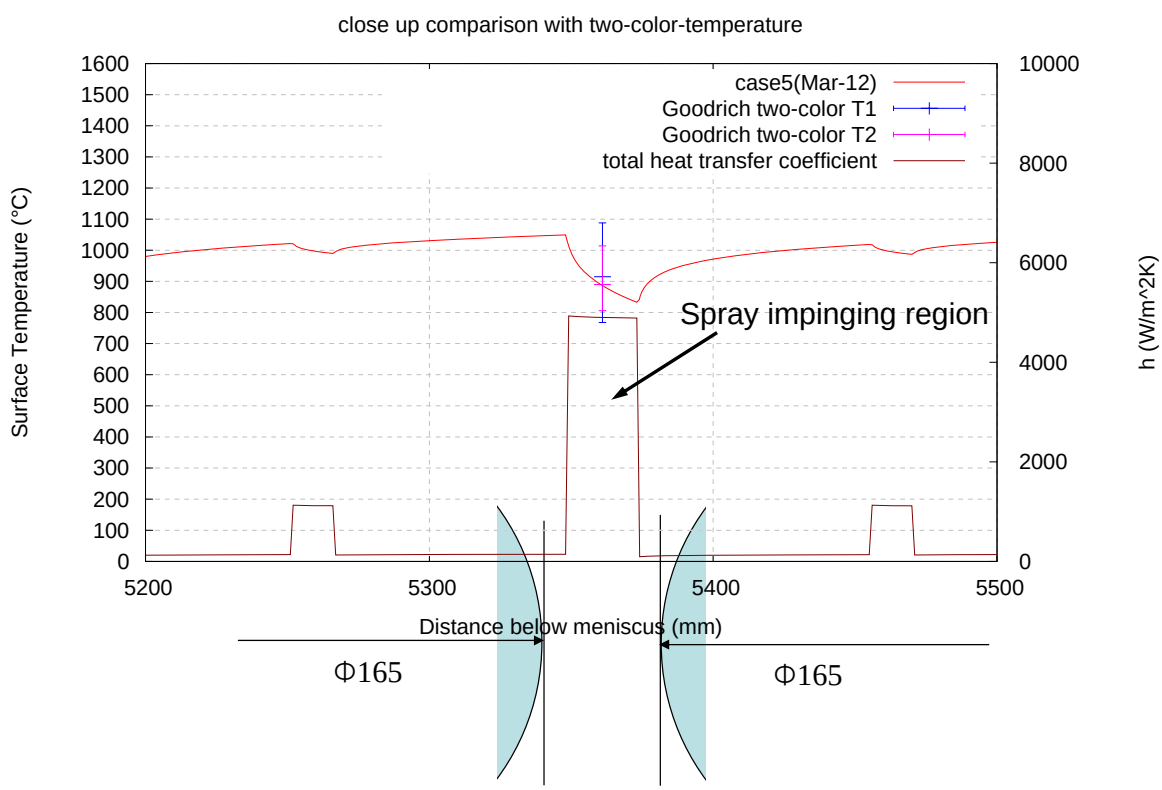
- case 4



Simulation and comparison

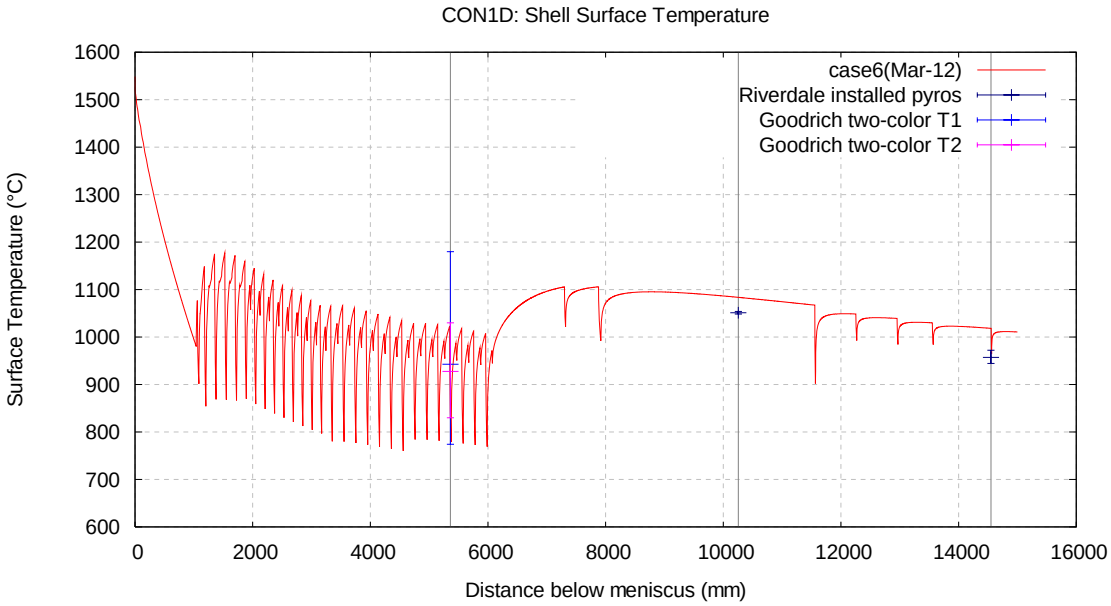
- case 5

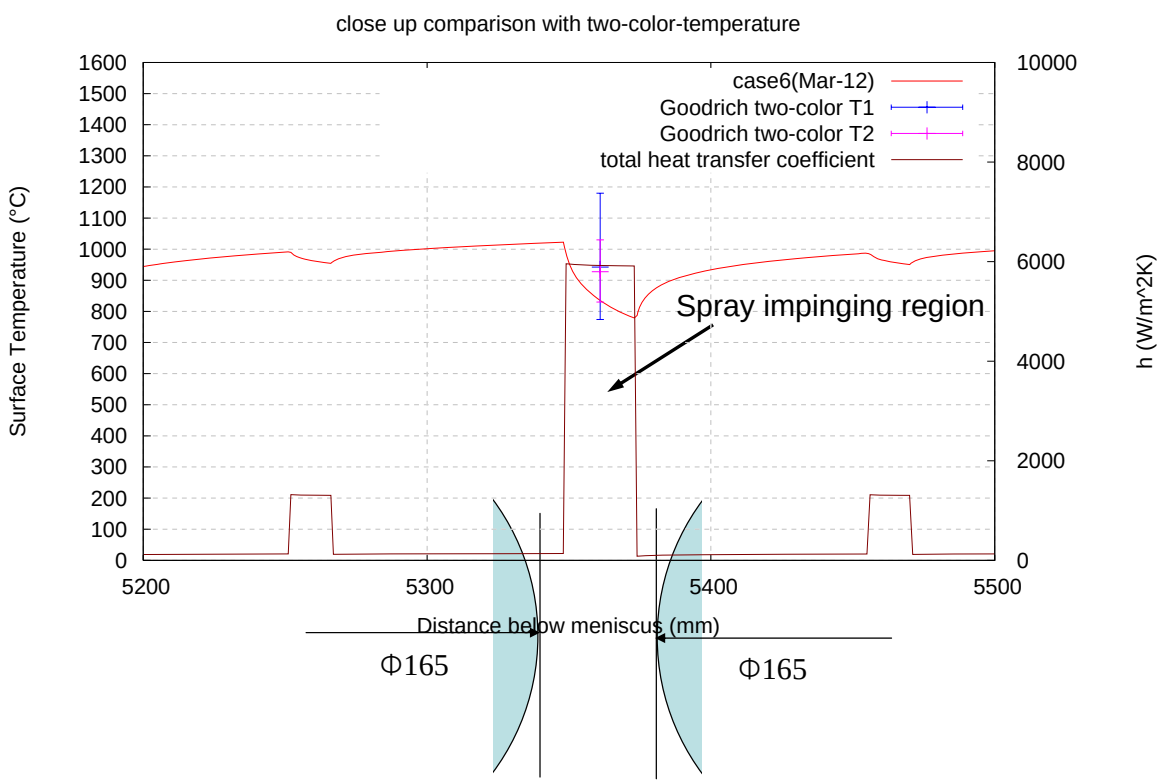




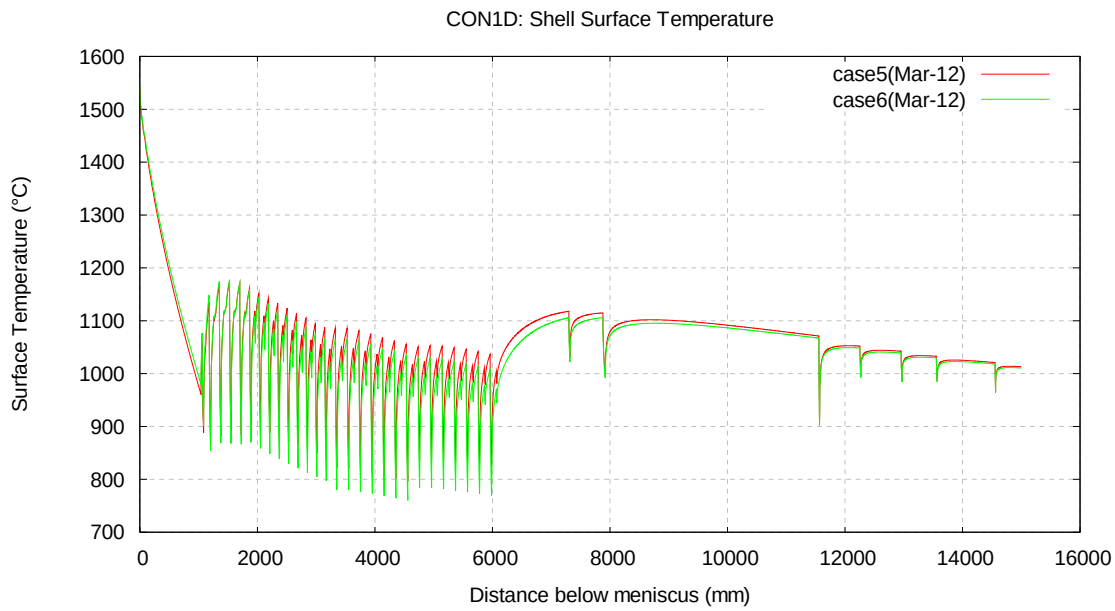
Simulation and comparison

- case 6





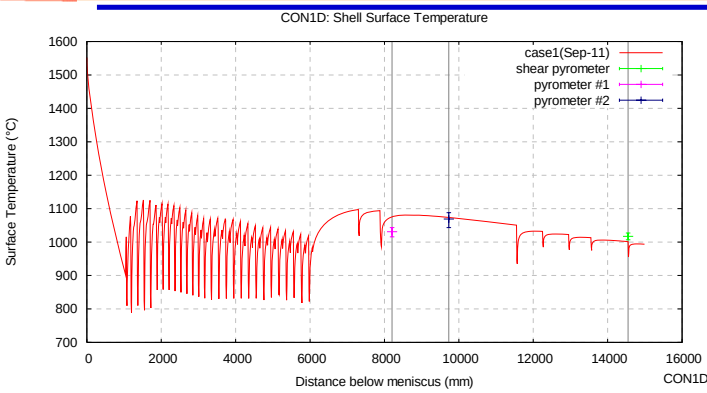
Comparison of case 5 and 6

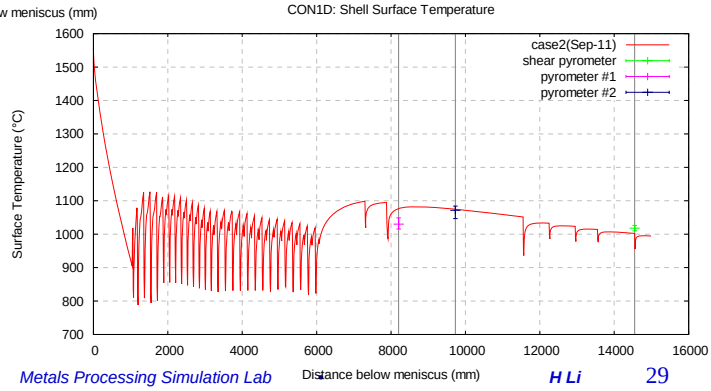


Simulation and comparison

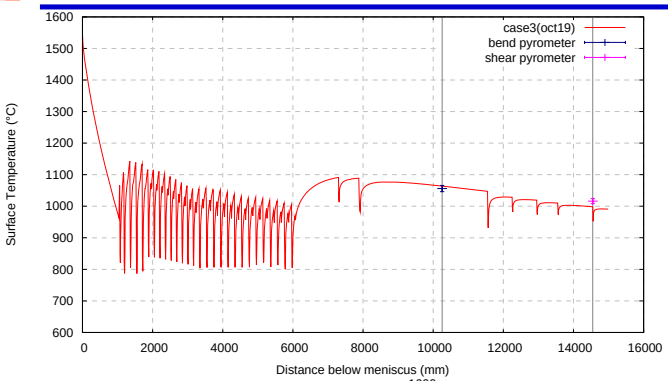
- The predictions are generally reasonable, being 1° C-43° C higher than pyrometers, (except for case3 at the shear position and case4).
- Increasing water flow rate (by ~25%) from case 5 to case 6 caused an increase in measured strand temperature (of 30° C in the strand, 13° C at the bend, and 3° C at the shear) Not expected in the model. The model predicted decreases of 50° C, 5° C, and 3° C.
- Reasons: a gas / water film barrier that decreased heat extraction with increasing water flow. Heat extracted by different rolls might vary with casting conditions such as water flow rate.
- Further investigation of accuracy of pyrometer measurements is also recommended.

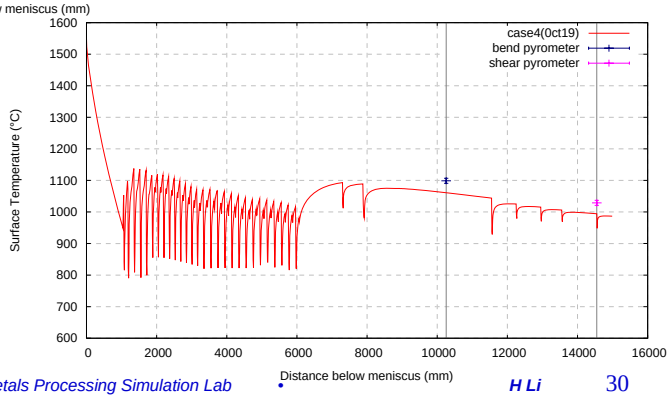
Consider Leidenfrost for Riverdale case 1~2



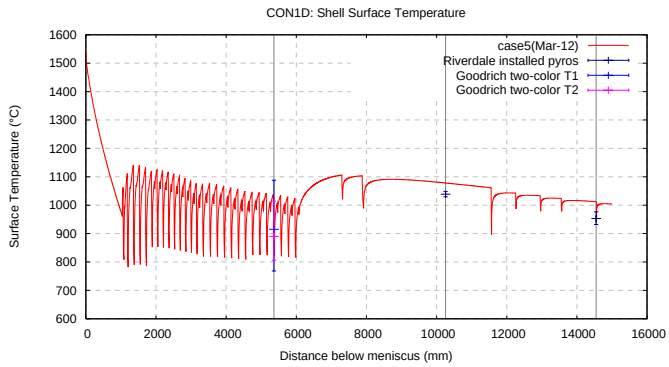


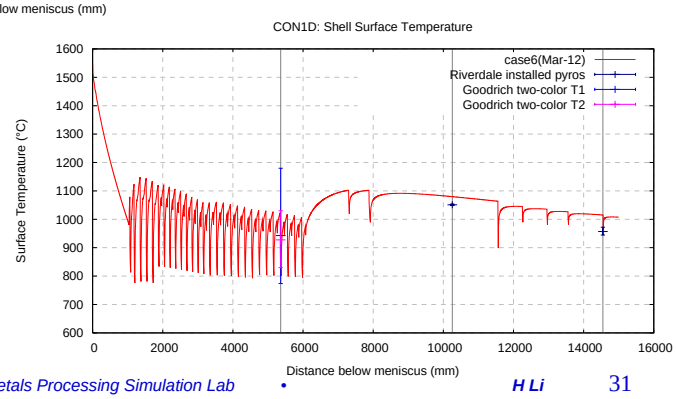
Consider Leidenfrost for Riverdale case 3~4



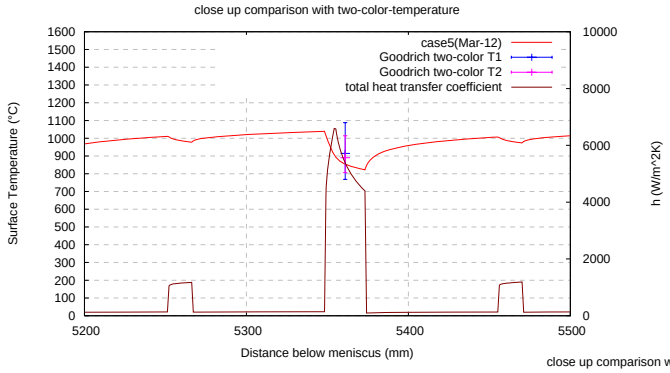


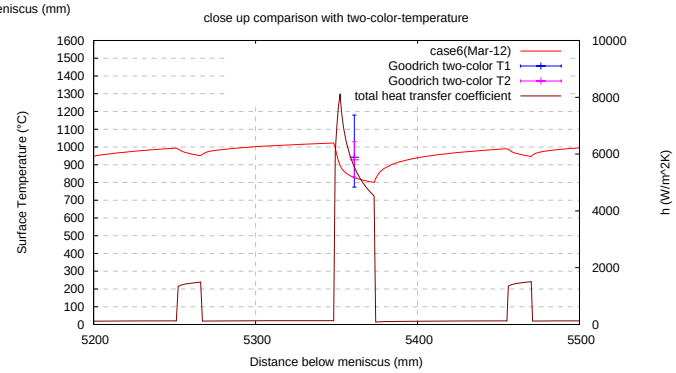
Consider Leidenfrost for Riverdale case 5~6



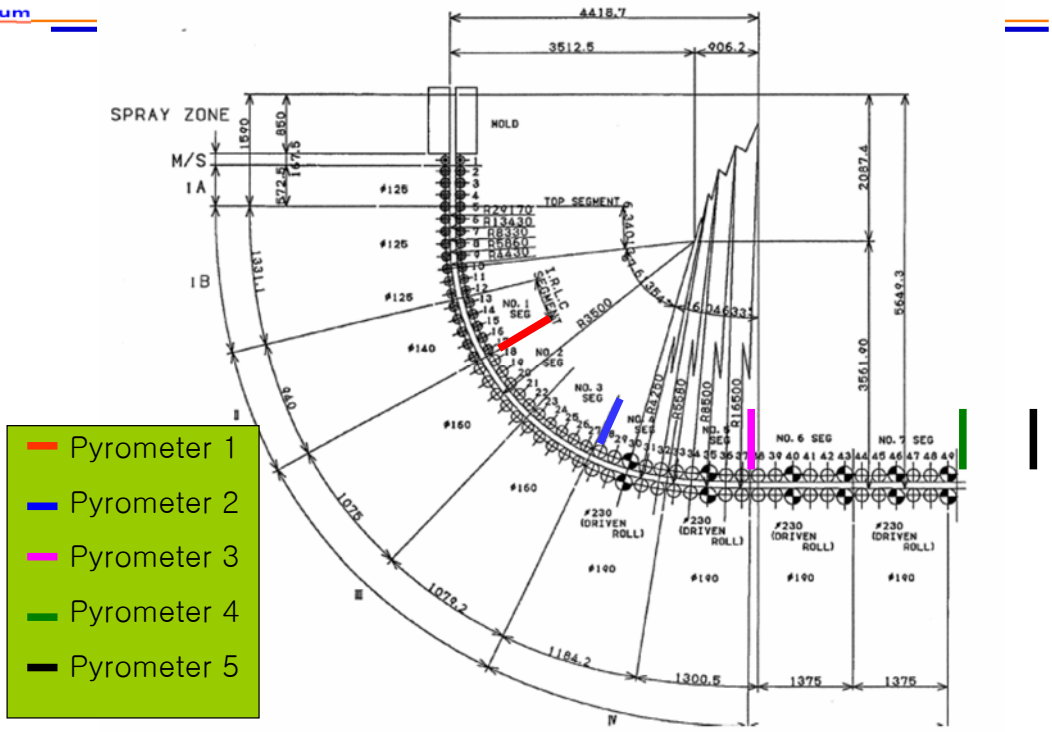


Consider Leidenfrost for Riverdale case 5~6





Pyrometer locations at Nucor



Pyrometer locations at Nucor

Model Name and Number	Modline® 5, 5R-141000, 4M5#25579
Length	1346 mm
Focus spot size	15.5 mm
Location of Pyrometer 1 from meniscus	3866.1 mm
Location of Pyrometer 2 from meniscus	6015.3 mm
Location of Pyrometer 3 from meniscus	8380 mm
Location of Pyrometer 4 from meniscus	11385 mm
Location of Pyrometer 5 from meniscus	13970 mm

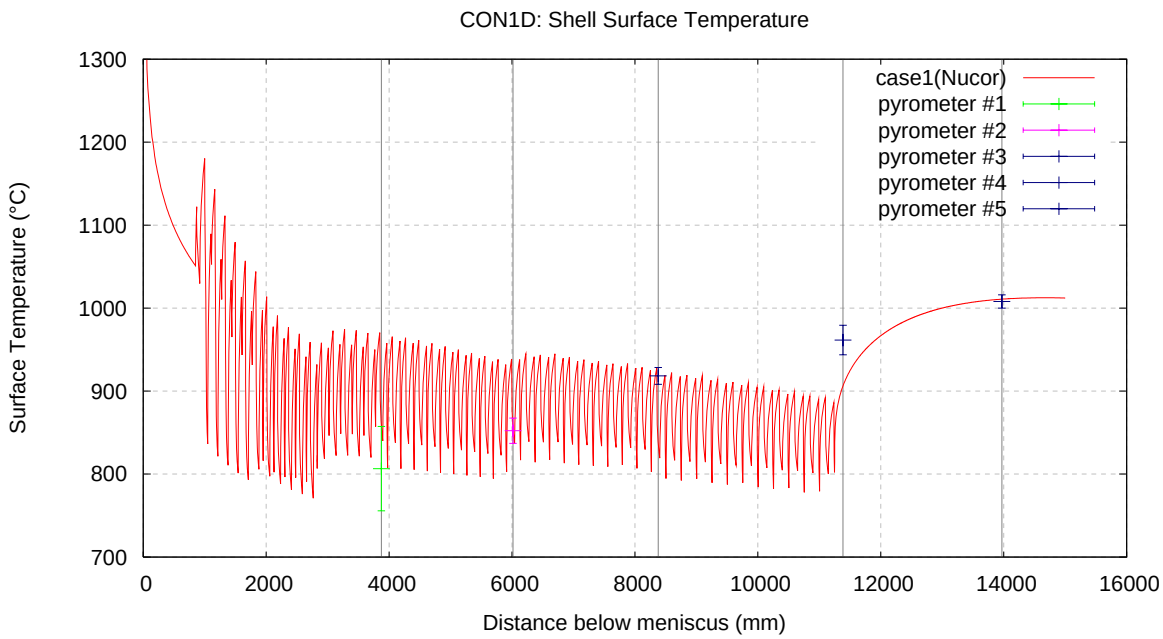
Experiments at Nucor

Case Number	Time	Steady/ Transient
1	01/13/06- 0950-1010	Steady
2	01/13/06- 1535-1610	Steady
3	01/16/06- 0945-1012	Steady
4	01/13/06 1610-1640	Transient

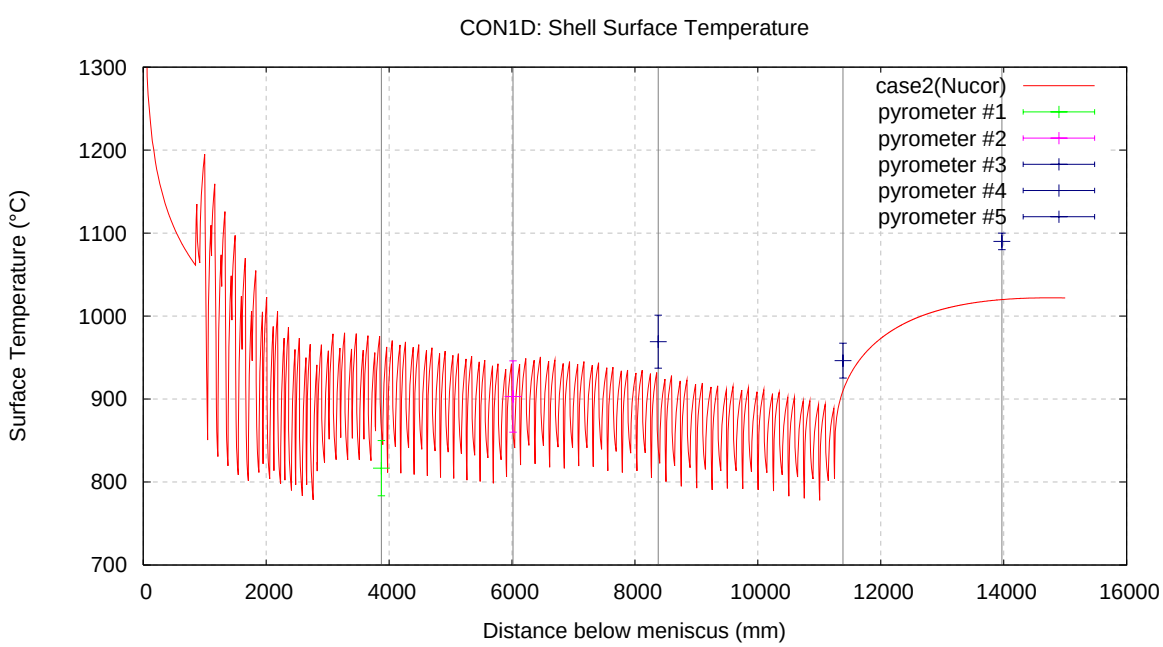
Casting conditions for Nucor case 1~3

Parameter	case1	case2	case3
Time of Experiment	9:50-10:10 Jan13, 2006	15:35-16:10 Jan13, 2006	9:45-10:12 Jan13, 2006
Casting Speed	3.44 m/min	3.61 m/min	3.03 m/min
Spray Pattern No.	2	4	1
Pouring Temperature	1542.2 ^{o}C	1547.8 ^{o}C	1556.9 ^{o}C
Caster	North	South	North
Composition (%)	C 0.247, Mn 1.09, S 0.0019, Al 0.039, Ca 0.0018, Si 0.175, P 0.014, Cu 0.087, N (leco) 0.0076		

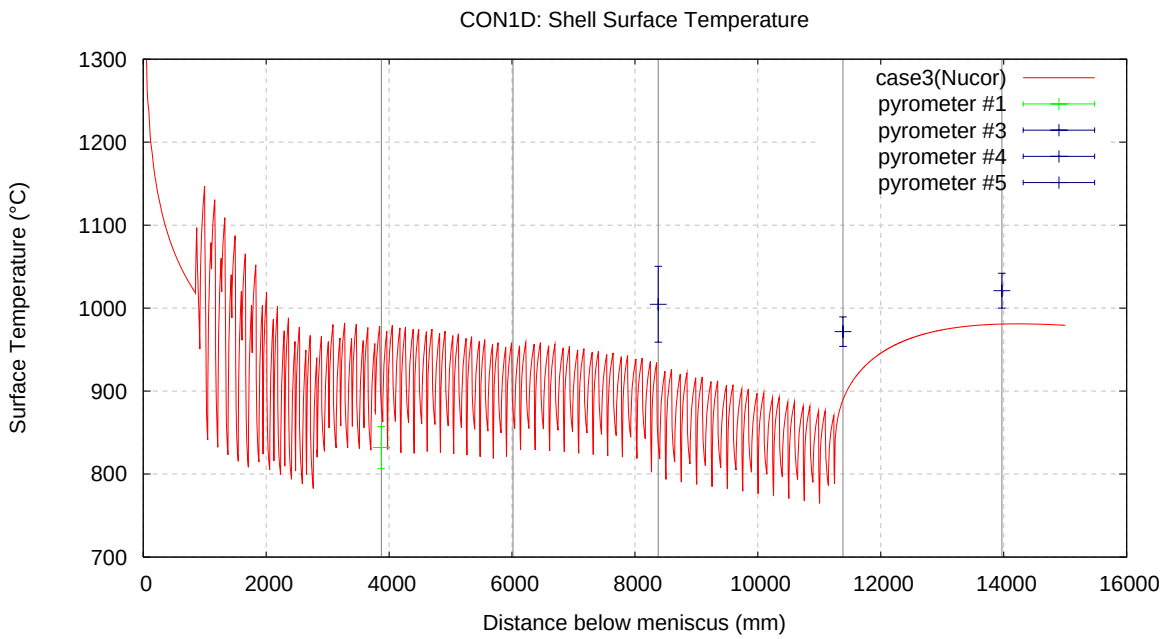
Consider Leidenfrost for Nucor case 1



Consider Leidenfrost for Nucor case 2



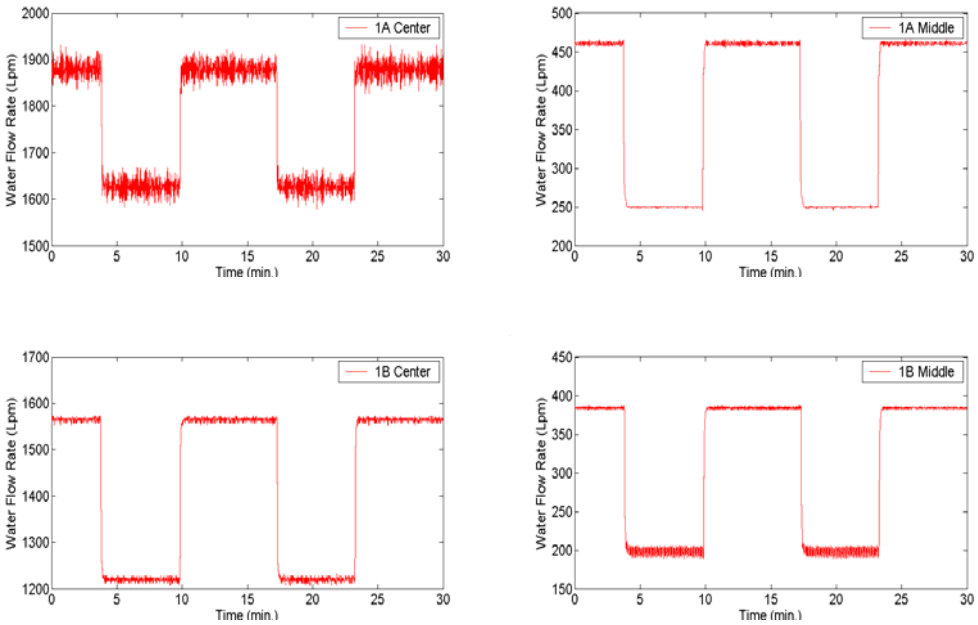
Consider Leidenfrost for Nucor case 3



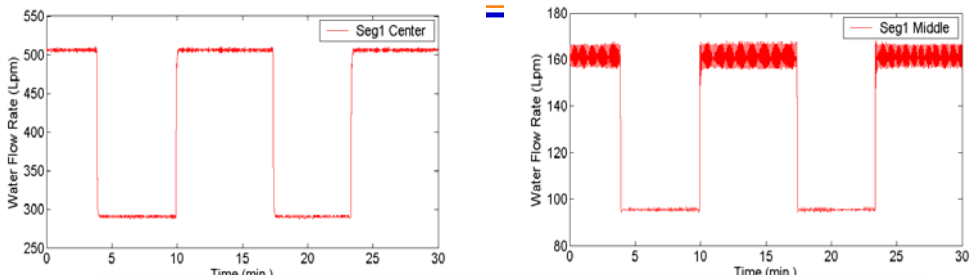
Transient case 4 at Nucor

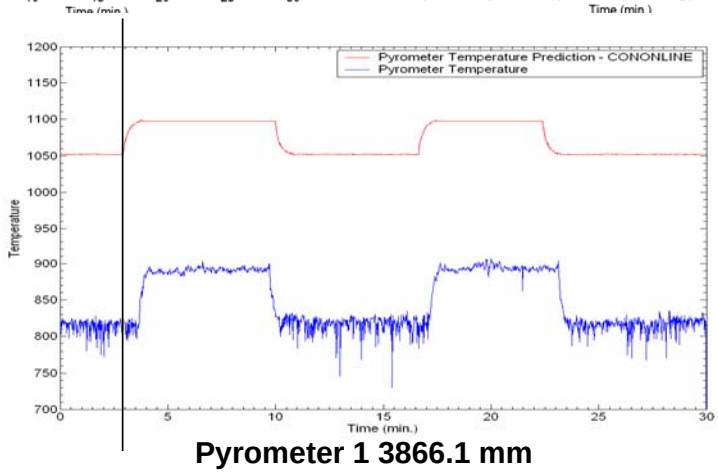
Parameter	Case 4
Time of Experiment	Jan. 13, 1610-1640 hrs.
Casting Speed	142.1 ipm (3.61 m/min) (0.06 m/s)
Spray Pattern No.	4 to 7
Composition of Elements (%)	C 0.247, Mn 1.09, S 0.0019, Al 0.039, Ca 0.0018, Si 0.175, P 0.014, Cu 0.087, N (leco) 0.0076
Caster	South
Pouring Temperature	1547.777 °C

Case 4 Spray Pattern Change



Case 4 Spray Pattern Change





Pyrometer 1 3866.1 mm

Conclusions

- CON1D model with Leidenfrost effect matches well with both Riverdale and Nucor caster measurements
- Transient behavior seems to be modeled reasonably

Ongoing work

- Further calibration
  - use better h-multipliers for incorporating Leidenfrost effect
  - change flat top heat transfer profile to wedge top profile
- Study transient cases with spray pattern and casting speed variation

Acknowledgements

- Continuous Casting Consortium Members (Nucor, Postech, LWB Refractories, Algoma, Corus, Labein, Mittal Riverdale, Baosteel, Steel Dynamics)
- National Science Foundation
  - GOALI DMI 05-00453 (Online)
- Other Graduate students, especially K. Zheng, B. Petrus