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Online Control of Spray Cooling Using CON1D

Software Sensor Development

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Project Description

- Problems
  - Temperature variations during cooling cause quality problems, e.g. cracks, especially under transient conditions
  - Desire to maximize casting speed, while maintaining quality and safe metallurgical length
- Incentive
  - Improving spray cooling control to achieve even 1% reduction in yield loss would save about $100 million each year.

Project Description

- Current control approaches
  - 1) Manual setting of water flow rates, which is difficult when casting speeds are high and response times must be short
  - 2) Setting water flow rates proportional to casting speed, which results in non-optimal cooling when transient conditions are encountered

Project Description

- Feedback Control
  - Conventional feedback control is difficult to implement successfully due to unreliability of temperature sensors.
  - Recent model-based predictive control systems do not accurately predict solidification in the mold, which is quite important
  - Desirable to seek an improved method to obtain feedback for more reliable control

Project Description

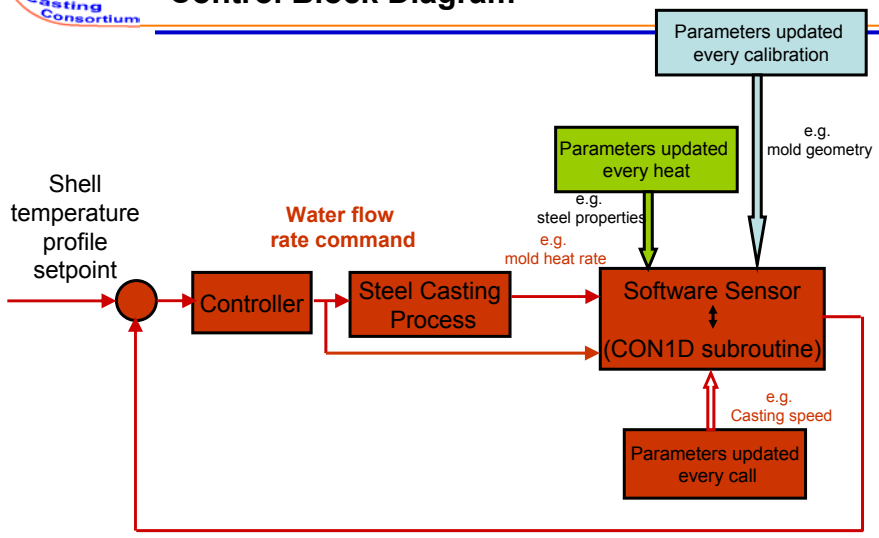
- CON1D is a fast, accurate and robust modeling tool to predict temperature and other related phenomena in a continuous thin slab caster.

- Solution
  - Develop a “software sensor” based on CON1D to predict temperature profile for feedback.

Project Description

- Objectives
  - To predict the heat transfer phenomena in a thin-slab continuous caster important to spray-cooling cracks
  - To create a fast and accurate computational tool to capture the above knowledge
  - To develop optimal spray cooling control algorithms
  - To integrate the computational tool and the control algorithms into an online control system for spray cooling in operating slab casters

Control Block Diagram



#1 Parameters to update every call

```
//CASTING CONDITION:
          1      Number of time-cast speed data points
                 (If=1, constant casting speed)
                 Next 2 lines contain time(s) and vc(m/min) data points
     0      200      210
     3.5    3.5      4.5
   1560.000       Pour temperature (C)
   ... ...
//SPRAY ZONE VARIABLES:
• 7      Number of zones
• No.  zone      rol.          water          spray        contct
•      starts   #   rad.      flowrate    width  length    angle  …
•      (mm)         (m)     (l/min/row)   (m)    (m)       (Deg)
• 1    850.0    1   0.062     85.200     1.640  0.050     10.00
• 2    940.0    5   0.062     168.100    0.987  0.050     10.00
   ...  ...
```

#2 Parameters to update every heat

```
//SLAB GEOMETRY:
  90.00000      Slab thickness (mm)
  1396.000      Slab width (mm)
  950.0000      Total mold length (mm)
  35.00000      WF Mold thickness with water channel (mm),(outer rad.,top)
  35.00000      WF Mold thickness with water channel (mm),(inner rad.,top)
    ... ...


//STEEL PROPERTIES: (Plain medium Carbon Steel)
0.0600 1.1500 0.0020 0.0100 0.1880    %C ,%Mn,%S ,%P ,%Si
0.0400 0.0400 0.1200 0.0100 0.0020    %Cr,%Ni,%Cu,%Mo,%Ti
0.0200 0.0010 0.0080 0.0350 0.0000    %Al,%V ,%N ,%Nb,%W
0.0000                        %Co,(additional components)
    ... ...
```

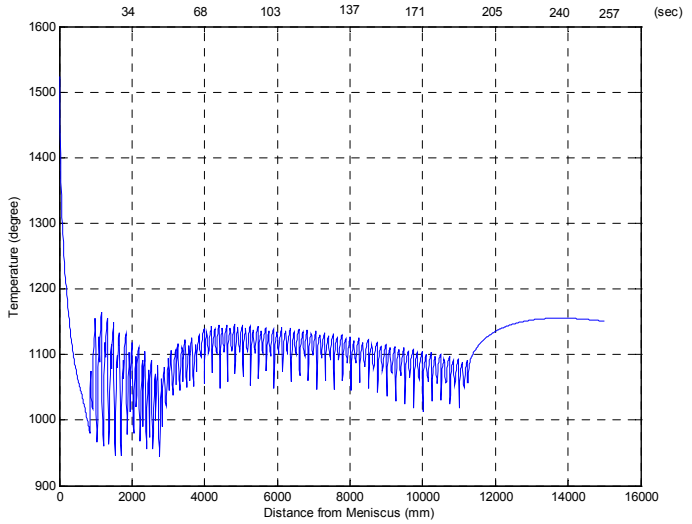

#3 Parameters to update when model is calibrated

```
 //SIMULATION PARAMETERS:
3.0E-02              Time increment (s)
      90     Number of slab sections
 ... ...
 //MOLD FLUX PROPERTIES:
 35.40 26.60  3.60  8.80  0.50    %CaO,%SiO2,%MgO,%Na2O,%K2O
 ... ...
//INTERFACE HEAT TRANSFER VARIABLES:
  0.5000000       Mold surface emissivity(-)
 ... ...
//MOLD WATER PROPERTIES:
 -1.000000       heat transfer coefficient(W/m^2K)
 ... ...
 //MOLD GEOMETRY:
•   20.00000      20.00000     Cooling water channel depth(mm)(WF,NF)
•    5.000000      5.000000     Cooling water channel width(mm)(WF,NF)
 ... ...
 //MOLD THERMOCOUPLES:
 ... ...
```

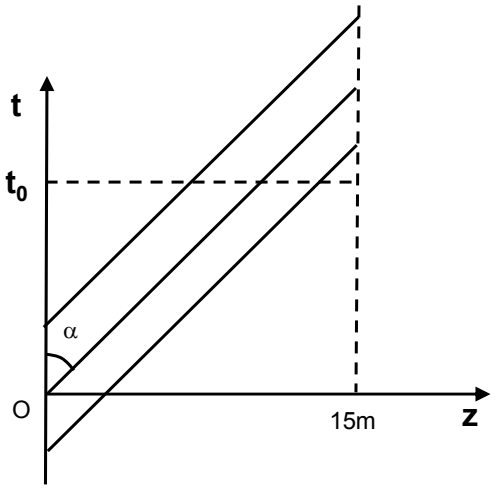
Software Sensor

- What we have: CON1D
  - CON1D is a fast, accurate and robust tool to predict temperature and other related phenomena in a continuous slab caster.
  - However, it predicts the temperature and other phenomena for only one slice at a time.

Typical CON1D result (constant speed = 3.5 m/min)

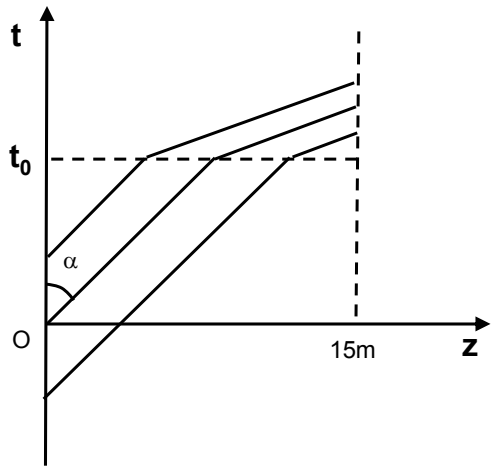


CON1D: constant speed



CON1D: varying speed

Need to model many slices to obtain the complete profile



Software Sensor

- What we need: the temperature profile along the whole caster updated every time increment, e.g. 1 sec
- It is desired ideally to simulate all the peak and dip locations.
- However, it exceeds the current computing capability (based on a PC)

Software Sensor

- Considering time constraint: a typical case
  - the simulation time step = 3e-2 sec, Casting speed = 3.7 m/min, 15/3.7=243 secs
  - It takes about 4 sec for single slice simulation.
  - Obtaining one second slice history requires 4/243 sec in real time.
  - Then we can do at most 243/4 ≈ 60 single slice simulation simultaneously.
  - The minimum interval between slices is 243/60 ≈ 4, which is just the time required for a single slice simulation.

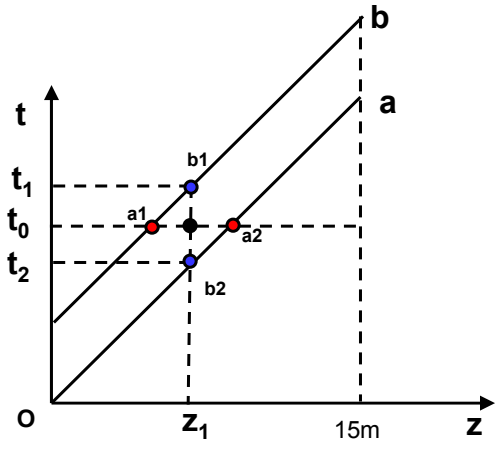
Software Sensor

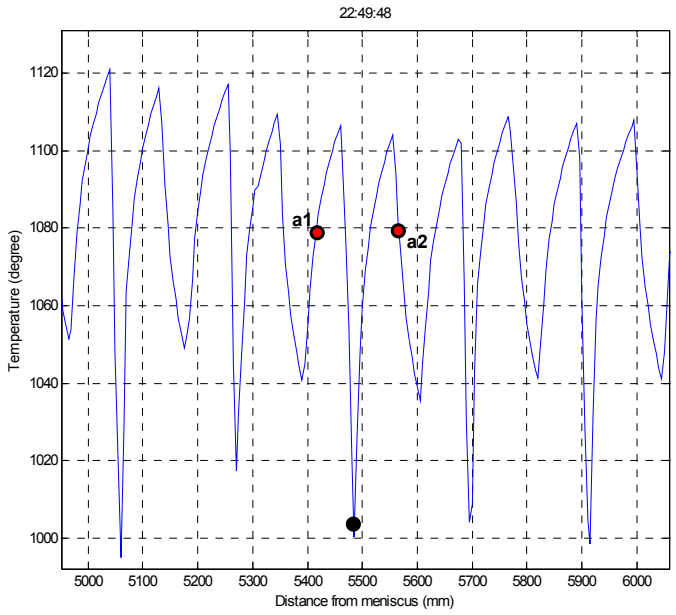
- The maximum number of slices in simulation is 60, but there are more than 180 peak and dip locations.
- Moreover, there is no guarantee that all slices only arrive at peak and dip locations at every second.

Software Sensor

- An approximation of the temperature profile can be obtained by spatial sampling and interpolating with a finite number of single slice simulation.
- Difficulty due to the oscillatory nature of the temperature profile

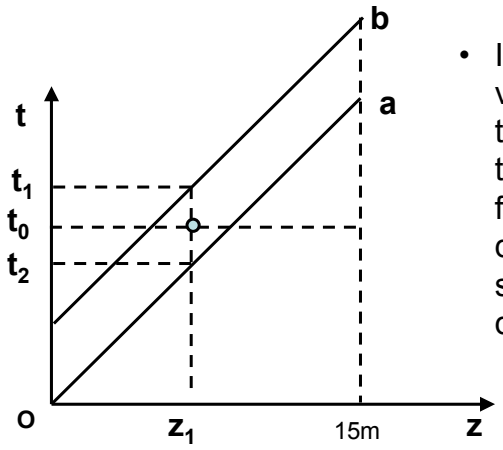
- Care must be taken in interpolation of the data between these slices due to the varying nature of the temperature profile.
- Horizontal interpolation is not as good as vertical interpolation.





- 2 schemes to handle the difficulty:
  - Predictive interpolation
  - Zero-order-hold

Predictive interpolation

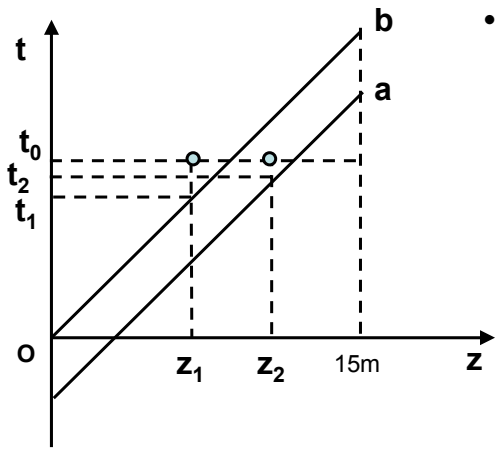


- Interpolate vertically using temperature at the same location from slice a (past data) and from slice b (future data)

Predictive interpolation

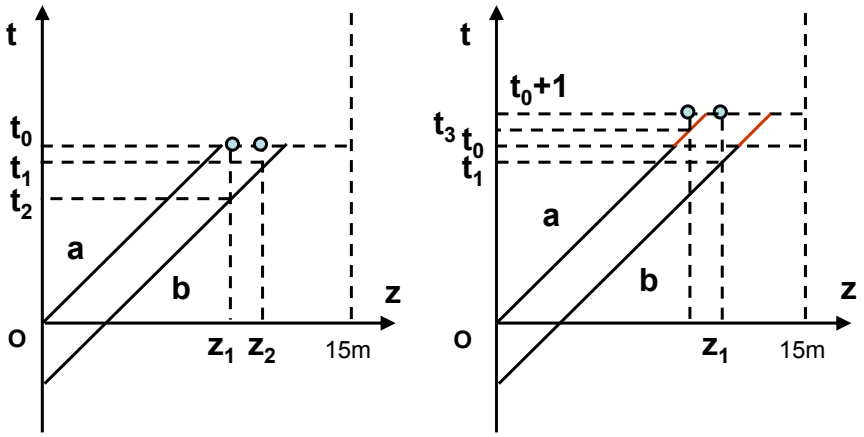
- Advantages
  - More accurate: first order accuracy, i.e. the interpolation is accurate when the change of temperature profile with time is linear.
- Disadvantages
  - Non-causal: it requires future information, e.g. casting speed, water spray rate.
- Suitable for offline simulation

Zero-order-hold interpolation



- Using temperature at the same location from slice a and b respectively

Exploiting the restart feature of con1d



Zero-order-hold interpolation

- Advantages
  - Causal: does not use future data, can be used for online temperature prediction.
- Disadvantages
  - Less accurate than prediction interpolation: zero order accuracy at non-simulated location, i.e. no error only when the temperature profile does not change with time.
- Chosen for the scheme in software sensor development. Approximation error can be reduced by increasing the number of slices in simulation at the cost of increasing computational load.

- Parameters to choose:
  - Time interval between slices
    - smaller, then more accurate, but computational load increased, minimum 4 secs.
  - Simulation time step
    - Same
  - Currently used
    - Dt=3x10-2 sec, slice interval = 5 secs

Demonstration

- Zero-order-hold version real time demonstration

Software sensor output

– Temperature profile prediction every second
  - test20050524225248.sna
  - test20050524225249.sna…

Distance (mm)	inner radius surf. Temp. (degree)	Outer radius surf. Temp. (degree)
0.0	1522.57	1522.57
5.0	1517.62	1517.62
10.0	1512.66	1512.66
15.0	1482.96	1482.96
20.0	1446.28	1446.28
25.0	1417.49	1417.49
30.0	1389.29	1389.29
… …		

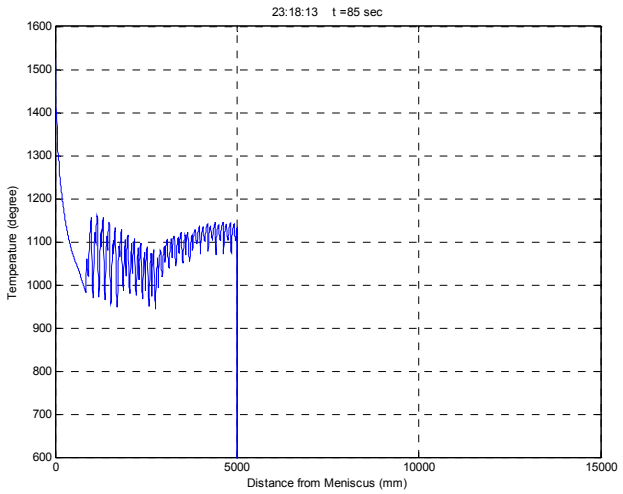
– slice temperature history and related data for single slice simulation of each slice every 5 seconds
  - test20050524225248.sht
  - test20050524225253.sht

Distance (mm)	Time (sec)	inner radius surf. Temp. (degree)	Outer radius surf. Temp. (degree)
0.0	0.00	1522.6	1522.6
11.1	0.18	1511.6	1511.6
20.4	0.33	1443.7	1443.7
31.5	0.51	1381.1	1381.1
40.7	0.66	1378.6	1378.6
51.8	0.84	1374.8	1374.8
…	…		

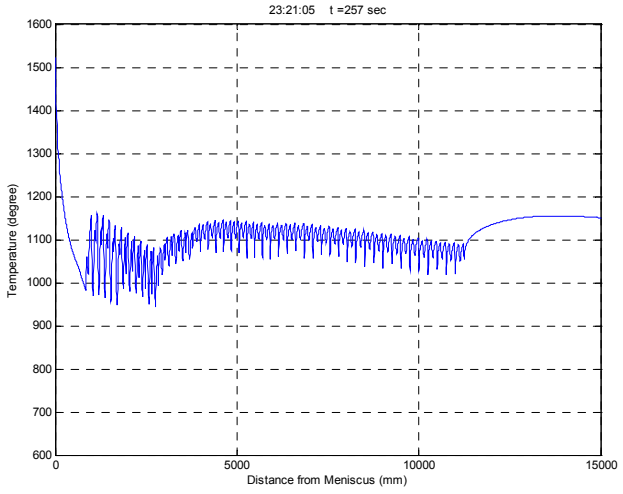
Software sensor output

- Two cases:
  – Case 1: water spray rate step response: water spray rate increases 4 times at t = 300 secs

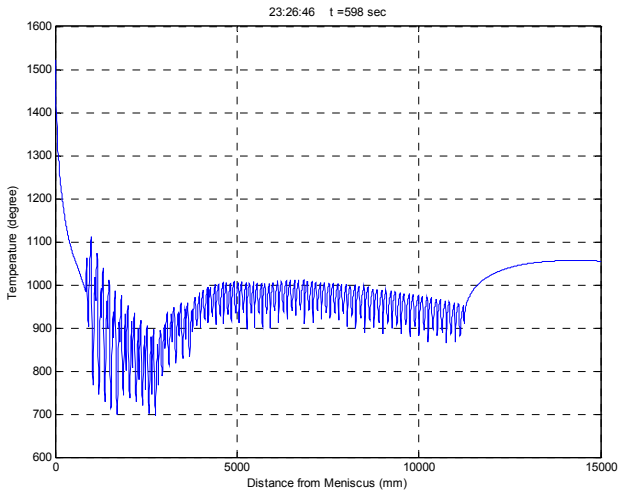
Software sensor output

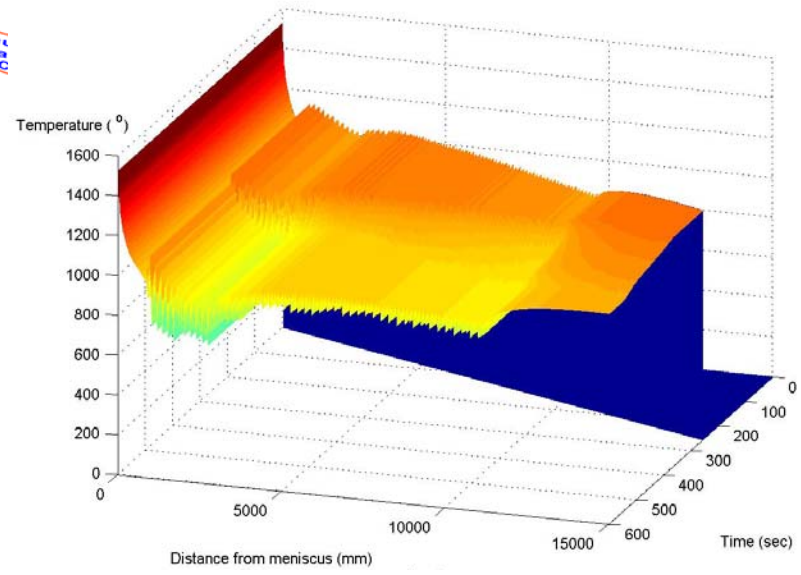


Software sensor output



Software sensor output

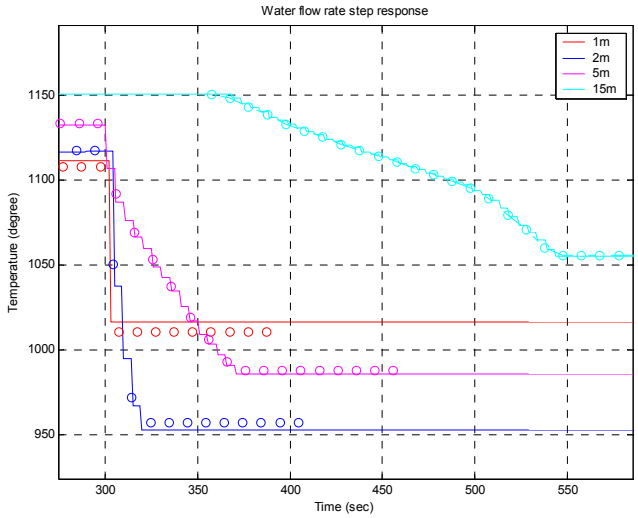




Validation

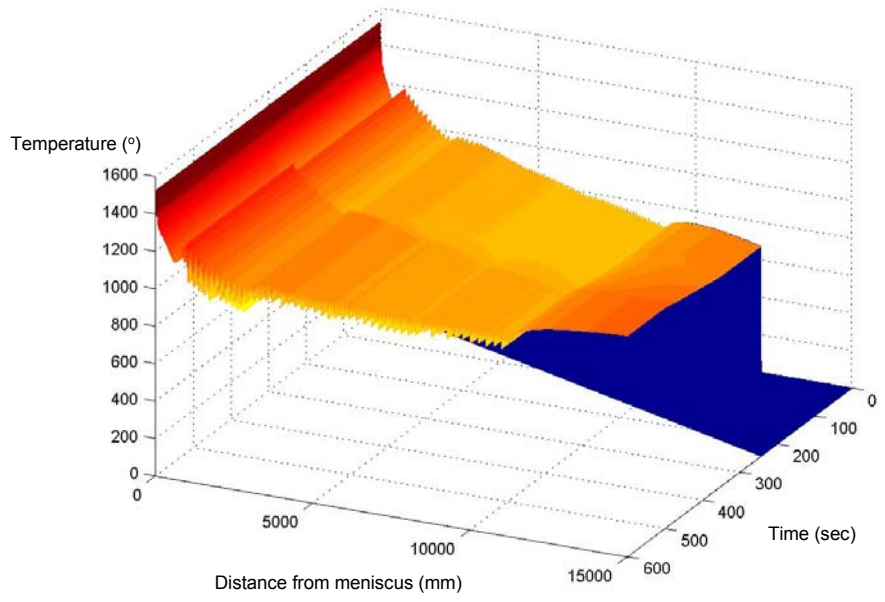
Solid: software sensor result;

Circles: result from Ya



- Phenomena
  - Response at 15m is delayed by 64 secs
  - It takes less time for slices that are closer to the meniscus to reach steady state. The times are 3, 20, 71 and 243 secs, respectively, for 1, 2, 5 and 15 meter responses.
- Explanation
  - The 64 sec is the time it takes for a slice to travel from the end of spray zone to 15m (at 3.5m/min).
  - The steady state times are the times it takes for slices to travel from the beginning of the spray zone to 1, 2, 5 and 15 meters, respectively.

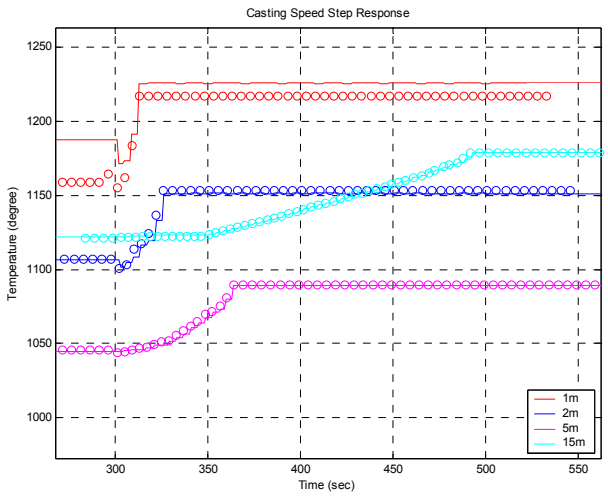
- Impact
  - Optimal water spray rates should vary with location instead of just proportional to casting speeds.
- Case 2: Casting speed step response
  - Casting speed starts at 3.7m/min and step to 4.7 m/min at t = 300 secs.



Casting speed step response

Solid: software sensor result;

Circles: result from Ya



- Phenomena
  - Response at 15m is delayed by 48 secs
  - It takes less time for slices that are closer to the meniscus to reach steady state. The times are 13, 26, 64 and 191 secs, respectively, for 1, 2, 5 and 15 meter responses.
- Explanation
  - The 48 sec is the time it takes for a slice to travel from the end of spray zone to 15m (at 4.7m/min).
  - The steady state times are the times it takes for slices to travel from the meniscus to 1, 2, 5 and 15 meters, respectively.

- Impact
  - Optimal water spray rate should vary with location.

Conclusion

- Based on the one slice predictor Con1D, a software sensor is developed that predicts temperature and related phenomenon for the whole continuous casting process
- Besides being used as the online temperature predictor for spray cooling control, the software sensor developed can also be conveniently used to investigate other sophisticated phenomena such as the response of the steel casting process to water spray rate step change, etc.

Future work

- Improve Software Sensor
- Improve spray cooling CON1D model prediction with plant and lab experiments
- Develop control system
- Implement and test new Software Sensor and control system in the steel plant

Future work – software sensor improvement

- Using uneven slice distribution in the prediction
  - The importance of temperature variations are not evenly distributed. Thus, in the area where tighter temperature control is required, i.e. the area between the end of the mold and 1m behind, more slices should be used in prediction to gain more accurate prediction using less effort than if we increase the slice density uniformly.

Future work – software sensor improvement

- Variable slice interval
  - It takes a slice 243 secs to travel from the beginning of the mold till the end of the process at a casting speed of 3.7 m/min. And it takes double amount of time if the casting speed is half of that.
  - If the intervals between slices are the same for the above two speeds, then the slower one would require double number of slices in simulation, meaning double amount of time in current scheme.

Future work – software sensor improvement

  - If slice interval does not change with casting speed, low speed operation of the software sensor would impose a huge computational load.