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New features of CON1D: Version 9.6

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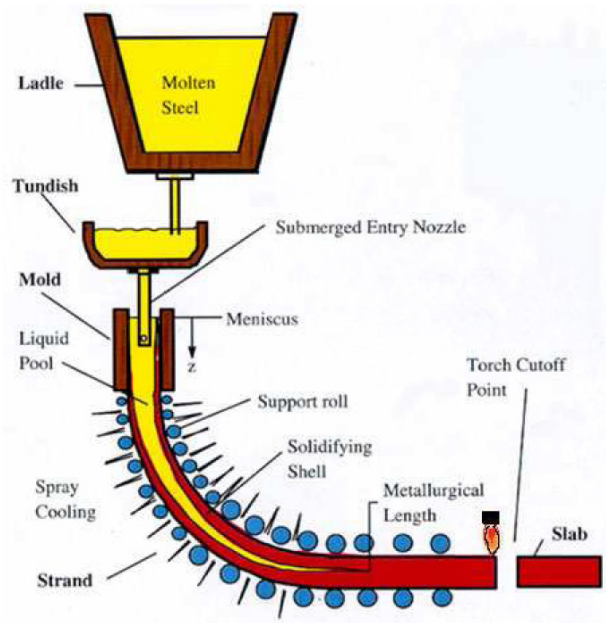
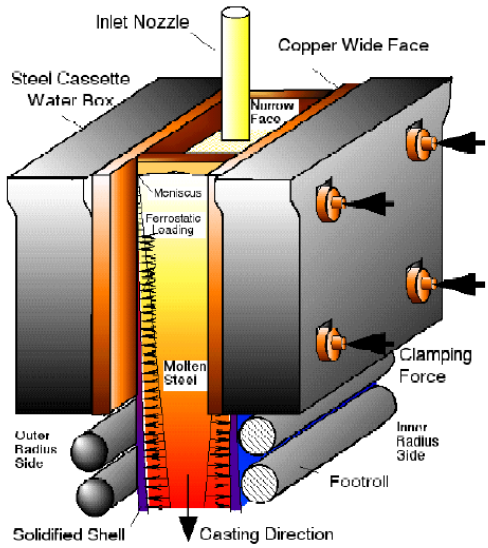
Acknowledgements

- Continuous Casting Consortium Members
  - Baosteel, Corus, Goodrich, Labein, LWB Refractories, Mittal, Nucor, Postech, Steel Dynamics, Ansys Inc.
- National Science Foundation
  - GOALI DMI 05-00453 (Online)
- Previous students developers of Con1d:
  - Bryant Ho, Guowei Li, Nick Youssef, Ya Meng,Ying Shang, David Stone
- Previous modeling work: Huan Li, A. Behera

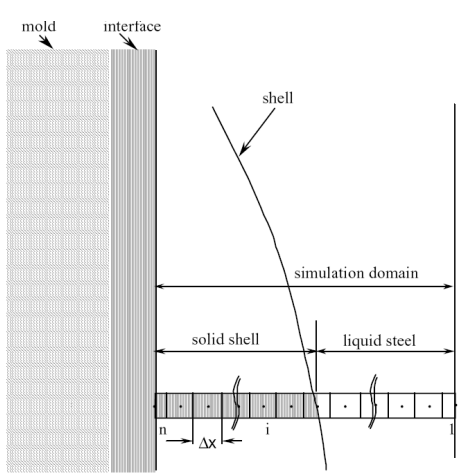
Continuous casting of steel

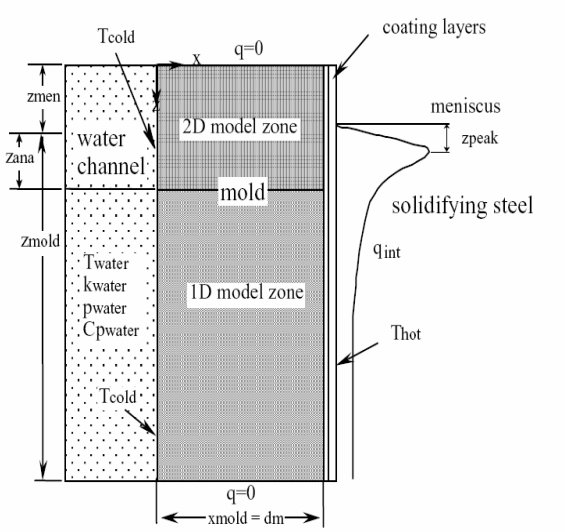




-ccc.mechse.uiuc.edu

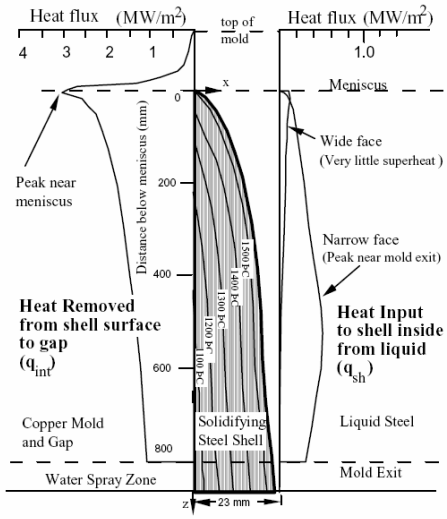
Review: Con1d simulation domain in the steel and mold





-Con1d9.6 user's manual

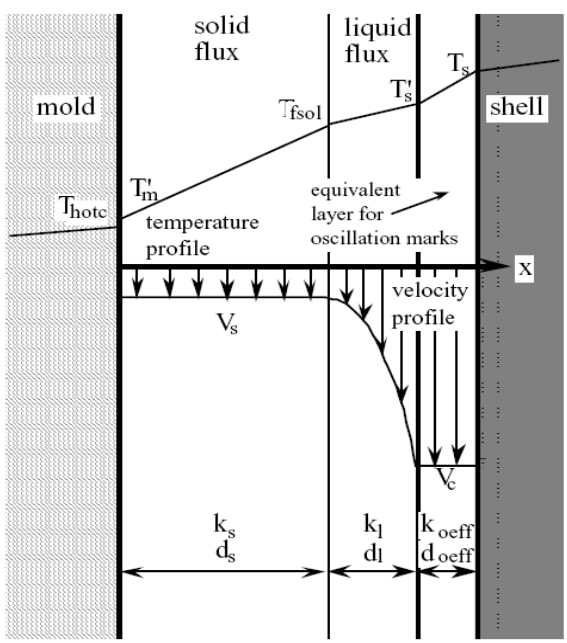
Review: Con1d heat flux in the mold



Model of solidifying steel shell showing typical isotherms and heat flux conditions

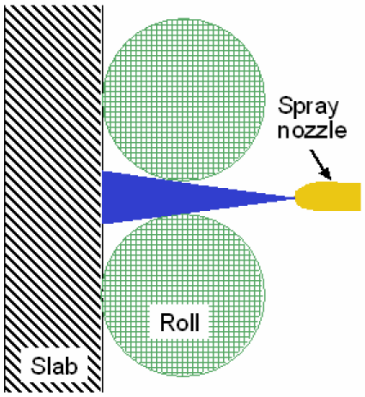
-Con1d9.6 user's manual

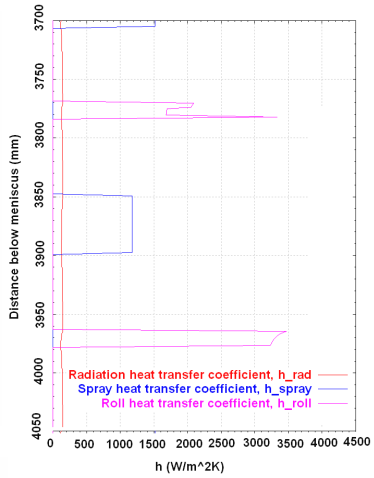
Review: Velocity and temperature profile assumed across interfacial gap

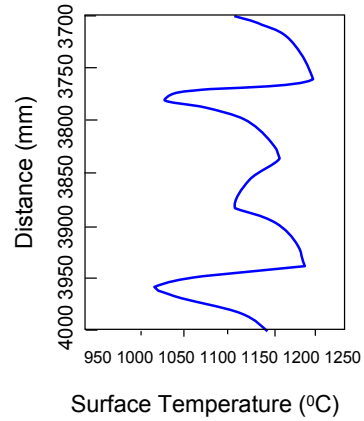


-Con1d9.6 user's manual

Review: Con1d heat transfer between rolls







$$h_{spray} = A \cdot Q_{water}^{c} \cdot \left(1 - b \cdot T_{spray}\right)$$ **---Nozaki's model**

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

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

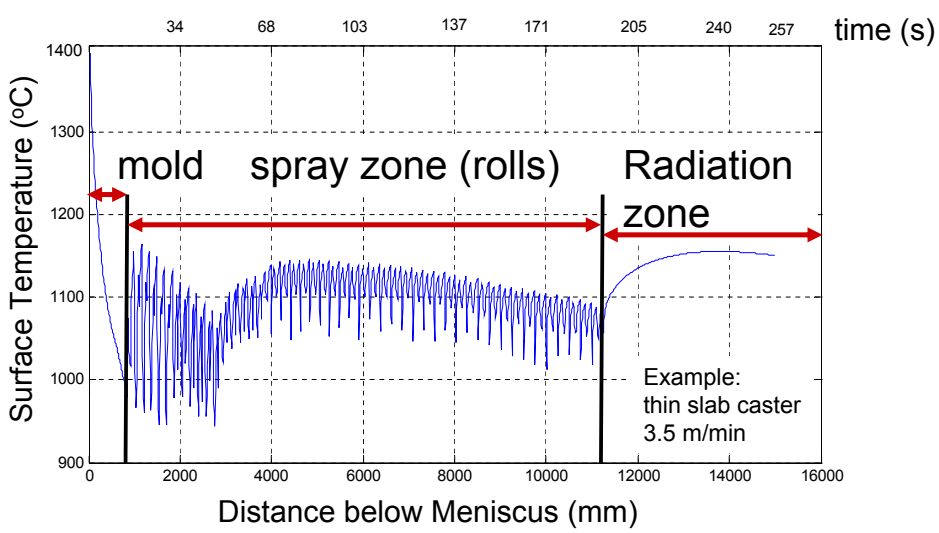
Q_{water} Water flux rate

T_{spray} Spraying water temperature

f_{roll} Fraction of heat extraction to roll

-A.Behera,2006,ccc report

Con1d predicts surface temperature down strand



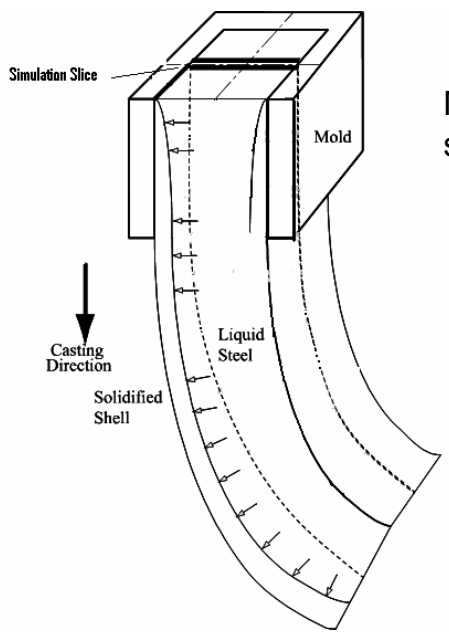
Note: reheating below mold; and after sprays variations caused by rolls (slab caster)

-A.Behera,2006,ccc report

New features for Con1d9.6

- Several minor bugs in Con1d8.0 are fixed in Con1d9.6.
- Two new options for defining interface (mold/shell) heat flux
  - enter average mold heat flux
  - enter mold cooling water temperature increase
- New simulation domain. (New domain)
- Spray zones heat transfer is assumed the same on both sides as the CON1D8 file. Changes should be made by the user to introduce differences in the CON1D9.6.
- New heat transfer coefficient profile. (Click here)
- Leidenfrost effect implemented. (Click here)
- Browsing the new example input file. (Click here)

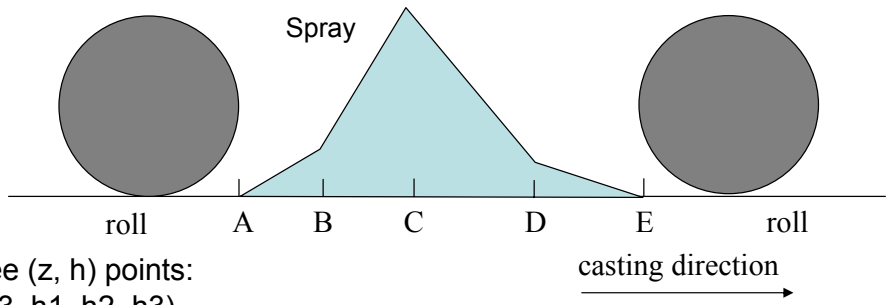
Simulation domain for Con1d9.6



Model both sides of caster at the same time (Inside and Outside Radius)

Go back

Spray-nozzle heat transfer coefficient can vary along caster (input as 4 piecewise linear line segments)



Input three (z, h) points:
(z1, z2, z3, h1, h2, h3)
z1=AB/AE, z2=AC/AE, z3=AD/AE\
The symmetry of profile is not required.

Nozaki correlation:

$$h_{\text{spray}} = A \cdot C \cdot \bar{W}^{n} \cdot (1 - bT)$$

- **A· C=0.3925, b=0.0075, n=0.55**
- **T is the cooling-water spray temperature**
- **W (L/m²s) is the average water flow rate in the spray zones.**
- **h_{spray} gives average heat transfer coefficient in the spray zone.**

Con1d8 just use h_{spary} in the spray zone.

h_A=0

h_B=h1*h_{spray}

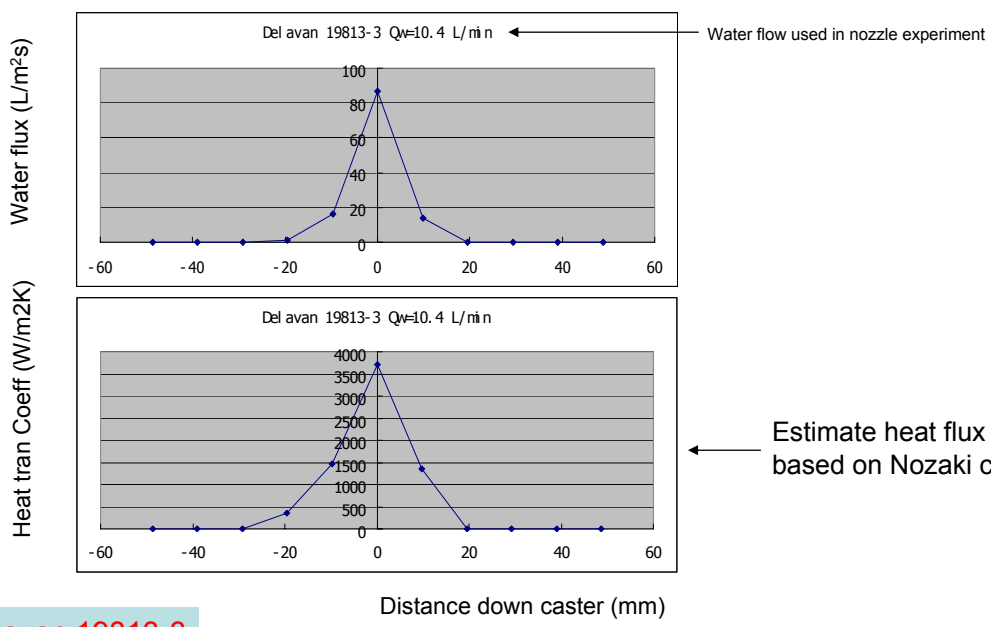
h_C=h2*h_{spray}

h_D=h3*h_{spray}

h_E=0

Example h profile

--from Vapalahti's 2006 ccc meeting report:
"Delavan Nozzle Characterization at CINVESTAV"



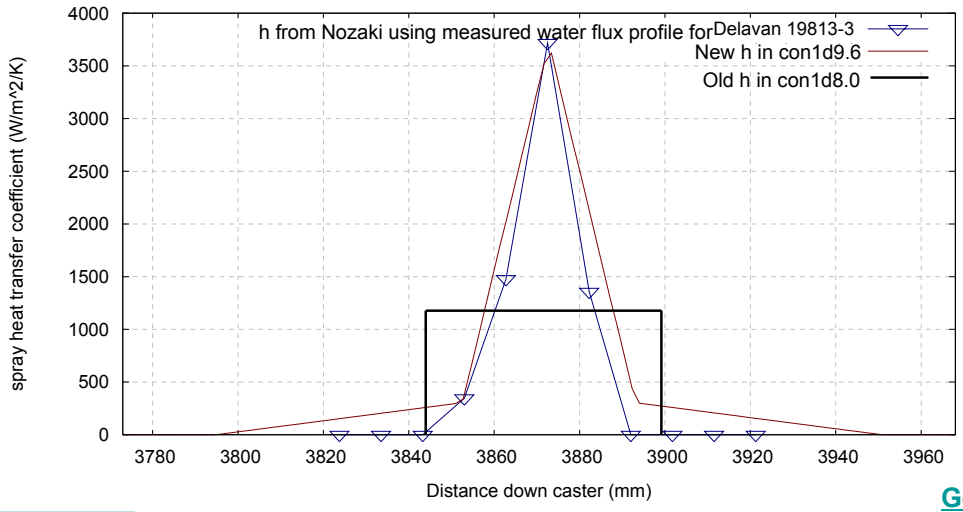
Delavan 19813-3

Compare h profiles

•New h profile in Con1d 9.6:

z1	z2	z3	h1	h2	h3
0.37	0.50	0.63	0.50	6.11	0.50

•The spray length is properly elongated due to the accumulation of water on the strand.



Go back

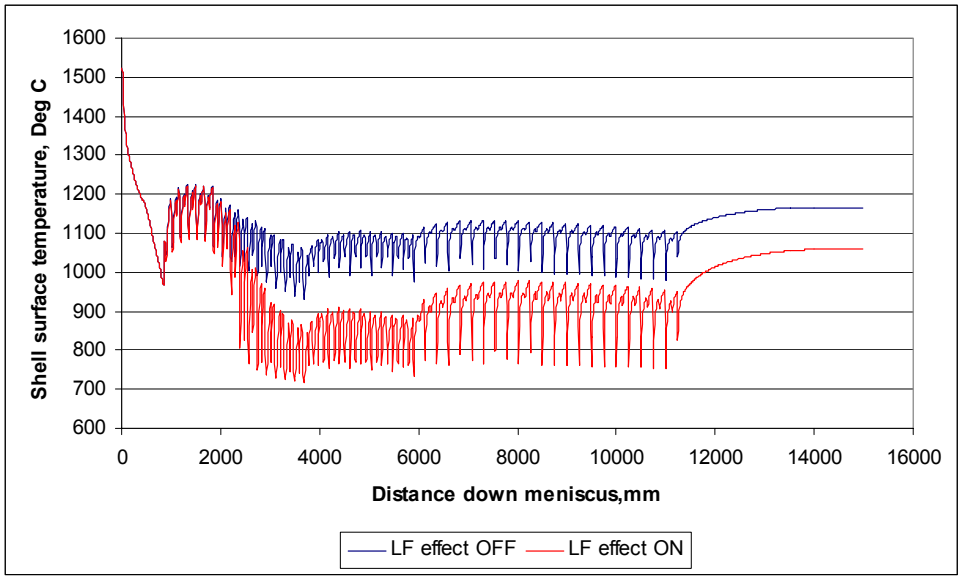
Delavan 19813-3

Leidenfrost effect (optional)

• To increase h to account for boiling heat transfer effect, a set of multipliers can be input to Con1d, such as follows:

h-multipliers	1.0	1.2	2.2	1.6	1.0
temperatures	700.	800	900.	1000	1050.

Leidenfrost effect on shell surface temperature prediction



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Con1d9.6 input file

```
CON1D-9.6 Slab Casting Heat Transfer Analysis
University of Illinois, Brian G. Thomas, 2008

Example Input Data (NU6-146)

#1 Parameters to update every call
//CASTING CONDITION:
      3        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. 300. 320.
3.70 3.70 4.70
  1553.000     Pour temperature (C)
  100.0000     Distance of meniscus from top of mold (mm)
  150.0000     Nozzle submergence depth (mm)

      0        New simulation or Restart (0=new; 1=restart)
  15000.00     Max. simulation length (must > z-distance)(mm)

      0        Calculate mold and interface (=0 flux casting, or =2 oil casting )
               or enter interface heat flux data starting at meniscus z=0 (=-1)
               or enter avg. mold flux (=-2), or enter cooling water temp. increase (=-3)
      9        Number of zmm and q data points (if above = -1)
               Next 2 lines contain zmm(mm) and q(kW/m2) data
   0.00   40.00   100.00   200.00   300.00   410.00   550.00   850.00   950.00
 5360.00  4000.00  3410.00  2600.00  2350.00  2340.00  2310.00  2000.00  2000.00
  2.4243   2.4243    Average mold heat flux (MW/m^2)(if above =-2)
 -9.8800  -9.8800    Mold cooling water temp. increase (Deg C)(if above =-3)
-1             Running mode (0=stop right now; -1=continue to run; positive integer ts
               = run the program for ts seconds.
```

Con1d9.6 input file (Cont…)

```
//SPRAY ZONE VARIABLES:
  8.700000   Minimum convection heat trans. coeff. (natural) (W/m^2K)
right side (inside radius):
  25.00000   Water and ambient temperature after spray zone(Deg C)
             spray zone condition:(heat tran.coeff.funct:h=A*C*W^n(1-bT))
             (Nozaki Model:A*C=0.3925,n=0.55,b=0.0075)
  1.570000     A(0=off)
 0.5500000     n
 7.4999998E-03  b
       11     Number of zones
No.  zone    rol.      water      spray      contct   frac.of  spray   conv   amb.
   starts   # rad.    flowrate   width  length  angle  q thr rol coeff   coeff  temp.   z1    z2    z3    h1    h2   h3
   (mm)     (m)      (l/min/row) (m)    (m)    (Deg)                    (W/m^2K) (C)
1   850.0   1 0.062   89.900    1.640  0.050  10.00  0.010    0.250   8.70   25.0  0.08  0.50  0.92  0.30  1.22  0.30
2   940.0   5 0.062   172.300   0.987  0.050  10.00  0.080    0.250   8.70   25.0  0.19  0.50  0.81  0.50  0.97  0.50
3  1767.0   6 0.062   107.800   0.987  0.050  10.00  0.220    0.250   8.70   25.0  0.14  0.50  0.86  0.70  1.36  0.70
4  2828.3   5 0.070   31.200    1.008  0.170  10.00  0.200    0.250   8.70   25.0  0.30  0.50  0.70  0.30  5.36  0.30
5  3773.6   1 0.080   11.000    1.620  0.176  10.00  0.360    0.250   8.70   25.0  0.37  0.50  0.63  0.50  6.11  0.50
6  3968.6   9 0.080   11.000    1.620  0.176  10.00  0.360    0.250   8.70   25.0  0.37  0.50  0.63  0.50  6.11  0.50
7  5903.6   1 0.095   15.200    1.680  0.204  10.00  0.360    0.250   8.70   25.0  0.34  0.50  0.66  0.02  0.92  0.02
8  6130.3   9 0.095   15.200    1.680  0.204  10.00  0.360    0.250   8.70   25.0  0.34  0.50  0.66  0.02  0.92  0.02
9  8260.0   1 0.095   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
10 8495.8  10 0.095   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
11 10995.8  1 0.115   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
   11246.0    End of last spray zone (mm)
       0      Consider Leidenfrost effect? (-1=yes;0=no)
       5      Number of points in the Leidenfrost effect curve (if above =-1)
              Next 2 lines contain Leidenfrost effect h-multipliers and temperatures
1.0   3.5   2.8   1.3   1
700. 800. 900. 1000. 1100.
```


Con1d9.6 input file (Cont…)

```
left side (outside radius):
  25.00000   Water and ambient temperature after spray zone(Deg C)
             spray zone condition:(heat tran.coeff.funct:h=A*C*W^n(1-bT))
             (Nozaki Model:A*C=0.3925,n=0.55,b=0.0075)
  1.570000     A(0=off)
 0.5500000     n
 7.4999998E-03  b
       11     Number of zones
No.  zone    rol.      water      spray      contct   frac.of  spray   conv   amb.
   starts   # rad.    flowrate   width  length  angle  q thr rol coeff   coeff  temp.   z1    z2    z3    h1    h2   h3
   (mm)     (m)      (l/min/row) (m)    (m)    (Deg)                    (W/m^2K) (C)
1   850.0   1 0.062   89.900    1.640  0.050  10.00  0.010    0.250   8.70   25.0  0.08  0.50  0.92  0.30  1.22  0.30
2   940.0   5 0.062   172.300   0.987  0.050  10.00  0.080    0.250   8.70   25.0  0.19  0.50  0.81  0.50  0.97  0.50
3  1767.0   6 0.062   107.800   0.987  0.050  10.00  0.220    0.250   8.70   25.0  0.14  0.50  0.86  0.70  1.36  0.70
4  2828.3   5 0.070   31.200    1.008  0.170  10.00  0.200    0.250   8.70   25.0  0.30  0.50  0.70  0.30  5.36  0.30
5  3773.6   1 0.080   11.000    1.620  0.176  10.00  0.360    0.250   8.70   25.0  0.37  0.50  0.63  0.50  6.11  0.50
6  3968.6   9 0.080   11.000    1.620  0.176  10.00  0.360    0.250   8.70   25.0  0.37  0.50  0.63  0.50  6.11  0.50
7  5903.6   1 0.095   15.200    1.680  0.204  10.00  0.360    0.250   8.70   25.0  0.34  0.50  0.66  0.02  0.92  0.02
8  6130.3   9 0.095   15.200    1.680  0.204  10.00  0.360    0.250   8.70   25.0  0.34  0.50  0.66  0.02  0.92  0.02
9  8260.0   1 0.095   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
10 8495.8  10 0.095   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
11 10995.8  1 0.115   19.700    1.680  0.212  10.00  0.360    0.250   8.70   25.0  0.39  0.50  0.61  0.01  1.13  0.01
   11246.0    End of last spray zone (mm)
       0      Consider Leidenfrost effect? (-1=yes;0=no)
       5      Number of points in the Leidenfrost effect curve (if above =-1)
              Next 2 lines contain Leidenfrost effect h-multipliers and temperatures
1.0   3.5   2.8   1.3   1
700. 800. 900. 1000. 1100.
```

Con1d9.6 input file (Cont…)

```
//MOLD COOLING WATER PARAMETERS:
 43.00000      Cooling water temperature at mold top(C)
 0.6200000     Cooling water pressure(MPa)
     1         Form of cooling water velocity/flowrate(1=m/s ; 2=L/s)
-8.500000    -8.500000    Cooling water velocity/flowrate per face (WF,NF)
                 (> 0 cooling water from mold top to bottom
                 < 0 cooling water from mold bottom to top)


#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:
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)
    1000      Grade flag
              (1000,304,316,317,347,410,419,420,430,999)
      1       If CK simple Seg. Model wanted for default Tliq,Tsol
              (1=yes,0=no)
 10.00000     Cooling rate used in Seg.Model(if above =1) (K/sec)
              Override defaults with following constants(-1=default)
-1.000000     Steel liquidus temperature (C)
-1.000000     Steel solidus temperature (C)
-1.000000     Steel density (g/cm^3)
-1.000000     Heat fusion of steel (kJ/kg)
-1.000000     Steel emissivity (-)
-1.000000     Steel specific heat (kJ/kg deg K)
-1.000000     Steel thermal conductivity (W/mK)
-1.000000     Steel thermal expansion coeff. (/K)
```


Con1d9.6 input file (Cont…)

```
#3 Parameters to update when model is calibrated
//SIMULATION PARAMETERS:
 849.0000      Z-distance for heat balance  (mm)
     0         Which shell to consider? (0=wide face; 1=narrow face)
     0         What type of mold?(0=slab, 1=funnel, 2=billet, -1=shell only)
     2         Which moldface to consider? (1=curved, 2=straight)
 1.000000      Is superheat treated as heatflux?
               0=no; 1=yes (take default); -1=yes (enter data)
    17         Number of zmm and q data points(if above = -1)
               Next 2 lines contain zmm(mm) and q(kW/m2) data
 10.   45.  100.  200.  300.  400.  500.  675.  720.  770.  980. 1120. 1370. 1470. 1575. 1700. 2000.
 20.   40.   58.   57.   28.   36.   88.  384.  408.  406.  321.  303.   98.   58.   38.   25.   20.
     1         Do you want (more accurate) 2d calculations in mold?
               (0=no; 1=yes; 2=yes, one extra loop for better taper)
 850.0000      Max. dist. below meniscus for 2d mold calcs (mm)
               (=mold length if above = 2)
3.0000000E-03  Time increment (s)
   180         Number of slab sections
 10.00000      Printout interval (mm)
0.0000000E+00  Start output at (mm)
 90.00000      Max. simulation thickness (mm)
               (Usually the slab thickness)
  200000       Max. number of iterations
     3         Shell thermocouple numbers below hot face (less than 10)
               Next line gives the distance below surface of thermocouples(mm)
 10.0   12.5   25.0
0.7000000      Fraction solid for shell thicknesss location (-)
 0             Do you want to print all the files  for the related information for each slice?
               (0=no; 1=yes;) (remark: choosing 1  would slow down the program)
```

Con1d9.6 input file (Cont…)

```
//MOLD FLUX PROPERTIES:
38.36 38.08  0.73 13.47  0.46    %CaO,%SiO2,%MgO,%Na2O,%K2O
 0.00  0.89  0.00  0.00  0.00    %FeO,%Fe2O3,%NiO,%MnO,%Cr2O3
 3.27  0.01  0.00  0.01  0.00    %Al2O3,%TiO2,%B2O3,%Li2O,%SrO
 0.00  8.60  0.33  0.00  0.23    %ZrO2,%F,%free C,%total C,%CO2
      1          number of Tfsol and viscosity exponent n
                 Next 3 lines contain zmm(mm) and tfol and expn data
   0.
1183.00
 2.700
 1.000000        Solid flux conductivity(W/mK)
      1          number of Liquid flux conductivity data
                 Next 2 lines contain zmm and Tkliquid data
   0.
 1.500
 0.9000000       Flux viscosity at 1300C (poise)
 2600.000        Mold flux density(kg/m^3)
 250.0000        Flux absorption coefficient(1/m)
-1.000000        Flux index of refraction(-)
                 (-1 = take default f(composition)
 0.9000000       Slag emissivity(-)
      1          Form of mold powder consumption rate(1=kg/m^2; 2=kg/t)
 5.5700000E-02   Mold powder consumption rate
 3.5000000E-02   Location of peak heat flux (m)
 1.000000        Slag rim thickness at metal level (meniscus) (mm)
 7.0000000E-02   Slag rim thickness at heat flux peak (mm)
 3.500000        Liquid pool depth (mm)
 80.00000        Solid flux tensile fracture strength (KPa)
 8000.000        Solid flux compress fracture strength (KPa)
 0.1700000       Solid flux Poisson ratio(-)
      1          number of slag static friction coeff data
                 Next 2 lines contain zmm and Static friction coeff
   0.
 0.500
 0.5000000       Moving friction coefficient between solid flux and mold wall
```


Con1d9.6 input file (Cont…)

```
//INTERFACE HEAT TRANSFER VARIABLES:
      2      Number of distance-vratio data points
             (1=constant ratio of solid flux velocity
             to casting speed)
             Next 2 lines contain zmm(mm) and ratio(-) data
   0. 1000.
0.000 0.128
 9.5000003E-05   Flux/mold or shell/mold contact resistance(m^2K/W)
 0.5000000       Mold surface emissivity(-)
 5.9999999E-02   Air conductivity(in oscillation marks)(W/mK)
      0          Osc.marks simulation flag(0=average,1=transient)
 7.9999998E-02   Oscillation mark depth(mm)
 1.500000        Width of oscillation mark (mm)
 3.750000        Oscillation frequency(cps)
                 (-1=take default cpm=2*ipm casting speed)
 6.200000        Oscillation stroke(mm)

//MOLD WATER PROPERTIES:
-1.000000        heat transfer coefficient(W/m^2K)
                 (-1=default=f(T), based on Sleicher and Rouse Eqn)
-1.000000        Water heat capacity(J/kgK)(-1=default=f(T))
-1.000000        Water density(kg/m3)(-1=default=f(T))

//MOLD GEOMETRY:
 41.00000        Narrow face (NF) mold thickness with water channel (mm)
 56.00000        Equivalent thickness of water box (mm)
-1.000000        Mean temperature diff between hot & cold face of NF (C)
 14.00000        17.00000    Cooling water channel depth(mm)(WF,NF)
 5.000000        9.000000    Cooling water channel width(mm)(WF,NF)
 13.00000        21.00000    Channel distance(center to center)(mm)(WF,NF)
-1.000000        -1.000000   Total channel cross sectional area(mm^2)(WF,NF)
                 (served by water flow line where temp rise measured)
 350.0000        350.0000    Mold thermal conductivity(W/mK)(WF,NF)
1.6000000E-05    Mold thermal expansion coeff. (1/K)
 0.0000          funnel height (mm)
 0.0000          funnel width (mm)
 0.0000          funnel depth at mold top (mm)
 3.500000        Machine outer radius(m)
 3.500000        Machine inner radius(m)
      6          Number of mold coating/plating thickness changes down mold
 No.  Scale     Ni      Cr      Others  Air gap  Z-positions  unit
 1    0.000     0.000   0.000   0.000   0.000    0.000        (mm)
 2    0.000     0.000   0.000   0.000   0.000    50.000       (mm)
 3    0.000     0.000   0.000   0.000   0.000    150.000      (mm)
 4    0.000     0.000   0.000   0.000   0.000    300.000      (mm)
 5    0.000     0.000   0.000   0.000   0.000    500.000      (mm)
 6    0.000     0.000   0.000   0.000   0.000    1100.000     (mm)
      0.550     72.100  67.000  1.000   0.060    Conductivity (W/mK)
```

Con1d9.6 input file (Cont…)

//MOLD THERMOCOUPLES:
0.0000000E+00 Offset distance towards hot face (mm)
45 Total number of thermocouples

No.	Distance beneath hot surface(mm)	Distance below meniscus(mm)
1	0.00	-70.00
2	0.00	-50.00
3	0.00	-20.00
4	0.00	-10.00
5	10.80	0.00
6	10.80	-20.00
7	10.80	-50.00
8	10.80	-20.00
9	10.80	-10.00
10	10.80	0.00
11	10.80	20.00
12	10.80	30.00
13	10.80	50.00
14	10.80	70.00
15	10.80	85.00
16	10.80	100.00
17	10.80	120.00
18	10.80	140.00
19	10.80	170.00
20	10.80	200.00
21	10.80	250.00
22	10.80	300.00
23	10.80	400.00
24	10.80	500.00
25	10.80	600.00
26	10.80	700.00
27	10.80	790.00
28	15.80	0.00
29	15.80	20.00
30	15.80	30.00
31	15.80	50.00
32	15.80	70.00
33	15.80	85.00
34	15.80	100.00
35	15.80	120.00
36	15.80	140.00
37	15.80	170.00
38	15.80	200.00
39	15.80	250.00
40	15.80	300.00
41	15.80	400.00
42	15.80	500.00
43	15.80	600.00
44	15.80	700.00
45	15.80	790.00

Future work

- Accurate Leidenfrost effect h-multipliers and temperatures needed.
- Continuous improvement for Con1d needed.