Metal Process Simulation Laboratory
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

Heat Transfer in Oscillation Marks Using Con1d

By

Ya Meng and Brian G. Thomas

Continuous Casting Consortium

Report

Submitted to

Allegheny Ludlum
ARMCO, Inc.
Columbus Stainless
Inland Steel
LTV
Stollberg, Inc.

March 18, 2000

Abstract

A heat transfer model CON1D has been used to simulate transient heat transfer in oscillation marks. The model is validated by analytical solution, measured data and previous 2D simulation results. A parametric study is then performed to investigate the effects of oscillation mark area, shape and pitch length. The results shows that oscillation marks have significant effect on decreasing heat transfer, cause fluctuation in heat flux, shell temperature and mold temperature. These results should be useful in interpreting transient mold thermocouple signals for on-line quality monitoring.

Objectives

The objective of this project is to increase the understanding of interfacial heat flow in the mold during continuous slab casting. In particular, the gap between the solidified steel shell and the mold wall was studied. The study determines the relative importance of surface profile (i.e. oscillation marks) of the solidified steel shell and the interfacial flux layer on mold heat transfer.

This term project is focused on the effects of oscillation mark on heat flux, shell thickness, shell temperature and mold temperature, and also the effects of oscillation mark area, shape and frequency (pitch length). The results include average values and local distribution of heat flux, shell temperature, shell thickness and mold temperature.

Background

Heat transfer in continuous casting molds is controlled primarily by heat conduction across the interface between the solidifying steel shell and the water-cooling copper mold. Heat conduction depends on the thermal resistance of four different layers, shown as Figure 1:

i) Air gap:

The air gap includes contact resistances at the flux/shell and flux/mold interface, and a gap due to shrinkage of the steel shell.

The equivalent air gap thickness can be specified as input data, or calculated by another model [1]. The shrinkage gap is affected by the mold taper and shell and mold distortion, which can be calculated by another model, such as CON2D. Air gap is important when simulating positions near the corner.

ii) Flux layers:

Solid flux layer exists adjacent to the mold wall. Depending on the cooling rate of mold flux, this layer may have a structure that is glassy, crystalline or a combination of both. Liquid flux layer exists when the steel surface temperature is above the melting temperature of mold flux.

The heat conduction across the flux layers depends on the flux velocity, crystalline temperature, flux viscosity, and flux states (glassy, crystalline or liquid), which are determined by the mold flux cooling rate and TTT diagram. The solid layer is assumed to move at constant velocity, which is a fraction of casting speed. The simple force balance governs velocity across the liquid layer:

$$\frac{\partial}{\partial x} m \frac{\partial V_Z}{\partial x} = (r_{Fe} - r_{Flux})^n g \qquad \textbf{Eqn. 1}$$

The flux viscosity depends on its state and is assumed as an exponential function of temperature. So the essential problem is using TTT diagram to determine mold flux state: glassy, crystalline or liquid. The TTT diagram can be specified as a user input subroutine or calculated in another model [2].

iii) Oscillation marks:

Oscillation marks produces a localized reduction in heat transfer and also consume more heat flux to affect the behavior of the flux layers thickness.

The oscillation marks can be incorporated into the model by using average depth and width. However, we can only get an average shell thickness and temperature distribution for that case. For an improved model, the oscillation marks' shape and pitch need to be taken into account to predict shell thickness and temperature at local position.

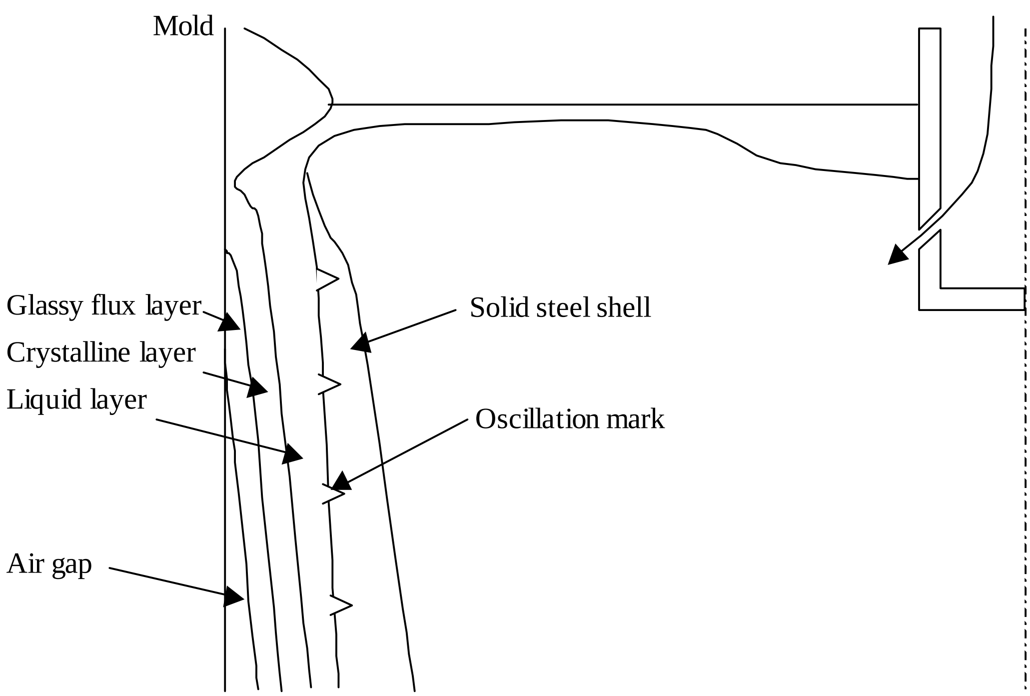

Figure 1. Schematic of interface between mold and solidifying steel shell

The majority of defects that occur in the continuous casting process originate in the mold during primary solidification of the steel shell. Of these defects, the most common are surface and subsurface cracks. These defects are usually a result of stress/strain generation due to extremely high heat transfer rates near the meniscus and/or phase transformation, and changes in physical properties due to metallurgical segregation and/or embrittlement. In order to reduce the occurrence of these defects, their mechanisms must be thoroughly understood.

To help prevent sticking between the shell and mold, and to entrain liquid mold flux into the interfacial gap, the mold is oscillated vertically throughout casting. Each oscillation cycle creates a depression in the solidifying shell at the meniscus, called an "oscillation mark". The cause of these depressions has been the subject of much study. They are believed to form due to a variety of different mechanisms, which may act in combination. These include freezing and overflow of the meniscus[3], thermal stress in the solidifying shell[4] and bending of the weak shell by the interaction between pressure in the liquid flux layer and ferrostatic pressure[3]. Oscillation marks are believed to increase the effective gap, reduce heat transfer, and retard shell growth. Reference [5] had a detailed treatment of the interfacial gap between the shell and mold, incorporated the effects of air gap, flux layers and oscillation marks. For simplicity, it used average thickness of air gap and oscillation marks.

To understand heat transfer across the interface between shell and mold, the relationship between oscillation mark and heat transfer needs to be quantified. This term project will focus on incorporating the details of oscillation marks into a well-developed mathematical model of continuous casting CON1D.

For simplicity, the model assumes a very simple flux behavior. Only solid layer (it does not distinguish glassy layer and crystalline layer) and liquid layer are considered, and the liquid layer keeps same thickness down the mold so oscillation marks are filled with liquid flux all the way. The present model ignores the crystallization behavior of mold powder, which is also an important aspect of heat transfer. That will be one part of the future work.

Estimation/Scaling

An estimation/scaling analysis may be performed in order to better understand the phenomena occurring in the oscillation marks. Figure 2 is the domain of the model. It can be assumed that this is a two-dimensional problem, therefore only references to the x and z directions will be made in the governing equations:

$$\frac{\partial T_s}{\partial t} = \frac{K_s}{r_s C_{ps}} \left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial z^2} \right) \qquad \textbf{Eqn. 2}$$

where the subscription s means the solidified steel shell.

Defining non-dimensional parameters:

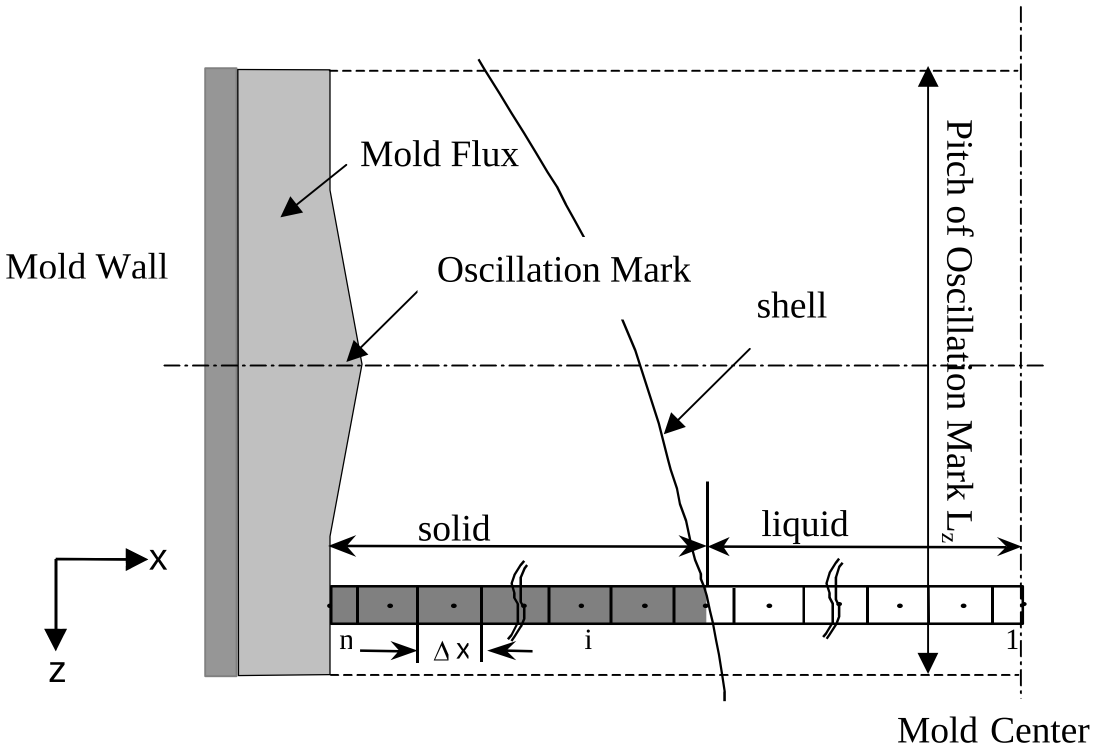

Figure 2. The domain of 2D model

(also used in 1D model as a period of the 1D domain)

$$x^* = \frac{x}{L_x}$$ **Eqn. 3**

$$z^* = \frac{z}{L_z}$$ **Eqn. 4**

$$t^* = \frac{t}{t_c}$$ **Eqn. 5**

$$q = \frac{T - T_0}{T_m - T_0}$$ **Eqn. 6**

Scaling the governing equation based on the above parameters, and rearranging gives:

$$\frac{\partial q}{\partial t^*} = \frac{a t_c}{L_x^2}\frac{\partial^2 q}{\partial x^{*2}} + \frac{a t_c}{L_z^2}\frac{\partial^2 q}{\partial z^{*2}}$$ **Eqn. 7**

The Peclet No.

$$Pe = \frac{V * L_z}{a}$$ **Eqn. 8**

substituting the values of parameters:

$$Pe = \frac{V * L_z}{k/(r \cdot c_p)} = \frac{0.01693m/s * 0.01195m}{29.288W/mK} * \left(7400kg/m\hat{\ }3 * 6903.6J/kgK\right) = 352.8 >> 1$$

so, the conduction of Z direction is too small to be considered, the second term of the scaled governing equation can be ignored. In addition, the terms with asterisks are all order one, the non-dimensional parameter t_c need to be defined:

$$t^* = \frac{L_x^2}{a} \qquad \textbf{Eqn. 9}$$

So, the governing equation is reduced to:

$$\frac{\partial q}{\partial t^*} = \frac{\partial^2 q}{\partial x^{*2}} \qquad \textbf{Eqn. 10}$$

with boundary conditions:

$$q = 1|_{x^*=1} \qquad \textbf{Eqn. 11}$$

$$\frac{\partial q}{\partial x^*}\ |_{x^*=0} = -\frac{q(t)\cdot d(t)}{(T_m - T_0)\cdot K} \qquad \textbf{Eqn. 12}$$

Applying the boundary conditions, analytical solution can be obtained:

$$T = T_m + \frac{q(t)}{K}\cdot\sqrt{p\cdot a_s\cdot t}\cdot erf\left(\frac{d(t)}{2\sqrt{a_s\cdot t}}\right) - \frac{q(t)}{K}\cdot\sqrt{p\cdot a_s\cdot t}\cdot erf\left(\frac{x}{2\sqrt{a_s\cdot t}}\right)$$

Eqn. 13

where,

T_m: Steel solidus temperature;
T_o: Steel surface temperature;
K: Steel heat conductivity;
C_{ps}, Steel specific heat capacity;

$a_s = \frac{K_s}{r_c C_{ps}}$, *steel thermal diffusivity;*

$r_{s,}$ *steel density;*

$d(t)$, *shell thickness.*

q(t): heat flux flows out steel surface at x=0; (refer to figure 4)

Approach and Methodology

From the simplified equation derived in the previous section, an one-dimensional heat transfer/solidification model CON1D has been developed by incorporating the analytical solutions. A detailed description of the model is presented elsewhere [6].

Temperature in the solidifying steel shell is governed by the 1D transient heat conduction equation :

$$rC_p * \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + \frac{\partial k}{\partial T}\left(\frac{\partial T}{\partial x}\right)^2 \qquad \textbf{Eqn. 14}$$

The model has been simplified into a 1-D transient solidification problem, assuming no heat conduction along casting direction. The boundary condition at solid/liquid steel interface is melting temperature. The boundary condition at shell surface is heat flux across the steel/mold interface, which can be calculated or from input file directly.

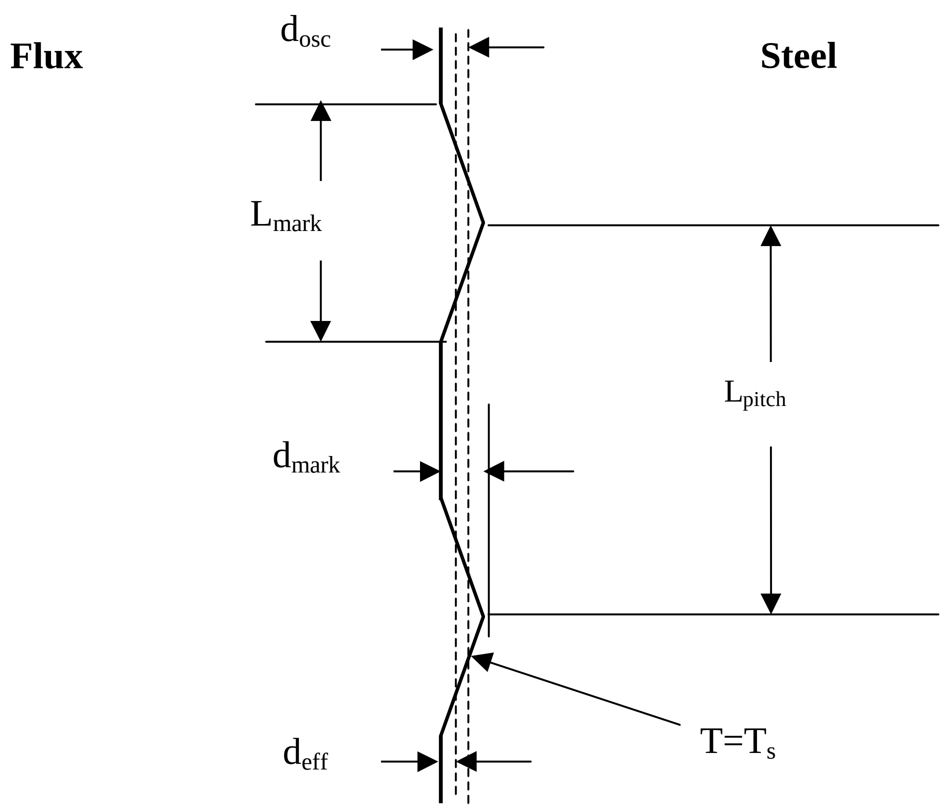

Figure 3. Model treatment of oscillation marks

How to decide the heat flux at boundary is a key question of the model. Figure 3 gives the model treatment of oscillation marks. The averge depth of oscillation marks (based on the volume balance) d_{osc}, is calculated from:

$$d_{osc} = \frac{L_{mark} d_{mark}}{2 * L_{pitch}} \qquad \textbf{Eqn. 15}$$

d_{osc} can be used to calculate the mold powder consumption increase due to oscillation marks. The average effective thickness of oscillation marks (based on heat balance) d_{eff}, is calculated from:

$$d_{oeff} = \frac{L_{mark} d_{mark}}{\left(L_{pitch} - L_{mark}\right)\left(1 + \frac{d_{mark} k_{gap}}{k_{mark} d_{gap}}\right) + L_{mark}} \qquad \textbf{Eqn. 16}$$

The model uses d_{eff} to predict the average effect of oscillation marks.

Table 1. Important process dimensions, parameters and material properties

Variable Name	**Test Case**	**Example Case**
Casting Speed (m/min)	1.0	1.016
Pour Temperature (^oC)	1456.1	1555
Working Mold Length (mm)	800	815
Slab Geometry (mm*mm)	1780*225	1500*203
Oscillation Marks pitch length (mm)	10	11.95
Osc. Mark Depth & Width (mm*mm)	1.0*5.0	0.546*6.99
Steel Solidus Temperature (^oC)	1456	1528
Steel Liquidus Temperature (^oC)	1456.1	1509
Steel Specific Heat (kJ/kgK)	0.67	0.69036
Steel Thermal Conductivity (W/mK)	46.5	29.288
Steel Density (kg/m^3)	7200	7400
Time Step dt (s)	0.001	0.003
Mesh Size dx (mm)	0.25	0.3

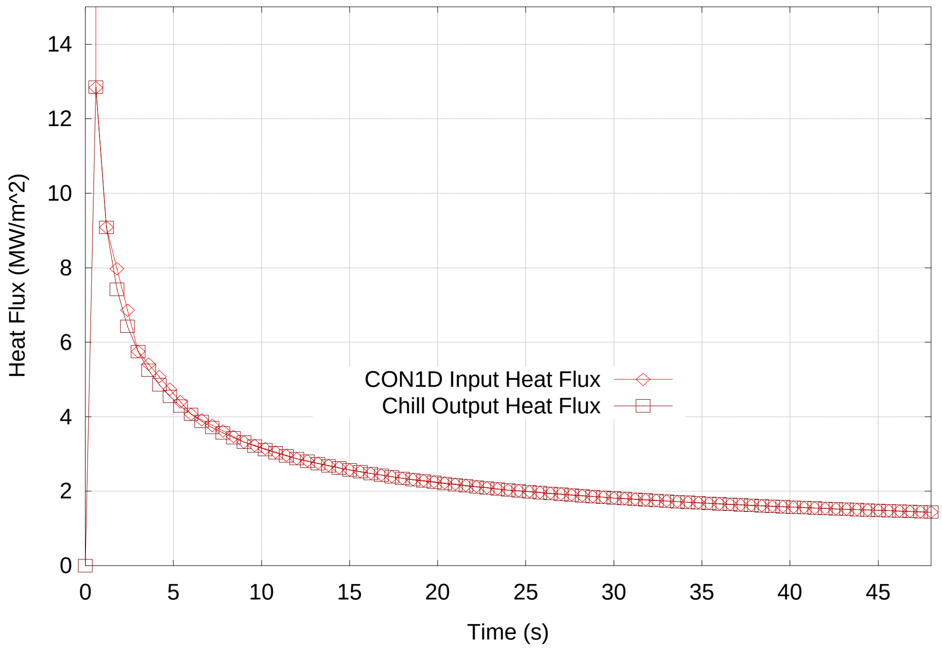

Figure 4. Boundary condition: Heat flux at shell-mold interface (for test case)

Figure 4 gives the heat flux for test problem, which comes from the analytical model CHILL and is input into CON1D as boundary condition.

Table 1 provides some simulation parameters and properties of the steel and mold being analyzed for test case[7] and example problem[8], other input conditions refer to attached input files (amk9.inp for test case, o001.inp for example problem). Table 2 gives the interface heat transfer variables for example problem. In parametric study, only change oscillation mark geometry (area, shape and pitch) and keep other conditions same to investigate the parameter effect. The mold flux consumption rate for each run is changed from 0.17 to 0.94kg/m^2 according to the oscillation mark area per unit slab length, assuming the flux layer thickness stays same for all cases, i.e., the liquid flux layer keep 0.2mm down the mold, the solid flux layer increase from 0 at meniscus to 1.0mm at mold exit (refer to figure 5).

Table 2. Interface heat transfer variable (for example problem)

Solid Flux Conductivity	1.24W/mK
Liquid Flux Conductivity	2.8W/mK
Air Conductivity	0.06W/mK
Flux/Mold Contact Resistance	2.3e-9m2K/W
Solid Flux Velocity	0.01Vcasting
Consumption Rate	0.57kg/m^2

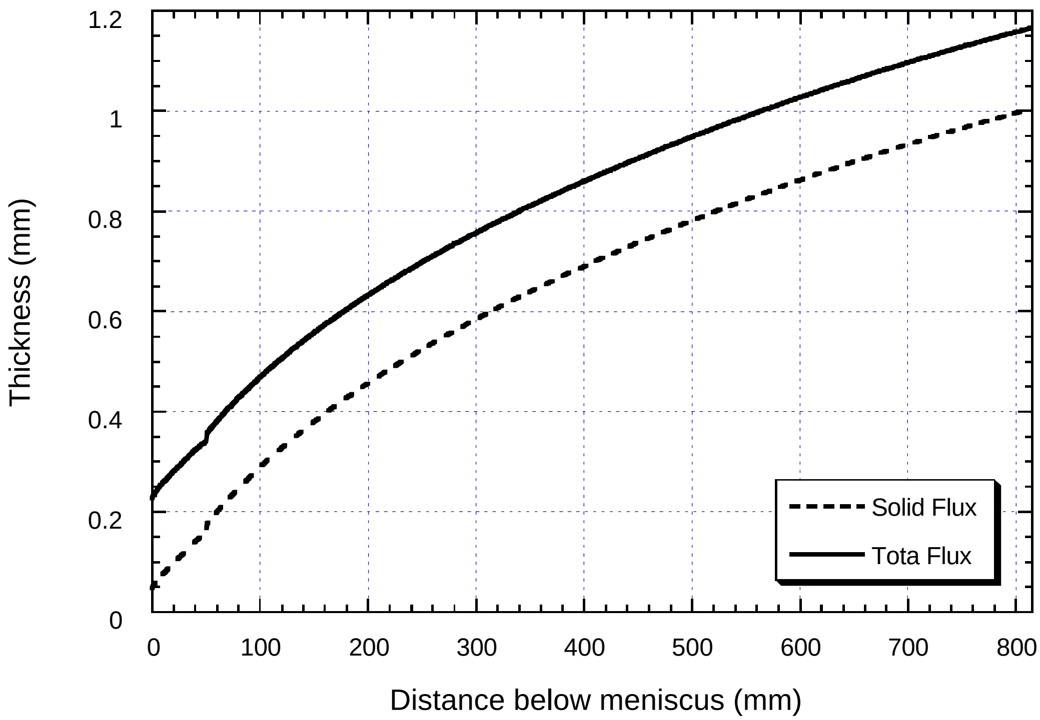

Figure 5. Mold powder thickness profile down the gap

The governing equation is solved at each time step using the explicit finite-difference discretization (a central difference scheme), using Fourier number to check time step size. The simulation domain is from meniscus to mold exit. The execution time of running CON1D for the test case is less then 1 minute on Pentium III 500 PC.

Model Validation

Analytical solution for the simple test case (conditions from Table I test case)

To test the validity of the current numerical model, shell growth predictions of both CON1D and an analytical model CHILL were compared. To do this, several modifications were made to the numerical model in order to produce results that could be accurately compared to analytical solution. First, an infinite heat transfer coefficient between shell and mold was defined, which is a condition that model Chill assumes. This modification essentially disabled the interface model, which is a phenomenon that model CHILL does not take into account. Next, the mold temperature was set to a constant value. Also, the difference between the steel's liquidus and solidus temperature was kept minimal to keep superheat effects negligible.

Figure 6 shows the comparison of shell temperature distribution at mold exit between CON1D and analytical solution, which was obtained in equation 13, substituting the shell thickness $\delta(t)$ and heat flux $q(t)$ came from CON1D (t=48s).

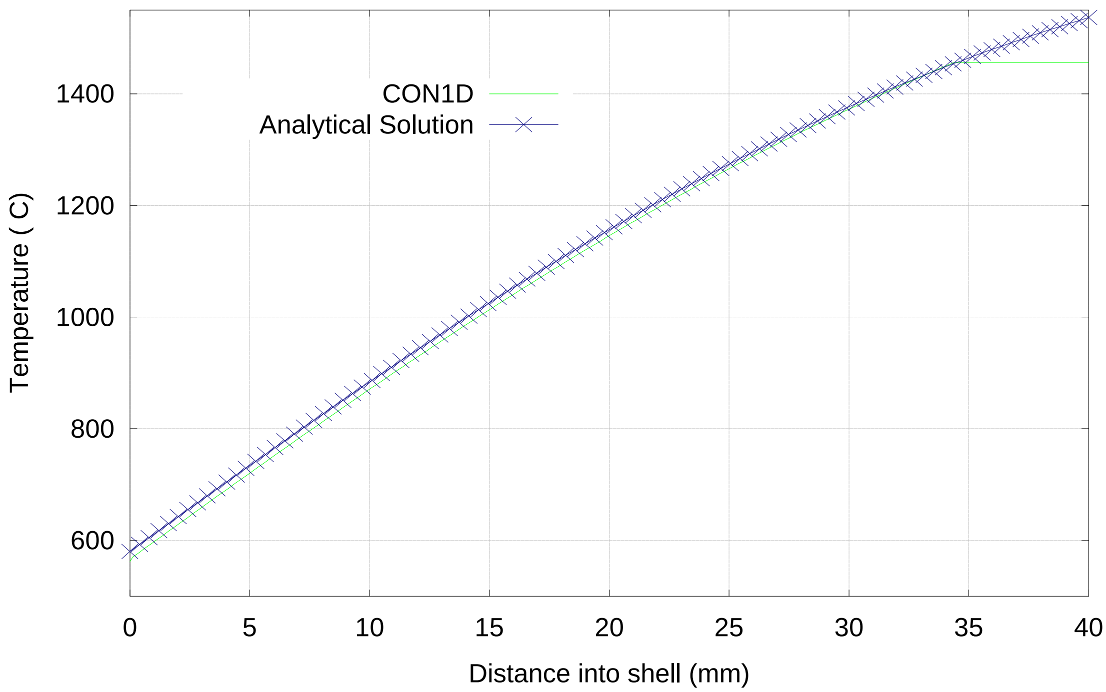

Figure 6. Shell temperature comparison
(at mold exit: t=48s, δ(t)=34.5mm, q(t)=1.437MW/m^2)

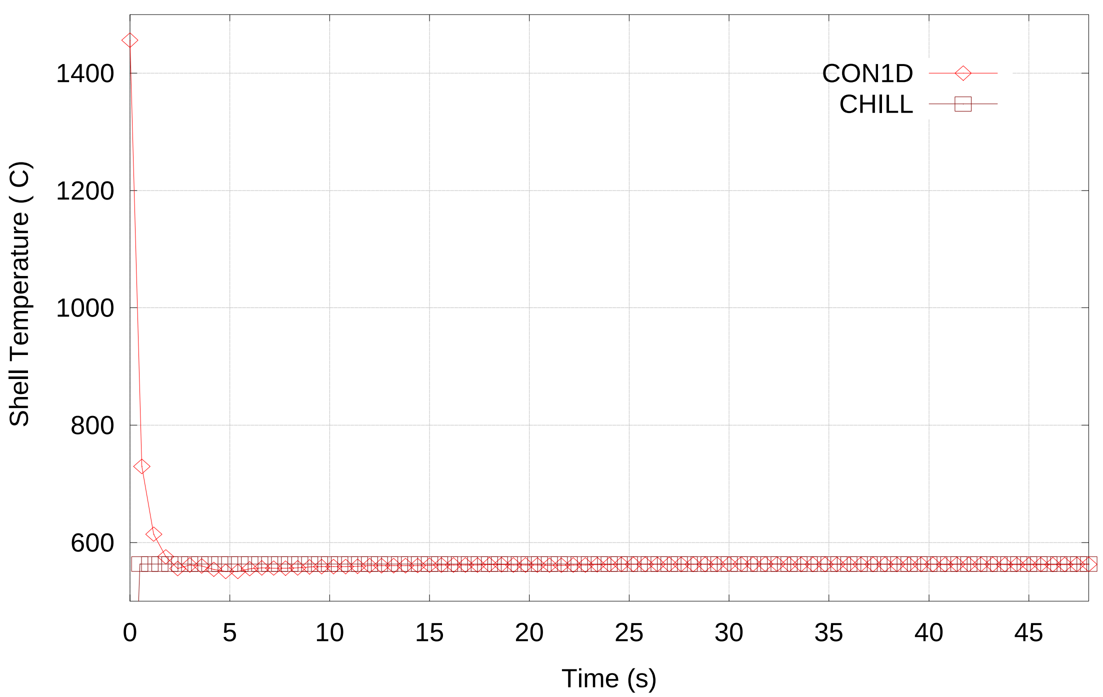

Figure 7. Shell surface temperature comparison

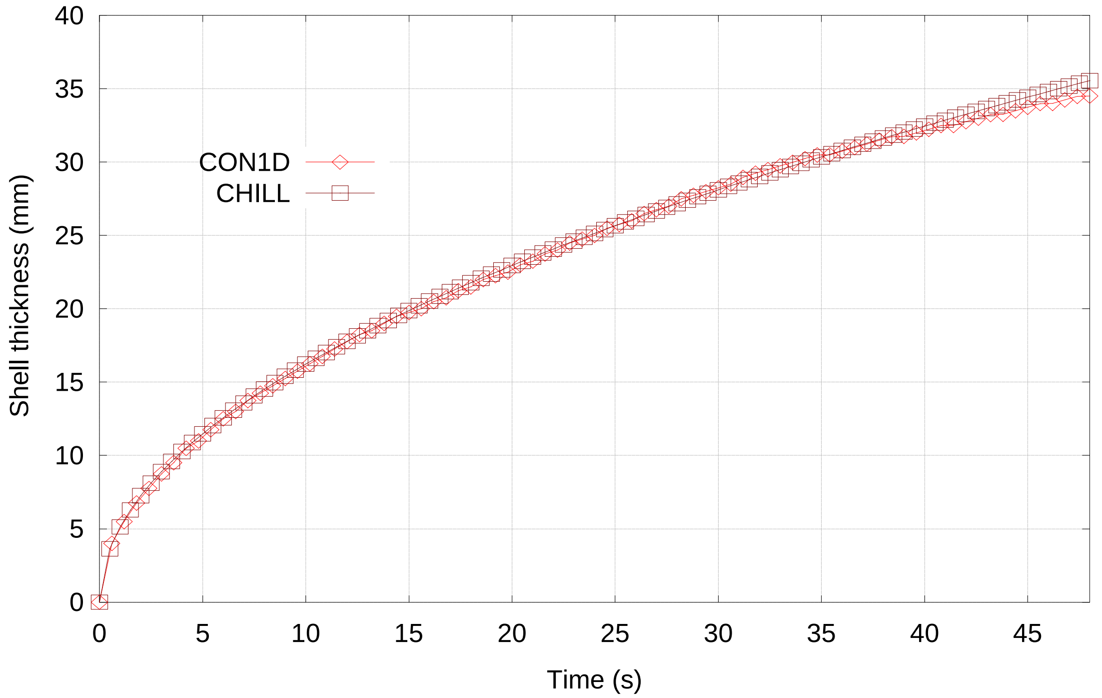

Figure 8. Shell thickness comparison

Figure 7,8 show the comparisons of CHILL and CON1D, which use the heat flux calculated from CHILL as input data. These results show that the numerical model works quite well in predicting shell growth behavior. In figure 6, the difference of shell surface temperature between CON1D and CHILL at very beginning is because that the heat flux at z=0 is infinite in Chill and decreases quickly when solidification beginning while the CON1D can only use a finite value and use linear interpolation of the first two input points to decide the heat flux value at very beginning. Looking at figure 8, a small fluctuation can be observed, which may be caused by the stable problem because too small difference between the steel's liquidus and solidus temperature.

Other validation

Through running the example problem, the model predicts shell temperature increase and a thinner shell thickness, which can be compared with previous 2D simulation results[8] and measured data. The comparison shows that the 1D model works well. The details will be discussed in the following Results section

Results

Using CON1D run a example problem, assuming it is a 1-D transient solidifying problem. The input parameters used in the simulation are given in Table 1 and 2, which are based on previous work[8] so the results can be compared with 2D simulation results.

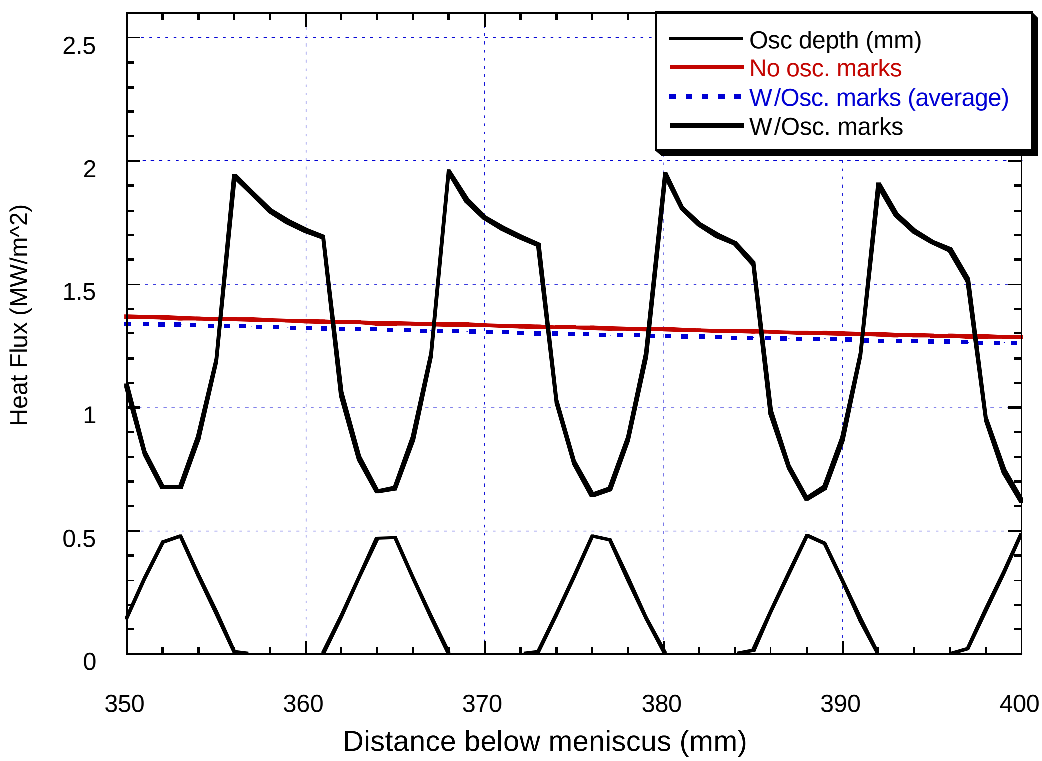

Figure 9. Heat flux across the interface

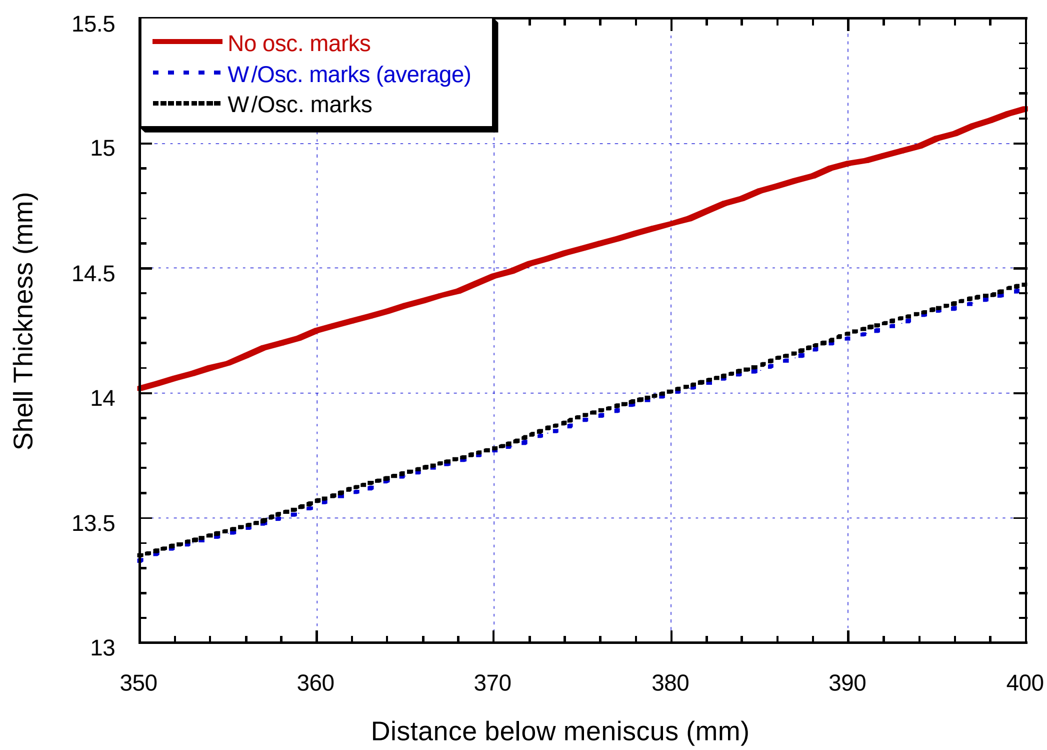

Figure 10. Shell thickness

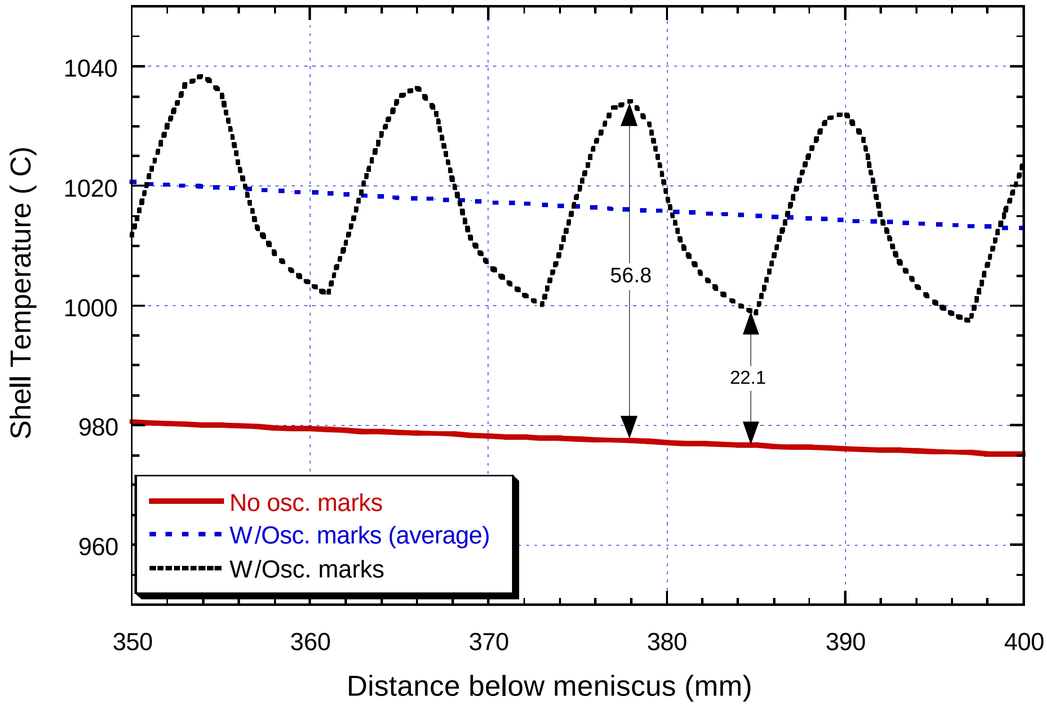

Figure 11. Shell temperature

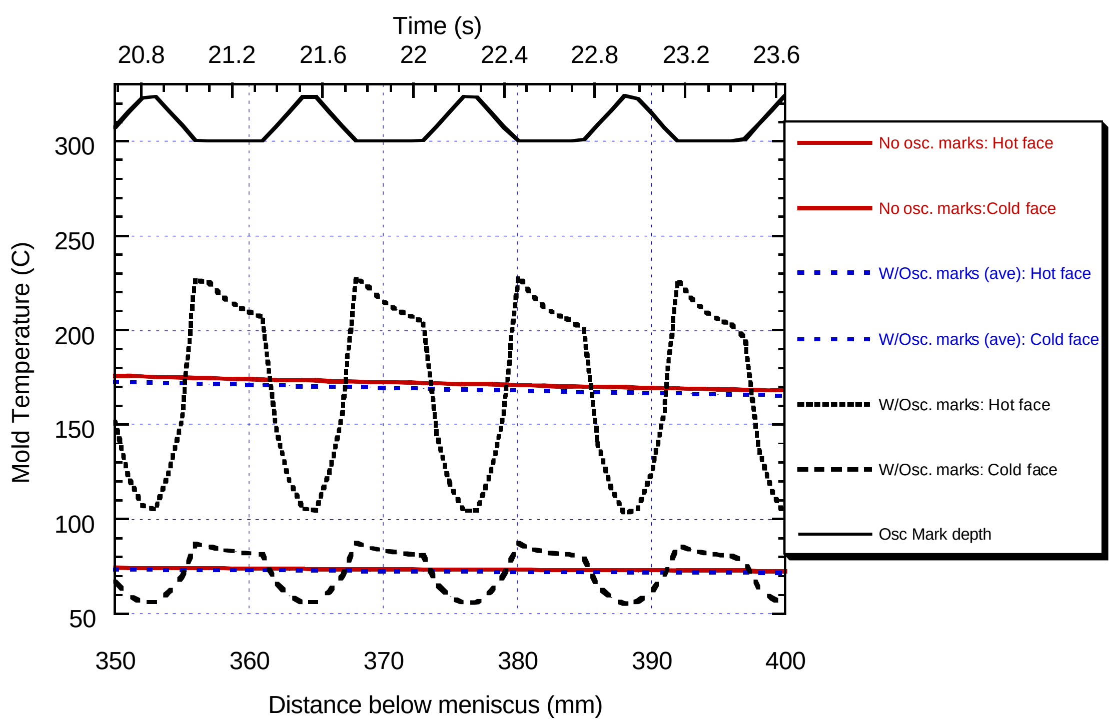

Figure 12. Mold temperature

Standard condition

First, run a standard case. The oscillation mark depth, width and pitch are 0.546mm*6.99mm and 11.95mm. Figure 9 is the local heat flux across the interface below meniscus 350mm to 400mm, the lower part is corresponding oscillation mark geometry. Figure 10~12 are shell thickness, shell temperature and mold temperature distribution separately at the same position with figure 9.

The results show clearly that the oscillation marks cause fluctuation in heat flux, shell temperature and mold temperature. In general, they decrease the heat transfer across the interface between steel surface and mold. The shell thickness is about 0.7mm thinner than no oscillation mark case. Shell surface temperature is more sensitive than shell thickness and corresponds directly with oscillation mark depth variation along the shell surface. Note that the oscillation marks increase the surface temperature even between the marks, where there is always a minimal gap between the shell and the mold. For example, at approximate 380mm below meniscus, the shell surface temperature increases are 56.8°C at oscillation mark root and 22.1°C at oscillation mark base. This matches with the 2D simulation done by David Lui[8] very well and validate the model from another side. Seen from figure 11, the heat flux fluctuation directly leads to mold temperature fluctuation, which shows the close relationship between the mold temperature and the heat flux. This relationship can be used to interpret the mold thermocouple temperature signals for on-line quality monitoring.

Parametric study

The calibrated CON1D model is then run to perform the parametric study on the effects of the oscillation mark area, shape pitch on heat transfer and shell growth.

i) Oscillation mark area

For a fair comparison, a series of analogue triangle is used to simulate the different oscillation mark (i.e. the depth and width of oscillation mark are proportionally decreased or increased). Figure 13 shows the oscillation mark area effect on heat flux. The average heat flux decreases with the increasing oscillation mark area, when the oscillation mark area is 3.2 mm2 per centimeter slab length, the total heat transfer in the mold decrease 9.29% compared to no oscillation mark case. Also the fluctuation of heat flux increases with the increasing oscillation mark area, and this fluctuation declines along with the distance down the mold because the growing shell plays a more and more important role in heat transfer to make the oscillation mark less important.

The calculated effect of oscillation mark area on shell thickness is illustrated in Figure 14. Shell thickness data are normalized by dividing the corresponding

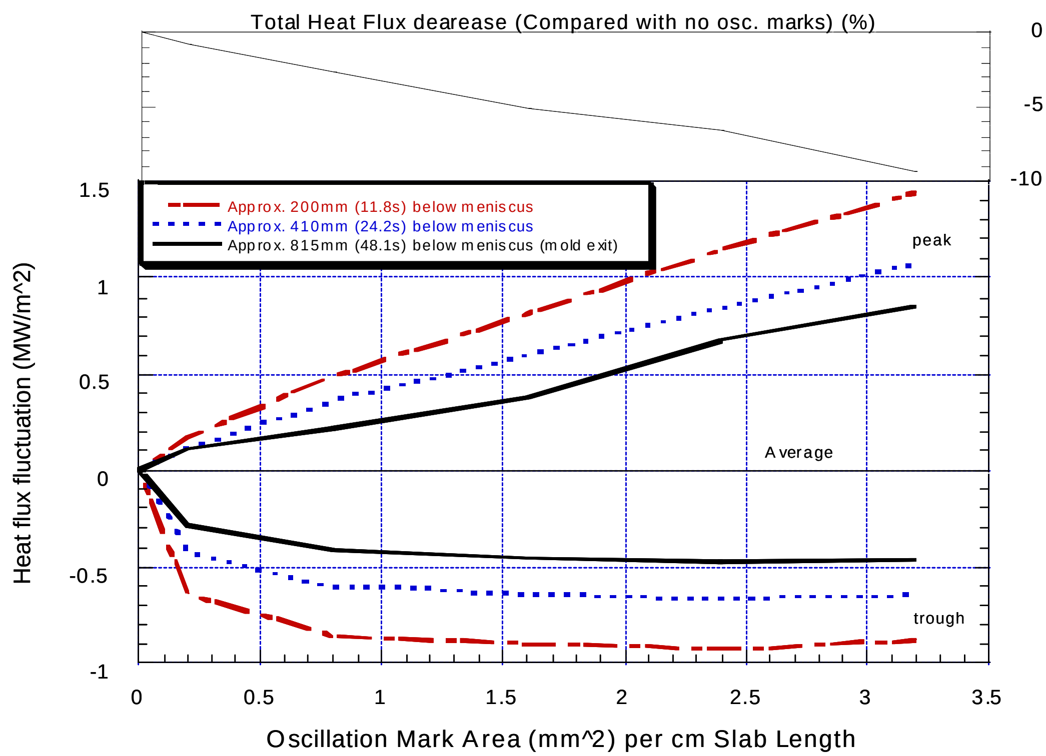

Figure 13. The effect of oscillation mark area on heat flux

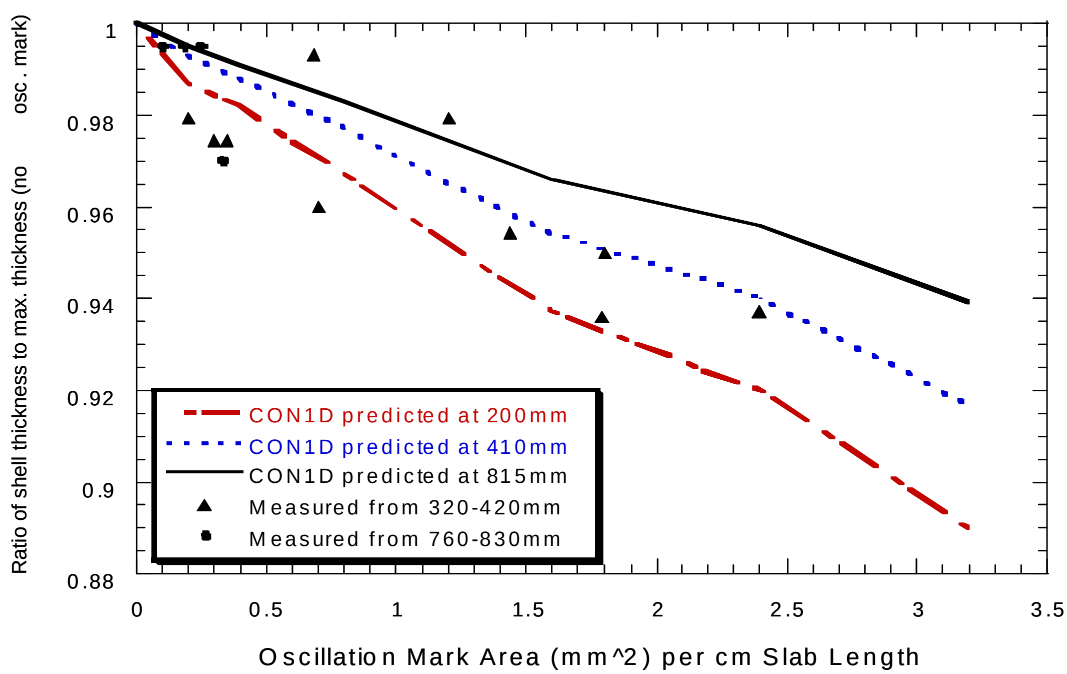

Figure 14. The effect of oscillation mark area on shell thickness

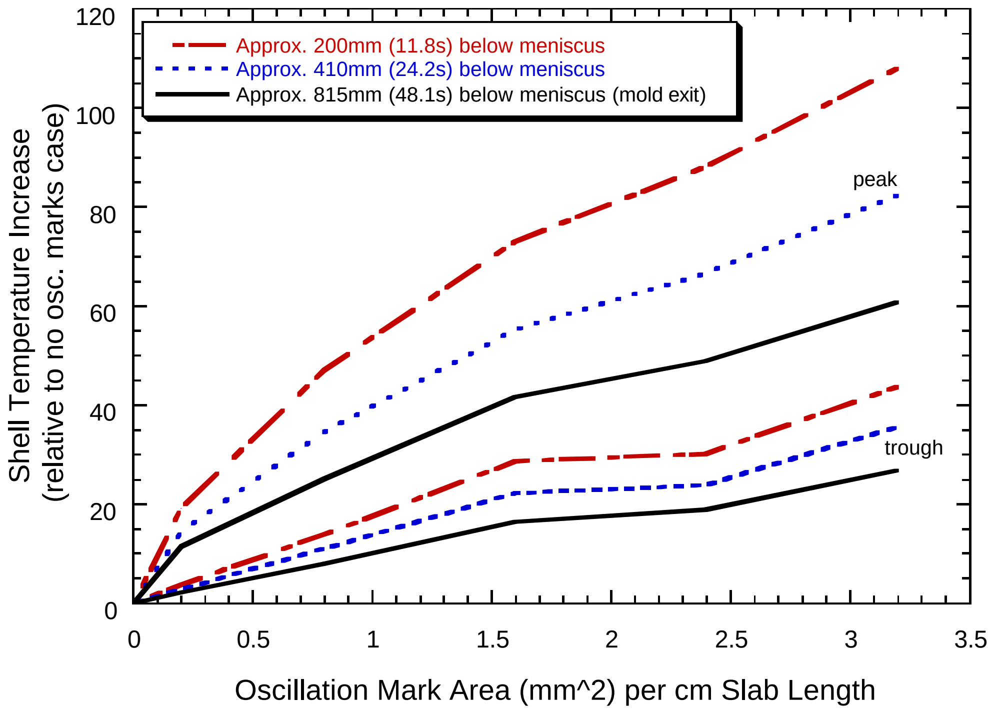

Figure 15. The effect of oscillation mark area on shell temp. variation

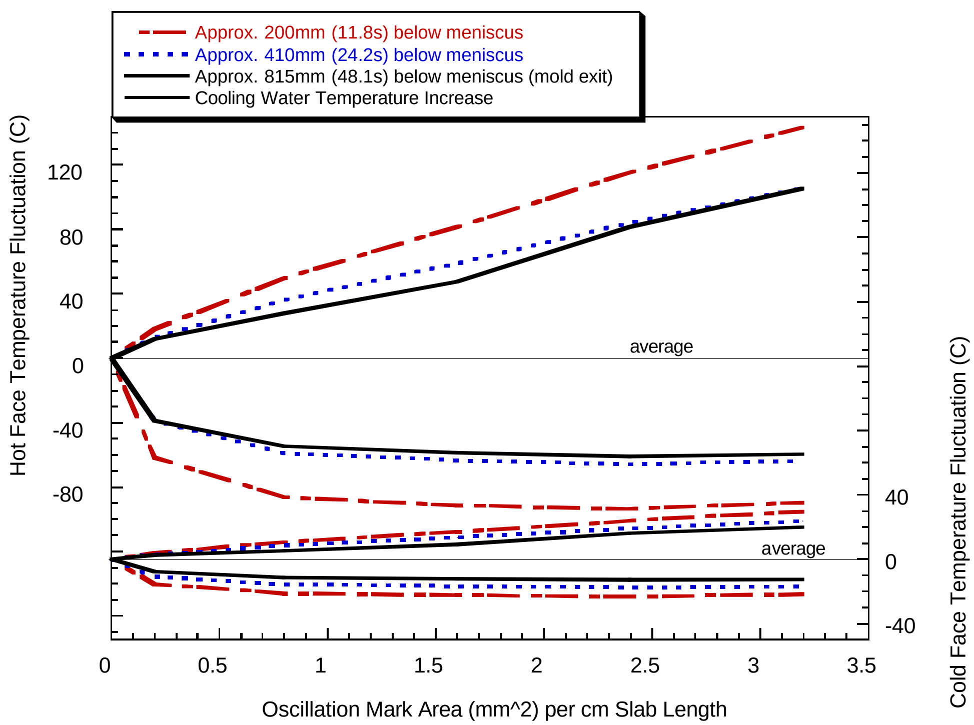

Figure 16. The effect of oscillation mark area on mold face temperature

thickness obtained with no oscillation marks, which has a maximum thickness for a given case. The results predict a thinner shell thickness with bigger oscillation marks as expected. The effect is greatest near the meniscus (see 200mm data), where the interfacial gap is the most influential factor controlling heat flow. This is consistent with the heat flux fluctuation in Figure 13.

Figure 15, 16 are shell and mold temperature variation with increasing oscillation mark area. They are both well consistent with heat flux condition. The mold cooling water temperature increase is from 9.7°C for no oscillation mark case to 8.8°C for biggest oscillation mark in this series (i.e. 3.2mm^2/cm). Read from Figure 16, for a medium oscillation mark (1.6mm^2/cm), the model predicts a variation from +47.7°C to –58.7°C relative to average value for mold hot face temperature near mold exit and from +9.2°C to –12.2°C for the cold face under same condition. Unfortunately, no mold thermocouple signal record to validate these results. But the model does give a potential way to validate itself and understand the relationship between thermocouple signals and the conditions of mold/steel interface.

ii) Oscillation mark shape

To investigate the effect of oscillation mark shape, keep the oscillation mark area same (1.91mm^2), double the oscillation depth and half its width, i.e. from the deep one 0.546mm*6.99mm to a shallow one 1.092mm*3.495mm. The results show that the deep oscillation mark has less effect on reducing heat flux (refer to fig. 17).

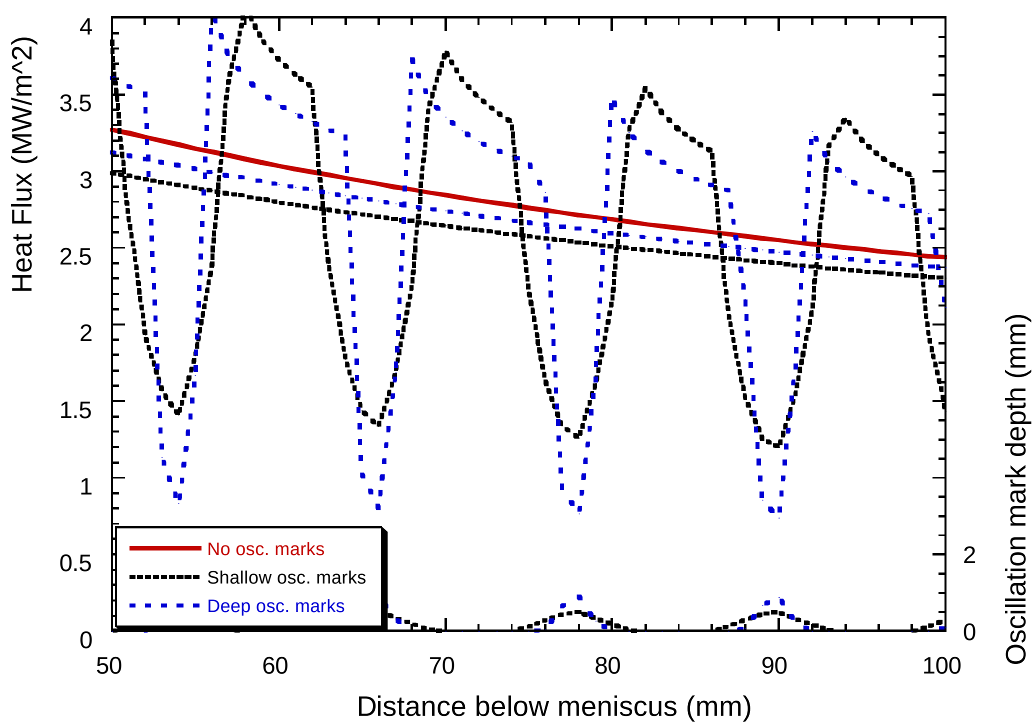

Figure 17. The effect of oscillation mark shape on heat flux

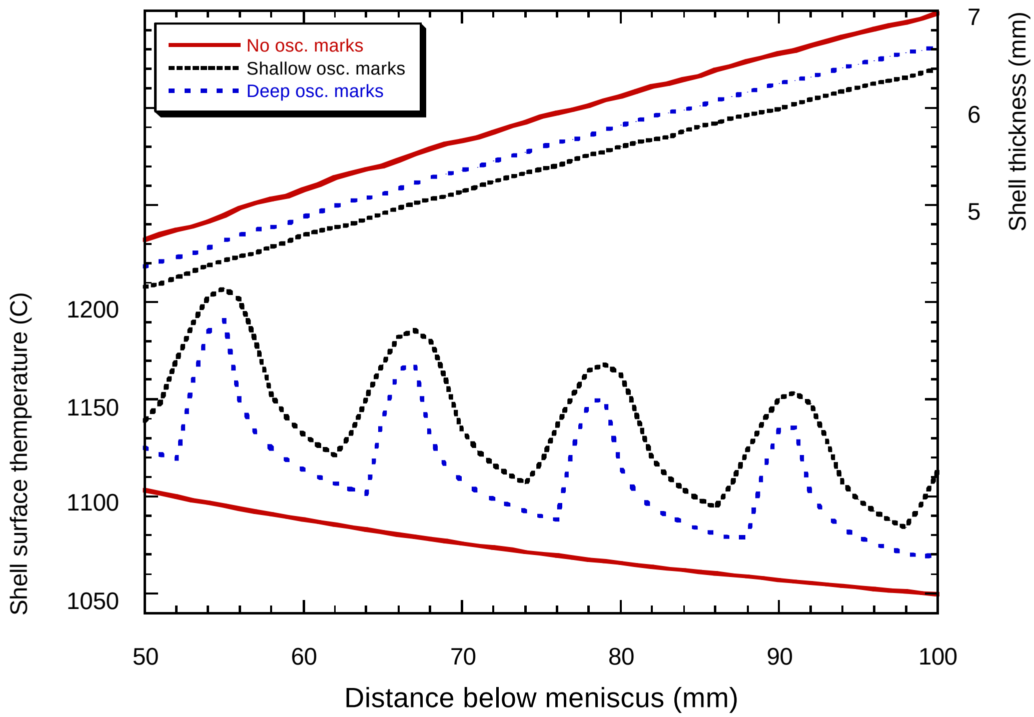

Figure 18. The effect of oscillation mark shape on shell

Correspondingly, the deeper oscillation mark case has a thinner shell thickness and lower shell surface temperature, as shown in Figure 18. Note that the x-axis is from 50mm to 100mm below meniscus, a position near to meniscus shows the shape effect clearer.

iii) Pitch length

From the point of average total heat transfer in the mold, double pitch has the same effect as half oscillation mark width. They allow more heat transfer across the interface. Specifically, the average total heat transfer decrease due to oscillation mark decreases from 5.12% for standard condition to 2.08% for double pitch (pitch=23.9mm) or half oscillation mark width (depth*width=0.546*3.495mm^2) case. Figure 19 compares the local heat flux profile for these different cases. It shows that both the double pitch case and half width case have a smaller positive heat flux deviation while the negative deviation stays same. It can be derived that the same trend will appear in mold temperature fluctuation.

Figure 20 is the shell surface temperature distribution. The results shows that the fluctuation for same oscillation mark area and shape almost stay same, i.e. about 35°C at 380mm below meniscus. But the double pitch case has a much lower temperature increase relative to no oscillation case.

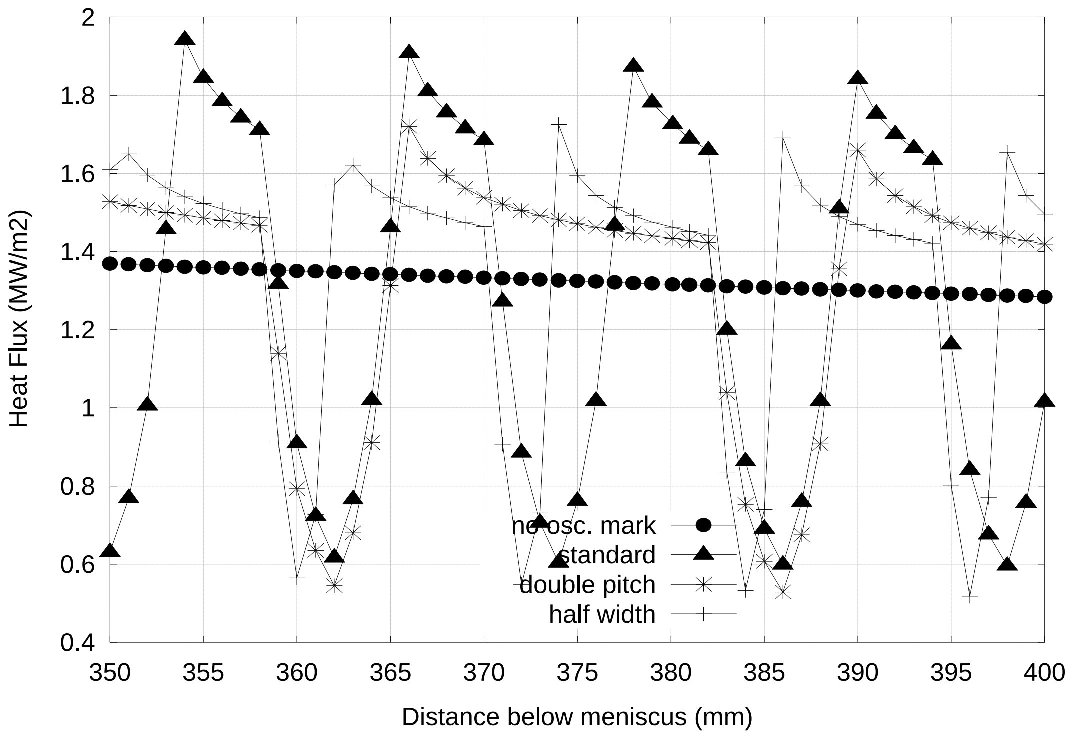

Figure 19. The effect of pitch on heat flux

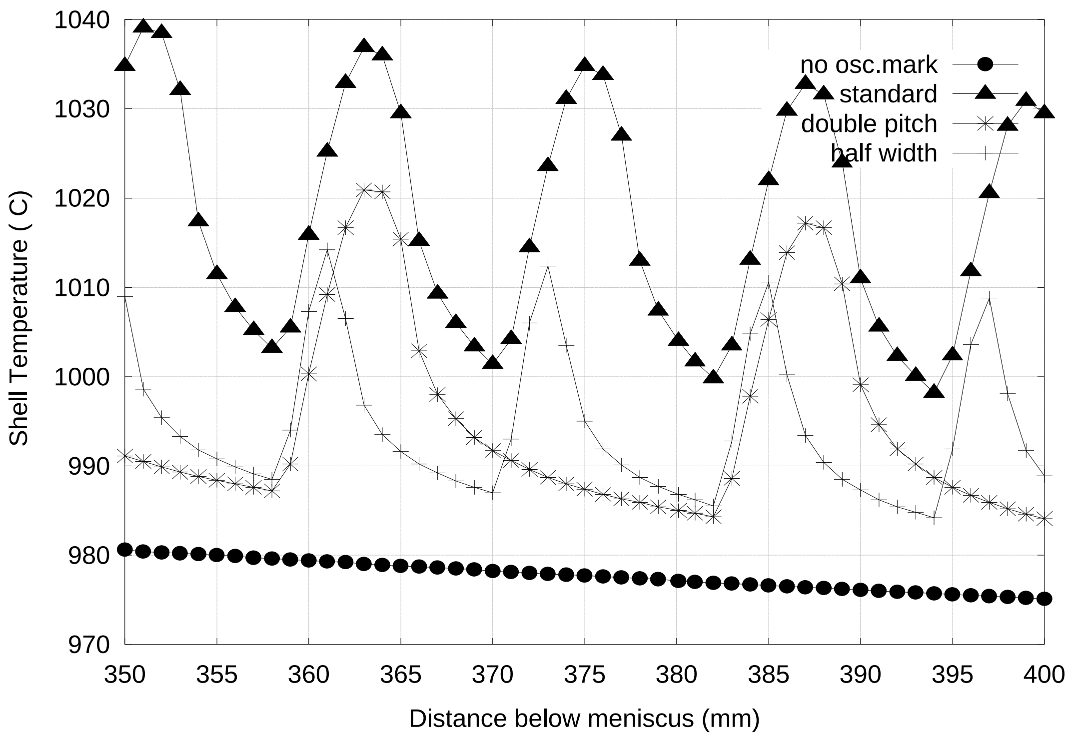

Figure 20. The effect of pitch on shell temperature

Discussion

From the above analysis, the oscillation mark problem can be treated as a 1D transient case. However, the results still need to be compared with 2D simulation and measured data.. If it is accurate enough is still in doubt because the 1D model ignores the heat conduction along casting direction. Also, limited by the 1D slice, the oscillation mark can not move with the shell in the simulation, the problem becomes a Eulerian system problem. At a specific position, the model need to decide if it meets the oscillation mark first, then calculates corresponding shell surface temperature. However, a more general case can be derived according to this 1D result, as shown in figure 21. It predicts the really happening in the shell.

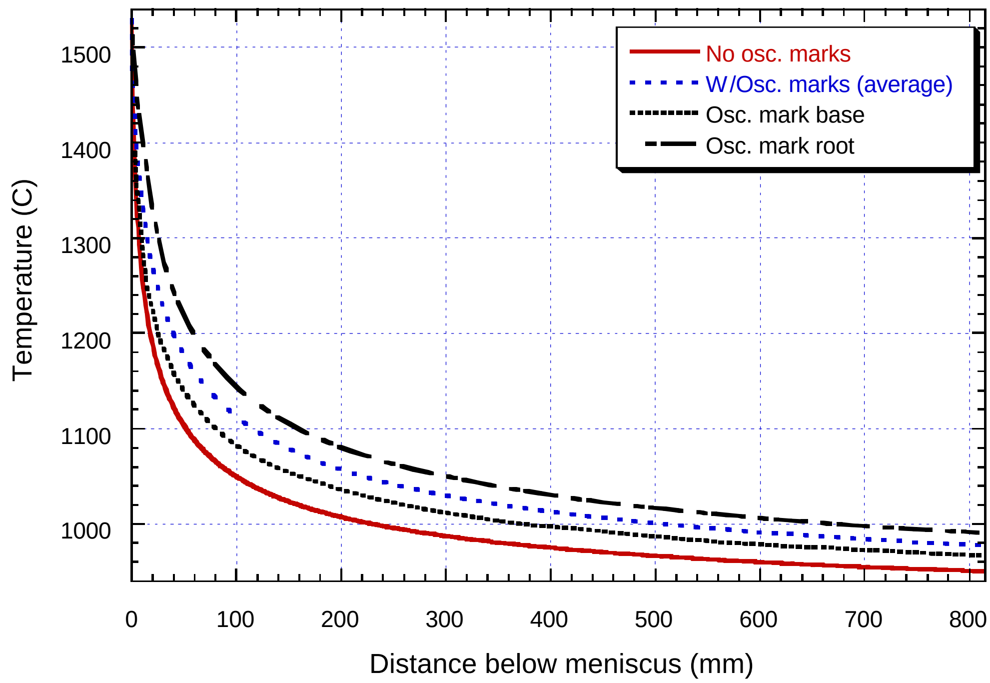

Figure 21. Shell surface temperature in reality

Conclusions

The effect of oscillation mark on heat transfer and temperature has been studied by applying calibrated 1D heat conduction model, CON1D. The following conclusions are reached:

i) Oscillation marks have important effect on heat transfer in flux layers. In general, they:
- impede heat transfer across the interface,
- decrease shell thickness,
- increase shell temperature,
- decrease mold temperature.

ii) Specifically, oscillation marks cause fluctuation in heat flux, mold temperature and shell temperature, and very slight variation in shell thickness.

iii) The fluctuations increase with increasing oscillation mark area, and decrease with distance down the mold.

iv) The shallow and wide oscillation has more effect on reducing heat transfer, therefore leads to a thinner shell thickness and higher shell temperature.

v) Increase oscillation pitch length decrease the effect of oscillation mark.

Implementation

On-line quality monitoring system should be developed to record the mold thermocouple signals. Because like shell surface temperature, mold temperature are more sensitive to changes in heat flux than is the shell thickness. Therefore, how the oscillation marks affect the temperature history of the slab surface can be detected by mold wall thermocouple. It is a good way to validate this model and also helpful to understand the mechanism for interfacial heat transfer better.

After being calibrated to match experimental measurements, the improved model CON1D can be implemented as an off-line model. The model results are implemented in the plant by parametric studies or “numerical experiment” to develop new design or change to standard operating practices.

For details, according to oscillation marks conditions, it can predict shell thickness, shell temperature, make crack formation analysis, optimize casting conditions (casting speed, mold flux consumption rate) etc.

Future Work

It is still worthy to develop the oscillation mark model into a 2-D model, deal the localized heat flux separately for different section, i.e. with oscillation mark or no oscillation mark. Through the present 1D model matches with previous 2D calculation very well, the theoretical explanation that the 1D advection term compensates the 2D conduction term is unclear and need to be studied further.

The present model oversimplified the interface between steel shell and mold conditions. Many aspects of the interface need to be analyzed in order to fully understand the phenomena that occur. These aspects include determination of the gap width, effects of solid flux layer velocity, viscosity and differing solid flux layer structures (crystalline, glassy), which can affect the heat flow across the gap. Once these are understood, more accurate models of the interfacial gap can be constructed.

Acknowledgements

I would like to thank Professor Brian G. Thomas for his guidance and support on this term project. The assistance of Chunsheng Li and other colleagues in metal processing simulation lab, UIUC is gratefully acknowledged.

References

[1] J.R. Popov etc. Formation of casting with complex geometry thermo-mechanical effects, growth and influence of the air gap. Int. J. Heat Mass Transfer. Vol.36, No.11, pp2861-2867,1993

[2] Ronald J. O'Malley. Report about kinetic model for mold flux crystallization. 1999

[3] E Takeuchi etc. The formation of oscillation marks in the continuously cast steel slabs. Metallurgical Transaction B Vol.15B Sep. 1984

[4] B. G. Thomas etc. Thermal distortion of solidifying shell near meniscus in continuous casting of steel. Solidification Science & Processing Conference, Honolulu, HI, 1995, JIM/TMS

[5] B. G. Thomas etc. Effect of transverse depressions and oscillation marks on heat transfer in the continuous casting mold. Sensors and Modeling in Materials Processing, pp117-142, 1998

[6] B. G. Thomas etc. CON1D manual version 4.1, 1998

[7] E Takeuchi etc. Effect of oscillation mark formation on the surface quality of continuously cast steel slabs. Metallurgical Transaction B Vol.16B Sep. 1985

[8] David Tak Kei Lui. Master thesis, 1995

Appendices

i) Index of figures

ii) Input file for test problem: amk9.inp

iii) Input file for example problem:
- n001.inp (no oscillation mark case)
- o001.inp (with oscillation mark case)

iv) Output file for example problem
- n001.ext (no oscillation mark case)
- o001.ext (with oscillation mark case)

APPENDIX I: Index of figures

APPENDIX II: Input file for test problem amk9.inp

```
                CON1D-4.11 Slab Casting Heat Transfer Analysis
                University of Illinois, Brian G. Thomas, 1999
Oscillation mark model test case
                          Input Data                                INP

 (1) CASTING CONDITIONS:
           1      Number of time-cast speed data points
                  (If=1, constant casting speed)
                  Next 2 lines contain time(s) and vc(m/min)data pts
     0.
     1.00
     1456.100000  Pour temperature (C)
      225.100000  Slab thickness (mm)
     1780.000000  Slab width (mm)
      800.000000  Working mold length (mm)
      166.666667  Z-distance for heat balance  (mm)
      265.000000  Nozzle submergence depth (mm)
           1      Spray conditions (1=normal; 2=minimum)

 (2) SIMULATION PARAMETERS:
           0      Which shell to consider? (0=wide face; 1=narrow face)
           2      Which mold face to consider(0=outer, 1=inner,
                  2=straight mold or narrow face)
           -1     Calculate mold and interface (=0)
                  or enter interface heat flux data (=-1, or +1 faster)
           15     Number of zmm and q data points (if above =1 or -1)
                  Next 2 lines contain zmm(mm) and q(kW/m2) data
0.   1.     10.    20.   50.   100.  150.  200.  250.  300.  400.  500.  600.  700.
800.
220294. 5000. 12850. 9087. 5747. 4064. 3318. 2874. 2570. 2346. 2032. 1817. 1659. 1536.
1437.
          0      Is superheat treated as heatflux?
                  0=no; 1=yes (take default); -1=yes (enter data)
          12      Number of zmm and q data points(if above = -1)
                  Next 2 lines contain zmm(mm) and q(kW/m2) data
    0.  100.  200.  260.  300.  500.  700. 1000. 1500. 2000. 3000. 10000.
   94.  97.   92.  109.  197.  211.    12.   14.   80.   20.    0.     0.
           0      Do you want (more accurate) 2d calculations
                  in mold? (0=no; 1=yes)
      200.000000  Max. dist. below meniscus for 2d mold calcs (mm)
     1.00000E-03  Time increment (s)
          200     Number of slab sections
           10.    Printout interval (mm)
             0    Start output at (mm)
      810.00000   Max. simulation length (mm) ( must greater than Z-distance )
       50.00000   Max. simulation thickness (mm)
                  (smaller of max. expected shell thickness &
                  half of slab thickness)
       1000000    Max. number of iterations
          0.75    Shell thermocouple position below hot face (mm)
             1    Fraction solid for shell thicknesss location (-)

 (3) STEEL PROPERTIES:
  .1600  .8000  .0200  .0200  .1500     %C,%Mn,%S,%P,%Si
   .000   .000   .000   .000   .000     %Cr,%Ni,%Cu,%Mo,%Ti
  .0500  .0000  .0000  .0000  .0000     %Al,%V,%N,%Nb,%W
  .0000                                %Co,(additional components)
        1000 Grade flag
                   (1000,304,316,317,347,410,419,420,430,999)
           0  Use segregation model?  (0=no,1=yes)
```

```
          1456.1  Steel liquidus temperature (C)
            1456  Steel solidus temperature (C)
       7.2000000  Steel density (g/cm^3)
      272.000000  Heat fusion of steel (kJ/kg)
   8.000000E-01  Steel emissivity (-)
            0.67  Steel specific heat (kJ/kg deg K)
            46.5  Steel thermal conductivity (W/mK)
       -1.000000  Steel thermal expansion coefficient (-)

(4) SPRAY ZONE VARIABLES:
       35.000000  Water and ambient temperature in spray zone(Deg C)
           5      Number of zones
No.  Zone starts at   #of rolls  Roll radius  Water flux   Fraction of
     (mm below top)   in zone       (m)       (l m-2 s-1)  q thru roll
  1       800.000          1         .064       8.090        .010
  2      2000.000          9         .086       3.110        .080
  3      2710.000         20         .127       1.760        .220
  4      8700.001         13         .162       1.320        .200
  5     13640.000         30         .222        .950        .360
        14000.000         End of last spray zone (mm)

(5) MOLD FLUX PROPERTIES:
36.70 40.80  3.60  2.16   .65    %CaO,%SiO2,%MgO,%Na2O,%K2O
  .00   .70   .00  1.26   .00    %FeO,%Fe2O3,%NiO,%MnO,%Cr2O3
 5.60   .00   .00   .00   .00    %Al2O3,%TiO2,%B2O3,%Li2O,%SrO
  .00   .00   .00   .00   .00    %ZrO2,%F,%free C,%total C,%CO2
       1080.0000  Mold flux solidification temperature(c)
        2.000000  Solid flux conductivity(W/mK)
        2.300000  Liquid flux conductivity(W/mK)
        10.00000  Flux viscosity at 1300C (poise)
     2800.000000  Mold flux density(kg/m^3)
      250.000000  Flux absorption coefficient(1/m)
       1.5000000  Flux index of refraction(-)
            (-1 = take default f(composition)
   9.000000E-01  Slag emissivity(-)
             6    Exponent for temperature dependency of viscosity
             1    Form of mold powder consumption rate(1=kg/m^2; 2=kg/t)

            1.05  Mold powder consumption rate
            0.00  Location of peak heat flux (m)
            0.80  Slag rim thickness at metal level (mm)
            0.50  Slag rim thickness above heat flux peak (mm)

(6) INTERFACE HEAT TRANSFER VARIABLES:
          13       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.    10.  20. 100. 200. 300. 400. 500. 600. 650. 700. 750. 800.
     .025 .054 .084 .068 .060 .056 .059 .064 .068 .070 .074 .081 .093
   5.000000E-09  Flux/mold contact resistance(m^2K/W)
   5.000000E-01  Mold surface emissivity(-)
   0.0600000000  Air conductivity(W/mK)
   1.000000000   Oscillation mark depth(mm)
   5.0000000000  Width of oscillation mark (mm)
       1.666667  Oscillation frequency(cps)
                 (-1=take default cpm=2*ipm casting speed)
       10.00000  Oscillation stroke(mm)

(7)  MOLD WATER PROPERTIES:
   6.150000E-01  Water thermal conductivity(W/mK)(-1=default=f(T))
```

```
   8.000000E-04  Water viscosity(Pa-s)(-1=default=f(T))
    4179.000000  Water heat capacity(J/kgK)(-1=default=f(T))
     995.600000  Water density(kg/m3)(-1=default=f(T))

(8) MOLD GEOMETRY:
       57.00000  Mold thickness including water channel (mm),(outer rad.,top)
       57.00000  Mold thickness including water channel (mm),(inner rad.,top)
      94.000000  Distance of meniscus from top of mold (mm)
      24.000000  Distance between cooling water channels(center to center)(mm)
     315.000000  Mold thermal conductivity(W/mK)
      30.000000  Cooling water temperature at mold top(C)
      0.2020000  Cooling water pressure(MPa)
      25.000000  Cooling water channel depth(mm)
       5.000000  Cooling water channel width(mm)
          1      Form of cooling water flowrate/velocity(1=m/s ; 2=L/s)
      7.800000   Cooling water flowrate per channel / velocity
                 (> 0 cooling water from mold top to bottom
                 < 0 cooling water from mold bottom to top)
   11.985000    11.760000 Machine radius(m) (outer &inner radius)
         9      Number of mold coating/plating thickness changes down mold
  No.   Scale       Ni       Cr       Others   Air gap    Z-positions   unit
  1      .00     1.000      .100      .000      .000         .000       (mm)
  2      .00     1.050      .100      .000      .000      100.000       (mm)
  3      .00     1.100      .100      .000      .000      200.000       (mm)
  4      .00     1.150      .100      .000      .000      300.000       (mm)
  5      .00     1.200      .100      .000      .000      400.000       (mm)
  6      .00     1.250      .100      .000      .000      500.000       (mm)
  7      .00     1.300      .100      .000      .000      600.000       (mm)
  8      .00     1.350      .100      .000      .000      700.000       (mm)
  9      .00     1.400      .100      .000      .000      810.000       (mm)

         .550    72.100    67.000     1.000      .060     Conductivity  (W/mK)

   2.500000E-01  Factor to aproximate nonlinear heat flow at
                 meniscus,(first guess for 2d analysis)
   5.000000E-03    6.500000E-02  Equivalent inner and outer radius
                 for meniscus heatflow aprox. (mm)

(9) Mold Thermocouples:
           9     Total number of thermocouples (space here for t.c. location)
No.     Distance beneath     Distance below
        hot surface(mm)      meniscus(mm)
 1           24                   -1
 2           24                   20
 3           24                   121
 4           24                   226
 5           24                   347
 6           24                   446
 7           24                   666
 8           24                   876
 9           24                   981
```

APPENDIX III: Input file for example problem

i) n001.inp: no oscillation mark case

```
               CON1D-4.13 Slab Casting Heat Transfer Analysis
               University of Illinois, Brian G. Thomas, 1999
 Oscillation mark model example problem: no osc. mark
                            Input Data                                INP

 (1) CASTING CONDITIONS:
          1      Number of time-cast speed data points
                 (If=1, constant casting speed)
                 Next 2 lines contain time(s) and vc(m/min)data pts
   0.
1.0160
     1555.000000  Pour temperature (C)
      203.000000  Slab thickness (mm)
     1500.000000  Slab width (mm)
      815.000000  Working mold length (mm)
      379.000000  Z-distance for heat balance  (mm)
      265.000000  Nozzle submergence depth (mm)
          1      Spray conditions (1=normal; 2=minimum;   3=maximum)

 (2) SIMULATION PARAMETERS:
          0      Which shell to consider? (0=wide face; 1=narrow face)
          0      Which mold face to consider(0=outer, 1=inner,
                 2=straight mold or narrow face)
          0      Calculate mold and interface (=0)
                 or enter interface heat flux data (=-1, or +1 faster)
          6      Number of zmm and q data points (if above =1 or -1)
                 Next 2 lines contain zmm(mm) and q(kW/m2) data
    0.    30.    50.   150.   600.  1000.
  300.   280.   230.   160.   130.   130.
        1.000000  Is superheat treated as heatflux?
                 0=no; 1=yes (take default); -1=yes (enter data)
         12      Number of zmm and q data points(if above = -1)
                 Next 2 lines contain zmm(mm) and q(kW/m2) data
   0.  100.  200.  260.  300.  500.  700. 1000. 1500. 2000. 3000. 10000.
  94.   97.   92.  109.  197.  211.   12.   14.   80.   20.    0.     0.
          1      Do you want (more accurate) 2d calculations
                 in mold? (0=no; 1=yes)
       50.000000  Max. dist. below meniscus for 2d mold calcs (mm)
    3.000000E-03  Time increment (s)
        100      Number of slab sections
        1.000000  Printout interval (mm)
    0.000000E+00  Start output at (mm)
      815.000000  Max. simulation length (must > z-distance)(mm)
         30.000  Max. simulation thickness (mm)
                 (smaller of max. expected shell thickness &
                 half of slab thickness)
      25000      Max. number of iterations
    3.990000E-01  Shell thermocouple position below hot face (mm)
    3.000000E-01  Fraction solid for shell thicknesss location (-)

 (3) STEEL PROPERTIES:
  .0440  .0220  .0060  .0100  .0090     %C,%Mn,%S,%P,%Si
   .000   .000   .000   .000   .000     %Cr,%Ni,%Cu,%Mo,%Ti
  .0490  .0000  .0000  .0000  .0000     %Al,%V,%N,%Nb,%W
  .0000                                %Co,(additional components)
        1000 Grade flag
                  (1000,304,316,317,347,410,419,420,430,999)
          0  Use segregation model?  (0=no,1=yes)
```

```
    1528.000000  Steel liquidus temperature (C)
    1509.000000  Steel solidus temperature (C)
       7.400000  Steel density (g/cm^3)
     271.960000  Heat fusion of steel (kJ/kg)
   8.000000E-01  Steel emissivity (-)
   6.903600E-01  Steel specific heat (kJ/kg deg K)
      29.288000  Steel thermal conductivity (W/mK)
      -1.000000  Steel thermal expansion coefficient (-)

(4) SPRAY ZONE VARIABLES:
      35.000000  Water and ambient temperature in spray zone(Deg C)
          5      Number of zones
No.  Zone starts at   #of rolls  Roll radius  Water flux   Fraction of
     (mm below top)   in zone       (m)       (l m-2 s-1)  q thru roll
  1       815.000          1        .064       8.090        .010
  2       940.000          9        .086       3.110        .080
  3      2710.000         20        .127       1.760        .220
  4      8700.002         13        .162       1.320        .200
  5     13640.000         30        .222        .950        .360
        14000.000         End of last spray zone (mm)

(5) MOLD FLUX PROPERTIES:
36.70 40.80  3.60  2.16   .65    %CaO,%SiO2,%MgO,%Na2O,%K2O
  .00   .70   .00  1.26   .00    %FeO,%Fe2O3,%NiO,%MnO,%Cr2O3
 5.60   .00   .00   .00   .00    %Al2O3,%TiO2,%B2O3,%Li2O,%SrO
  .00   .00   .00   .00   .00    %ZrO2,%F,%free C,%total C,%CO2
    900.000000  Mold flux solidification temperature(c)
        1.24000  Solid flux conductivity(W/mK)
        2.80000  Liquid flux conductivity(W/mK)
       1.280000  Flux viscosity at 1300C (poise)
    2500.000000  Mold flux density(kg/m^3)
     900.000000  Flux absorption coefficient(1/m)
       1.500000  Flux index of refraction(-)
           (-1 = take default f(composition)
   9.000000E-01  Slag emissivity(-)
           0.85  Exponent for temperature dependency of viscosity
          1      Form of mold powder consumption rate(1=kg/m^2; 2=kg/t)

           0.17  Mold powder consumption rate
   0.000000E+00  Location of peak heat flux (m)
   8.000000E-01  Slag rim thickness at metal level (mm)
   5.000000E-01  Slag rim thickness above heat flux peak (mm)

(6) INTERFACE HEAT TRANSFER VARIABLES:
          1      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.
  .01
   2.300000E-09  Flux/mold contact resistance(m^2K/W)
   5.000000E-01  Mold surface emissivity(-)
   6.000000E-02  Air conductivity(W/mK)
       0.000001  Oscillation mark depth(mm)
       0.000001  Width of oscillation mark (mm)
       1.417000  Oscillation frequency(cps)
                 (-1=take default cpm=2*ipm casting speed)
      10.000000  Oscillation stroke(mm)

(7)  MOLD WATER PROPERTIES:
```

```
   6.150000E-01  Water thermal conductivity(W/mK)(-1=default=f(T))
   7.977000E-04  Water viscosity(Pa-s)(-1=default=f(T))
    4179.000000  Water heat capacity(J/kgK)(-1=default=f(T))
     995.600000  Water density(kg/m3)(-1=default=f(T))

(8) MOLD GEOMETRY:
      56.800000  Mold thickness including water channel (mm),(outer rad.,top)
      46.800000  Mold thickness including water channel (mm),(inner rad.,top)
      85.000000  Distance of meniscus from top of mold (mm)
      29.000000  Distance between cooling water channels(center to center)(mm)
     314.700000  Mold thermal conductivity(W/mK)
      30.000000  Cooling water temperature at mold top(C)
   2.020000E-01  Cooling water pressure(MPa)
      25.000000  Cooling water channel depth(mm)
       5.000000  Cooling water channel width(mm)
         1       Form of cooling water velocity/flowrate(1=m/s ; 2=L/s)
       7.600000  Cooling water velocity/flowrate per face
                 (> 0 cooling water from mold top to bottom
                 < 0 cooling water from mold bottom to top)
      12.000000       11.760000 Machine radius(m) (outer &inner radius)
         7       Number of mold coating/plating thickness changes down mold
  No.   Scale       Ni       Cr       Others   Air gap    Z-positions   unit
  1      .000     1.000      .050      .000      .000        .000       (mm)
  2      .000     1.000      .050      .000      .000     200.000       (mm)
  3      .000     1.000      .050      .000      .000     400.000       (mm)
  4      .000     1.000      .050      .000      .000     450.000       (mm)
  5      .000     1.000      .050      .000      .000     450.100       (mm)
  6      .000     1.000      .050      .000      .000     600.000       (mm)
  7      .000     1.000      .050      .000      .000     820.100       (mm)
         .550    80.000    72.000     1.000      .060    Conductivity  (W/mK)

   2.500000E-01  Factor to aproximate nonlinear heat flow at
                 meniscus,(first guess for 2d analysis)
   5.000000E-03    6.500000E-02  Equivalent inner and outer radius
                 for meniscus heatflow aprox. (mm)

(9) MOLD THERMOCOUPLES:
         0       Total number of thermocouples

(10) Additional Data:
    6465.517000  Total channel cross sectional area(mm^2)
                 (served by water flow line where temp rise measured)
         0       Osc.marks simulation flag(0=average,1=transient)
```

ii) o001.inp: with oscillation mark case

```
                CON1D-4.13 Slab Casting Heat Transfer Analysis
                University of Illinois, Brian G. Thomas, 1999
  Oscillation mark model example problem: with osc. mark
                              Input Data                              INP
(1) CASTING CONDITIONS:
          1       Number of time-cast speed data points
                  (If=1, constant casting speed)
                  Next 2 lines contain time(s) and vc(m/min)data pts
    0.
1.0160
     1555.000000  Pour temperature (C)
      203.000000  Slab thickness (mm)
     1500.000000  Slab width (mm)
      815.000000  Working mold length (mm)
      379.000000  Z-distance for heat balance  (mm)
      265.000000  Nozzle submergence depth (mm)
          1       Spray conditions (1=normal; 2=minimum;   3=maximum)

 (2) SIMULATION PARAMETERS:
          0       Which shell to consider? (0=wide face; 1=narrow face)
          0       Which mold face to consider(0=outer, 1=inner,
                  2=straight mold or narrow face)
          0       Calculate mold and interface (=0)
                  or enter interface heat flux data (=-1, or +1 faster)
          6       Number of zmm and q data points (if above =1 or -1)
                  Next 2 lines contain zmm(mm) and q(kW/m2) data
     0.    30.    50.   150.   600.  1000.
   300.   280.   230.   160.   130.   130.
        1.000000  Is superheat treated as heatflux?
                  0=no; 1=yes (take default); -1=yes (enter data)
         12       Number of zmm and q data points(if above = -1)
                  Next 2 lines contain zmm(mm) and q(kW/m2) data
    0.  100.  200.  260.  300.  500.  700. 1000. 1500. 2000. 3000. 10000.
   94.   97.   92.  109.  197.  211.   12.   14.   80.   20.    0.     0.
          1       Do you want (more accurate) 2d calculations
                  in mold? (0=no; 1=yes)
       50.000000  Max. dist. below meniscus for 2d mold calcs (mm)
    3.000000E-03  Time increment (s)
        100       Number of slab sections
        1.000000  Printout interval (mm)
    0.000000E+00  Start output at (mm)
      815.000000  Max. simulation length (must > z-distance)(mm)
         30.000   Max. simulation thickness (mm)
                  (smaller of max. expected shell thickness &
                  half of slab thickness)
       25000      Max. number of iterations
    3.990000E-01  Shell thermocouple position below hot face (mm)
    3.000000E-01  Fraction solid for shell thicknesss location (-)

 (3) STEEL PROPERTIES:
  .0440  .0220  .0060  .0100  .0090     %C,%Mn,%S,%P,%Si
   .000   .000   .000   .000   .000     %Cr,%Ni,%Cu,%Mo,%Ti
  .0490  .0000  .0000  .0000  .0000     %Al,%V,%N,%Nb,%W
  .0000                                %Co,(additional components)
        1000 Grade flag
                   (1000,304,316,317,347,410,419,420,430,999)
           0  Use segregation model?  (0=no,1=yes)
```

```
     1528.000000  Steel liquidus temperature (C)
     1509.000000  Steel solidus temperature (C)
        7.400000  Steel density (g/cm^3)
      271.960000  Heat fusion of steel (kJ/kg)
    8.000000E-01  Steel emissivity (-)
    6.903600E-01  Steel specific heat (kJ/kg deg K)
       29.288000  Steel thermal conductivity (W/mK)
       -1.000000  Steel thermal expansion coefficient (-)

(4) SPRAY ZONE VARIABLES:
       35.000000  Water and ambient temperature in spray zone(Deg C)
           5      Number of zones
No.  Zone starts at   #of rolls  Roll radius  Water flux   Fraction of
     (mm below top)   in zone       (m)       (l m-2 s-1)  q thru roll
  1       815.000          1        .064       8.090        .010
  2       940.000          9        .086       3.110        .080
  3      2710.000         20        .127       1.760        .220
  4      8700.002         13        .162       1.320        .200
  5     13640.000         30        .222        .950        .360
        14000.000         End of last spray zone (mm)

(5) MOLD FLUX PROPERTIES:
36.70 40.80  3.60  2.16   .65    %CaO,%SiO2,%MgO,%Na2O,%K2O
  .00   .70   .00  1.26   .00    %FeO,%Fe2O3,%NiO,%MnO,%Cr2O3
 5.60   .00   .00   .00   .00    %Al2O3,%TiO2,%B2O3,%Li2O,%SrO
  .00   .00   .00   .00   .00    %ZrO2,%F,%free C,%total C,%CO2
     900.000000  Mold flux solidification temperature(c)
         1.24000  Solid flux conductivity(W/mK)
         2.80000  Liquid flux conductivity(W/mK)
        1.280000  Flux viscosity at 1300C (poise)
     2500.000000  Mold flux density(kg/m^3)
      900.000000  Flux absorption coefficient(1/m)
        1.500000  Flux index of refraction(-)
            (-1 = take default f(composition)
    9.000000E-01  Slag emissivity(-)
            0.85  Exponent for temperature dependency of viscosity
           1      Form of mold powder consumption rate(1=kg/m^2; 2=kg/t)

            0.57  Mold powder consumption rate
    0.000000E+00  Location of peak heat flux (m)
    8.000000E-01  Slag rim thickness at metal level (mm)
    5.000000E-01  Slag rim thickness above heat flux peak (mm)

(6) INTERFACE HEAT TRANSFER VARIABLES:
           1      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.
  .01
  2.300000E-09  Flux/mold contact resistance(m^2K/W)
    5.000000E-01  Mold surface emissivity(-)
    6.000000E-02  Air conductivity(W/mK)
           0.546  Oscillation mark depth(mm)
        6.990000  Width of oscillation mark (mm)
        1.417000  Oscillation frequency(cps)
                  (-1=take default cpm=2*ipm casting speed)
       10.000000  Oscillation stroke(mm)

(7)  MOLD WATER PROPERTIES:
    6.150000E-01  Water thermal conductivity(W/mK)(-1=default=f(T))
    7.977000E-04  Water viscosity(Pa-s)(-1=default=f(T))
     4179.000000  Water heat capacity(J/kgK)(-1=default=f(T))
```

```
     995.600000  Water density(kg/m3)(-1=default=f(T))

(8) MOLD GEOMETRY:
      56.800000  Mold thickness including water channel (mm),(outer rad.,top)
      46.800000  Mold thickness including water channel (mm),(inner rad.,top)
      85.000000  Distance of meniscus from top of mold (mm)
      29.000000  Distance between cooling water channels(center to center)(mm)
     314.700000  Mold thermal conductivity(W/mK)
      30.000000  Cooling water temperature at mold top(C)
   2.020000E-01  Cooling water pressure(MPa)
      25.000000  Cooling water channel depth(mm)
       5.000000  Cooling water channel width(mm)
          1      Form of cooling water velocity/flowrate(1=m/s ; 2=L/s)
       7.600000  Cooling water velocity/flowrate per face
                 (> 0 cooling water from mold top to bottom
                 < 0 cooling water from mold bottom to top)
      12.000000       11.760000 Machine radius(m) (outer &inner radius)
          7      Number of mold coating/plating thickness changes down mold
  No.   Scale        Ni       Cr       Others   Air gap    Z-positions   unit
  1      .000     1.000      .050      .000      .000        .000       (mm)
  2      .000     1.000      .050      .000      .000     200.000       (mm)
  3      .000     1.000      .050      .000      .000     400.000       (mm)
  4      .000     1.000      .050      .000      .000     450.000       (mm)
  5      .000     1.000      .050      .000      .000     450.100       (mm)
  6      .000     1.000      .050      .000      .000     600.000       (mm)
  7      .000     1.000      .050      .000      .000     820.100       (mm)
         .550    80.000    72.000     1.000      .060    Conductivity  (W/mK)

   2.500000E-01  Factor to aproximate nonlinear heat flow at
                 meniscus,(first guess for 2d analysis)
   5.000000E-03    6.500000E-02  Equivalent inner and outer radius
                 for meniscus heatflow aprox. (mm)

(9) MOLD THERMOCOUPLES:
          0      Total number of thermocouples

(10) Additional Data:
    6465.517000  Total channel cross sectional area(mm^2)
                 (served by water flow line where temp rise measured)
          1      Osc.marks simulation flag(0=average,1=transient)
```

APPENDIX IV: Output file for example problem

i) n001.ext: no oscillation mark case

```
               CON1D-4.13 Slab Casting Heat Transfer Analysis
               University of Illinois, Brian G. Thomas, 1999
 Oscillation mark model example problem: no osc. mark
EXIT                 Calculated Conditions at mold Exit                  EXT


      Initial casting speed:                          16.93    (mm/s)
      Carbon content:                                 .0440    (%)
      Wide face simulation:

 (1) Derived values:
      Liquidus Temp:                                1528.00    Deg C
      Solidus Temp:                                 1509.00    Deg C
      Peritectic Temp:                                  .00    Deg C
      AE3 Temp:                                      885.71    Deg C
      AE1 Temp:                                      723.26    Deg C

      Carbon equivalent:                              .0477    (%)
 *** using initial value of casting speed ***
      Negative strip time:                              .27    (s)
      Positive strip time:                              .44    (s)
      Pitch(spacing betweeen oscillation marks):      11.95    (mm)
      % Time negative strip:                          37.58    (%)
      Average percent negative strip velocity:        67.36    (%)
 *** end of comment ***
      Cooling water velocity:                          7.60    (m/s)
      Cooling water flow rate per face:             49.1379    (L/s)
      Average mold flux thickness:                    .0230    (mm)
      (based on consumption rate)
      (assuming flux moves at casting speed)
      min. heat trans. coeff. on mold cold face       27.81    kW/m2K
      max. heat trans. coeff. on mold cold face       99.23    kW/m2K
      Water boiling temperature:                   120.5283    Deg C
      Max cold face temperature:                   195.4896    Deg C
      Mold water temp diff(in hot channel):          9.7106    Deg C
      Mold water temp diff(over all channels):       9.7106    Deg C
 *** Warning: There is danger of boiling in
      the water channels!
      Mean heat flux in mold:                       1623.30    (kW/m^2)

 (2.1) Heat balance (at  379.03 mm:)
      Heat Extracted:                                 50.50    (MJ/m^2)
      Heat Input to shell inside:                      3.15    (MJ/m^2)
      Super Heat:                                       .06    (MJ/m^2)
      Latent Heat in mushy region:                     1.07    (MJ/m^2)
      Latent Heat in Solid region:                    28.07    (MJ/m^2)
      Sensible Cooling:                               18.86    (MJ/m^2)
      Total Heat:                                     51.22    (MJ/m^2)
      Error In Heat Balance:                           1.42    (%)

 (2.2) Heat balance (at  815.02 mm:)
      Heat Extracted:                                 78.13    (MJ/m^2)
      Heat Input to shell inside:                      3.58    (MJ/m^2)
      Super Heat:                                       .08    (MJ/m^2)
      Latent Heat in mushy region:                     1.84    (MJ/m^2)
      Latent Heat in Solid region:                    43.17    (MJ/m^2)
      Sensible Cooling:                               30.32    (MJ/m^2)
      Total Heat:                                     78.98    (MJ/m^2)
```

```
     Error In Heat Balance:                           1.10    (%)

 (3) Variables calculated at moldexit( 815.02 mm):
     % taper (per mold, narrow face):                 1.47    (%)
     Shell thickness:                                22.62    (mm)
     Liquid flux film thickness:                     .1614    (mm)
     Solid flux film thickness:                     1.0047    (mm)
     Total flux film thickness:                     1.1661    (mm)
     Shell surface temperature:                     950.28    Deg C
     Mold hot face temperature:                     168.52    Deg C
     Heat flux:                                      .9023    (MW/m^2)
```

ii) o001.inp: with oscillation mark case

```
          CON1D-4.13 Slab Casting Heat Transfer Analysis
          University of Illinois, Brian G. Thomas, 1999
 Oscillation mark model example problem: with osc. mark
EXIT                    Calculated Conditions at mold Exit                  EXT


     Initial casting speed:                          16.93    (mm/s)
     Carbon content:                                 .0440    (%)
     Wide face simulation:

 (1) Derived values:
     Liquidus Temp:                                1528.00    Deg C
     Solidus Temp:                                 1509.00    Deg C
     Peritectic Temp:                                  .00    Deg C
     AE3 Temp:                                      885.71    Deg C
     AE1 Temp:                                      723.26    Deg C

     Carbon equivalent:                              .0477    (%)
 *** using initial value of casting speed ***
     Negative strip time:                              .27    (s)
     Positive strip time:                              .44    (s)
     Pitch(spacing betweeen oscillation marks):      11.95    (mm)
     % Time negative strip:                          37.58    (%)
     Average percent negative strip velocity:        67.36    (%)
 *** end of comment ***
     Cooling water velocity:                          7.60    (m/s)
     Cooling water flow rate per face:             49.1379    (L/s)
     Average mold flux thickness:                    .0770    (mm)
     (based on consumption rate)
     (assuming flux moves at casting speed)
     min. heat trans. coeff. on mold cold face       27.81    kW/m2K
     max. heat trans. coeff. on mold cold face       98.91    kW/m2K
     Water boiling temperature:                   120.5283    Deg C
     Max cold face temperature:                   194.9454    Deg C
     Mold water temp diff(in hot channel):          9.2242    Deg C
     Mold water temp diff(over all channels):       9.2242    Deg C
 *** Warning: There is danger of boiling in
     the water channels!
     Mean heat flux in mold:                       1541.90    (kW/m^2)

 (2.1) Heat balance (at  379.03 mm:)
     Heat Extracted:                                 46.87    (MJ/m^2)
     Heat Input to shell inside:                      3.15    (MJ/m^2)
     Super Heat:                                       .06    (MJ/m^2)
     Latent Heat in mushy region:                     1.51    (MJ/m^2)
     Latent Heat in Solid region:                    26.26    (MJ/m^2)
     Sensible Cooling:                               16.66    (MJ/m^2)
```

Total Heat:	47.65	(MJ/m^2)
Error In Heat Balance:	1.67	(%)

(2.2) Heat balance (at 815.02 mm:)

Heat Extracted:	74.21	(MJ/m^2)
Heat Input to shell inside:	3.58	(MJ/m^2)
Super Heat:	.08	(MJ/m^2)
Latent Heat in mushy region:	2.14	(MJ/m^2)
Latent Heat in Solid region:	41.36	(MJ/m^2)
Sensible Cooling:	27.97	(MJ/m^2)
Total Heat:	75.12	(MJ/m^2)
Error In Heat Balance:	1.23	(%)

(3) Variables calculated at moldexit(815.02 mm):

% taper (per mold, narrow face):	1.43	(%)
Shell thickness:	21.87	(mm)
Liquid flux film thickness:	.1693	(mm)
Solid flux film thickness:	.7413	(mm)
Total flux film thickness:	.9106	(mm)
Shell surface temperature:	966.56	Deg C
Mold hot face temperature:	202.16	Deg C
Heat flux:	1.1454	(MW/m^2)