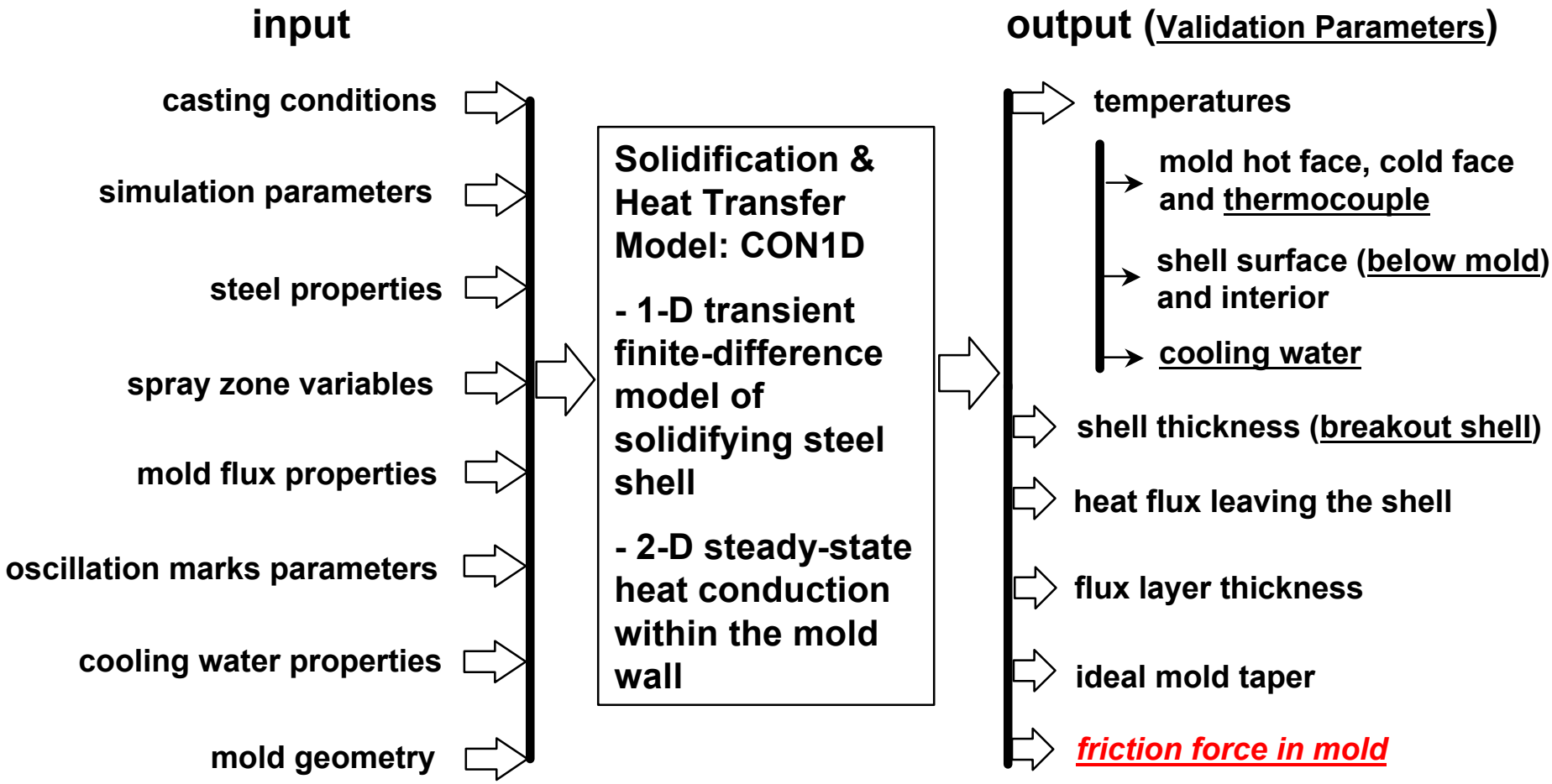
Modeling Interfacial Flux layer Phenomena in the Shell/Mold Gap Using CON1D

Ya Meng

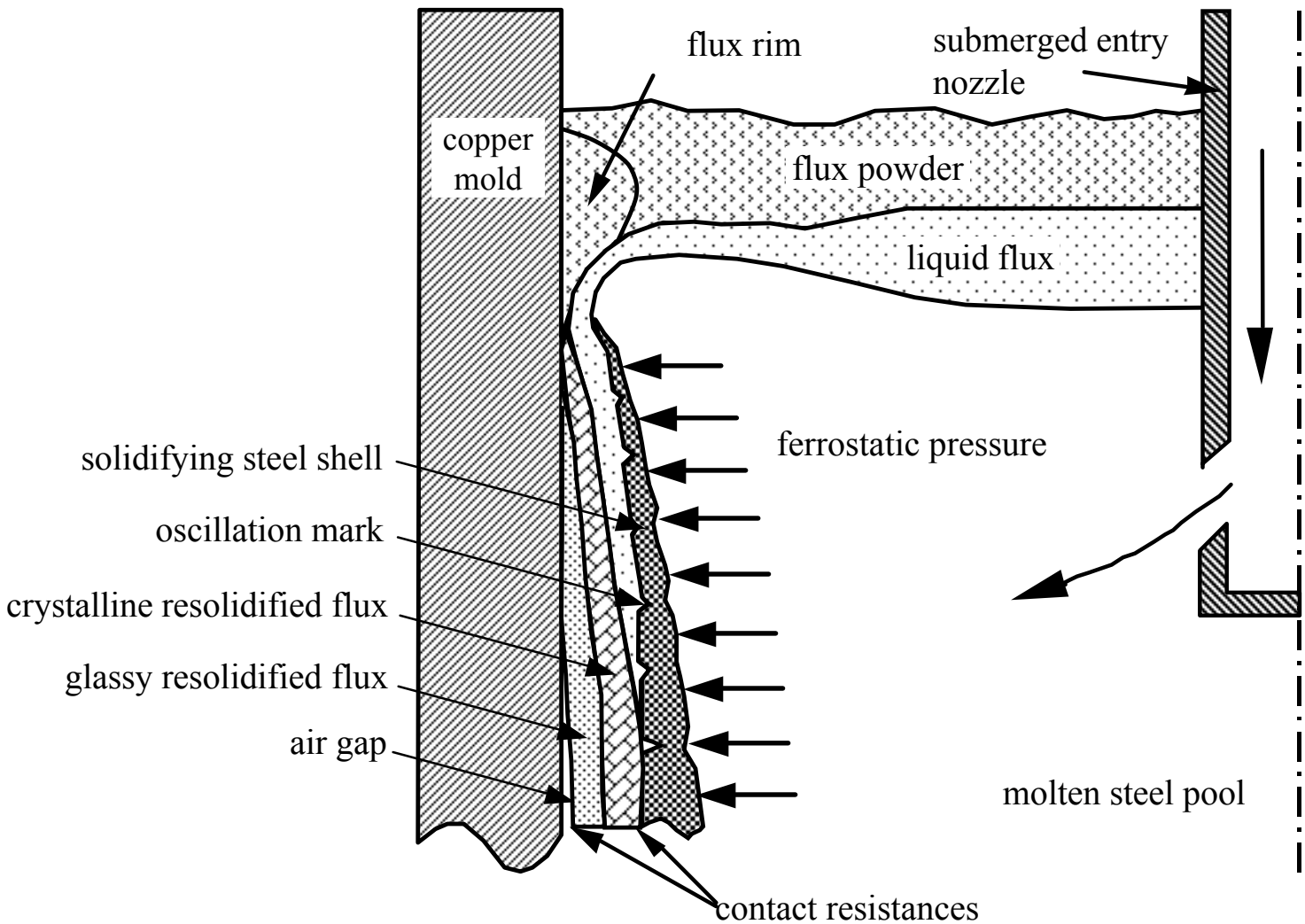
Department of Materials Science &. Engineering
University of Illinois at Urbana-Champaign

September 25, 2000

Introduction



Schematic of Continuous Casting Process



Improvements to CON1D5.0

- CON1D version 5.0 manual and new format of input file
- New output file XXXX.frc, which out put the phase fractions of shell surface and a certain depth (user input) under surface
- New spray zone model
- New oscillation mark model (optional)
- New taper calculation model
- Cooling water temperature rise adjustment by the program itself

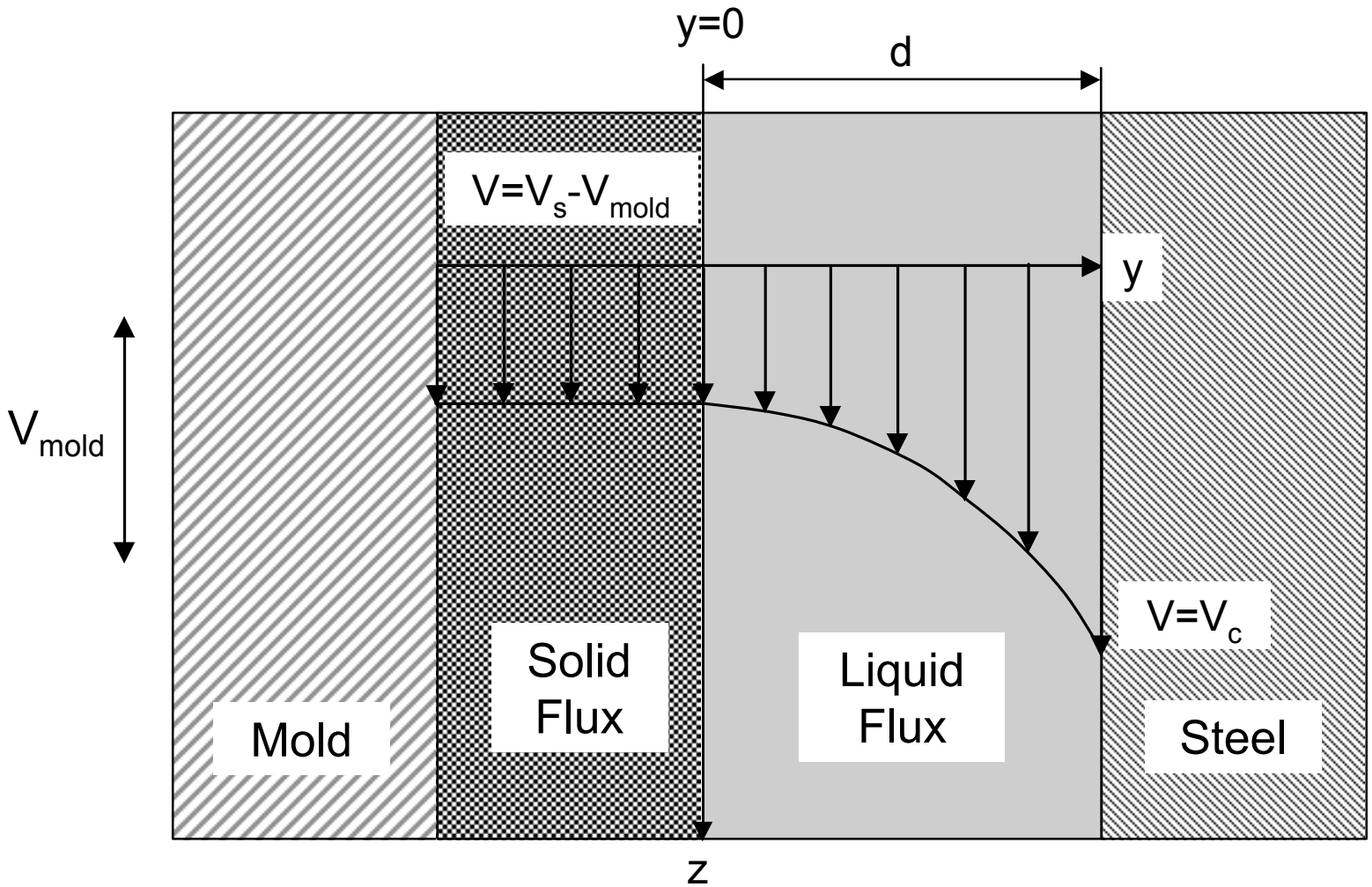
$$\Delta T_{\text{modified cooling water}} = \Delta T_{\text{cooling water}} * \frac{w_{ch} d_{ch}}{L_{ch}} * \frac{slab\,width}{totcharea}$$

- make model calibration with water ΔT measurement easier

Improvements to CON1D6.1

- CON1D version 6.1 manual and new format of input file
- New shear stress model (subroutine shear.f), predicts shear stress in the shell/mold gap and calculates friction forces during one mold oscillation cycle. Results are written into new output file XXXX.shr.
- New analytical segregation model (optional), is developed by Young Mok Won.
- Add a series of thermocouples below steel shell surface to predict steel shell temperature, results are written into new output file XXXX.sst.

Schemetic Profile of Flux Velocity



Friction Model Description

<u>Momentum balance equation</u> of flux flow in the gap:

$$r\left(\frac{DV}{Dt}+V\cdot\nabla V\right)=-\nabla P+(\nabla t)+rg \qquad (1)$$

Assume:

- Uncoupled time dependent motion (mold oscillation)
- Fully developed laminar flow
- Flow of flux only along Z axis (casting direction)

Eq. (1) is simplified:

$$\frac{\partial t_{yz}}{\partial y}+rg=0 \qquad (2)$$

$$\Rightarrow t_{yz}=-rgy+c_1 \qquad (3)$$

Friction Model Description

<u>Constitutive equation</u> for shear stress-velocity gradient in flux layer:

$$t_{yz} = m \frac{\partial V_z}{\partial y} \qquad (4)$$

Assume:

- $$m = m_s \left(\frac{T_s - T_{sol}}{T - T_{sol}} \right)^n \qquad (5)$$

Where: μ_s is flux viscosity at the interface with steel surface

T_s is steel surface temperature

T_{sol} is flux solidification temperature

n is empirical constant chosen to fit measured data

- Linear temperature gradient across flux layers

So:

$$t_{yz} = m_s \frac{d^n}{y^n} \frac{\partial V_z}{\partial y} \qquad (6)$$

Friction Model Description

Substitute Eq.(6) into Eq.(3):

$$\frac{\partial V_z}{\partial y} = -\frac{\rho g y^{n+1} + c_1 y^n}{\mu_s d^n} \qquad (7)$$

Boundary Conditions: (mold/flux & flux/steel interfaces)

$$V_z \big|_{y=0} = V_w = V_s - V_{mold}(t) \qquad (8)$$

$$V_z \big|_{y=d} = V_c \qquad (9)$$

$$\Rightarrow c_1 = \frac{(V_c - V_s)\mu_s (n+1)}{d} + \frac{\rho g d (n+1)}{n+2} \qquad (10)$$

Substitute C_1 into Eq.(7) and evaluate at y=d:

$$\frac{\partial V_z}{\partial y}\Big|_{y=d} = \frac{(n+1)(V_c - V_w)}{d} + \frac{\rho g d}{\mu_s (n+2)} \qquad (11)$$

Friction Model Description

At flux/steel interface when there is liquid flux layer:

$$\tau_{liquid} = \mu_s \frac{(n+1)(V_c - V_w)}{d} + \frac{\rho g d}{(n+2)} \qquad (12)$$

At solid/mold or solid/steel interface:

$$\tau_{solid} = f \cdot \rho_{steel} g z \qquad (13)$$

where, ϕ is coefficient of sliding friction (ϕ =0.4)

So the shear stress in mold/steel gap is:

$$\tau = Min(\tau_{liquid}, \tau_{solid}) \qquad (14)$$

The friction force for one mold face is:

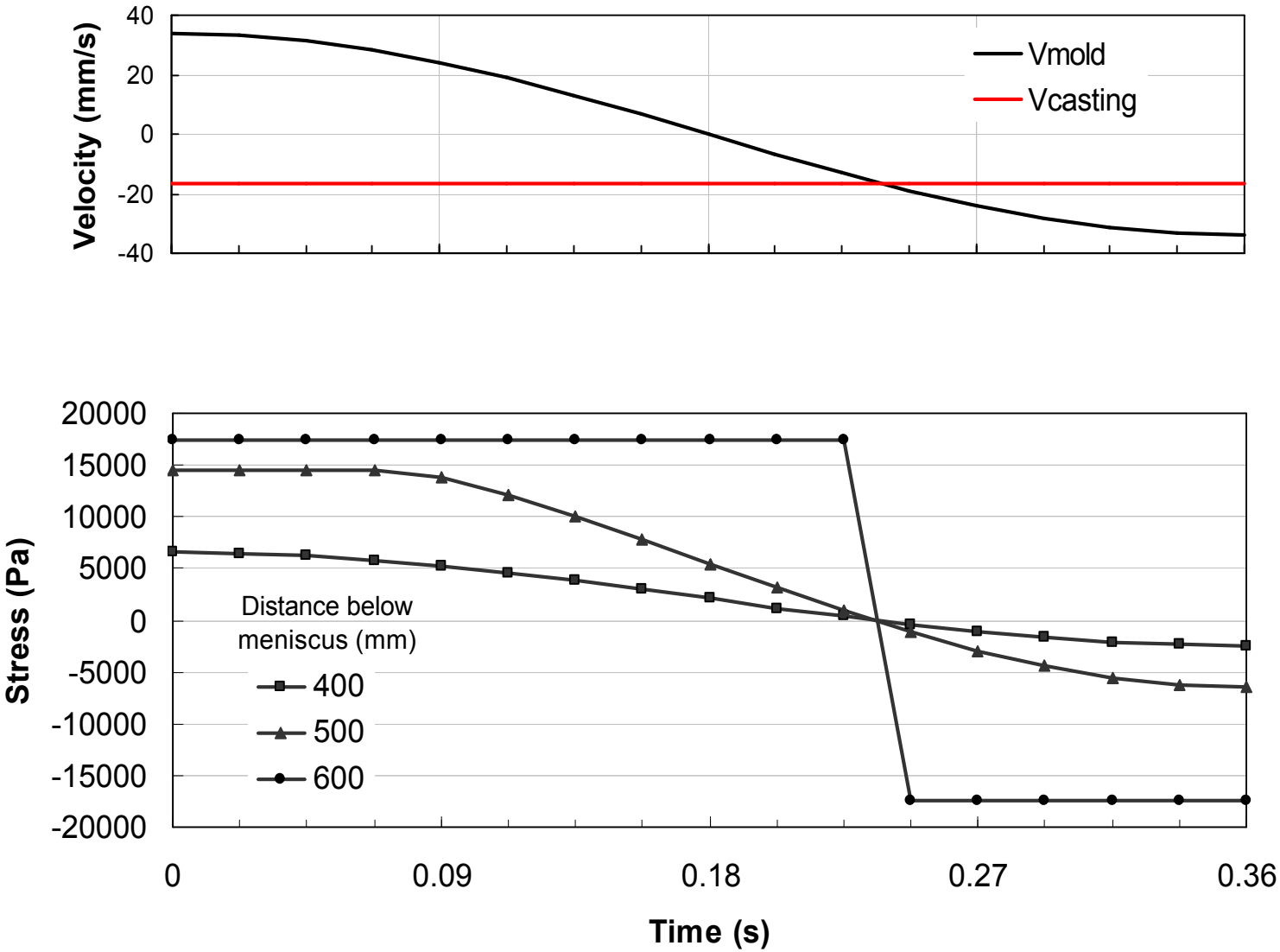
$$f = \int_0^{Z_{mold}} \tau \cdot w \cdot dz \qquad (15)$$

where, w is slab width for wide face, slab thickness for narrow face

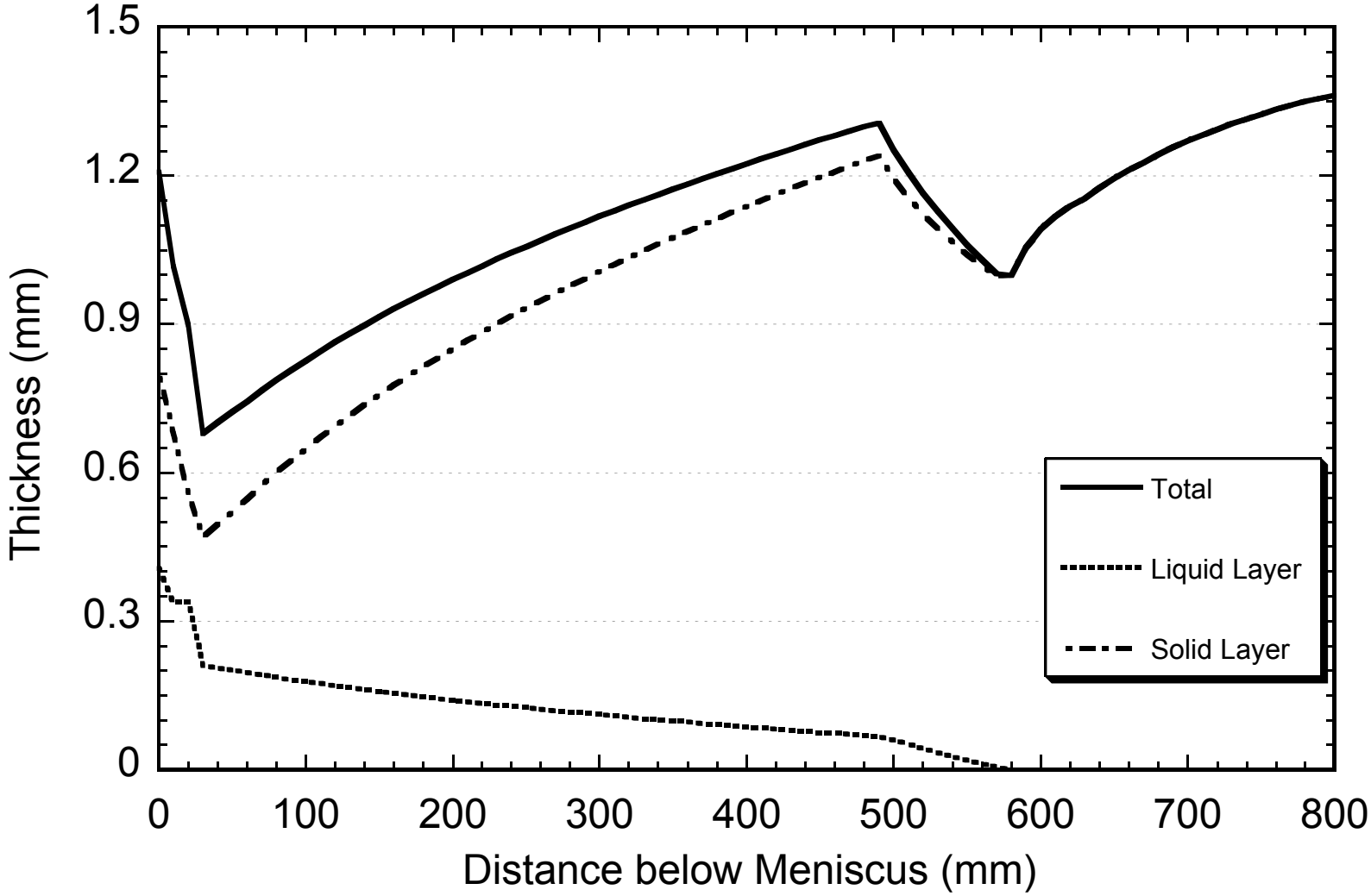
Example Application: Case 1

Casting Speed:	1.0m/min
Pour Temperature:	1550 ^{o}C
Slab Geometry:	1500mm*230mm
Nozzle Submergence depth:	265mm
Working Mold Length:	800mm
Time Step:	dt=0.001s
Mesh Size:	dx=0.5mm
Fraction Solid for Shell Thickness location:	0.3
Carbon Content:	0.05%
Mold Powder Solidification Temperature:	1080 ^{o}C
Mold Powder Conductivity (solid/liquid):	1.5/1.5W/mK
Mold Powder Viscosity at 1300 ^{o}C:	8.72poise
Exponent for temperature dependency of viscosity:	1.65
Mold Powder Consumption Rate:	0.45kg/m^2
Oscillation Mark Geometry (depth*width):	0.45*4.5mm^2
Mold Oscillation Frequency:	83.3cpm
Oscillation Stroke:	7.8mm
Negative Strip Ratio of Velocity:	0.3
Mold Thickness (including water channel):	51mm
Initial Cooling Water Temperature:	30 ^{o}C
Water Channel Geometry (depth*width*distance):	25mm*5mm*29mm
Cooling Water Flow rate:	7.8m/s

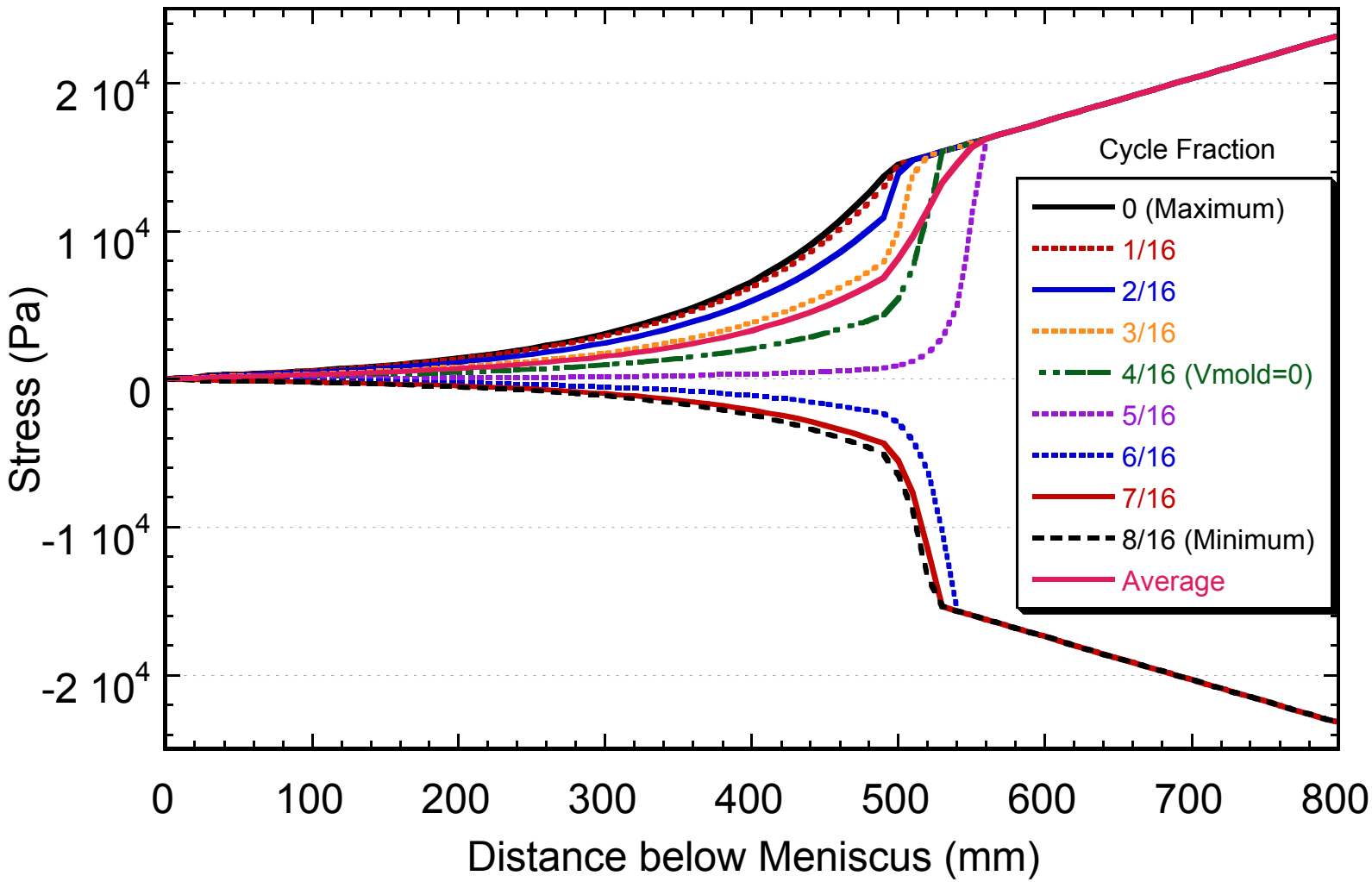
Shear Stress at Different Position down the Mold during Half Oscillation Cycle (Case 1)



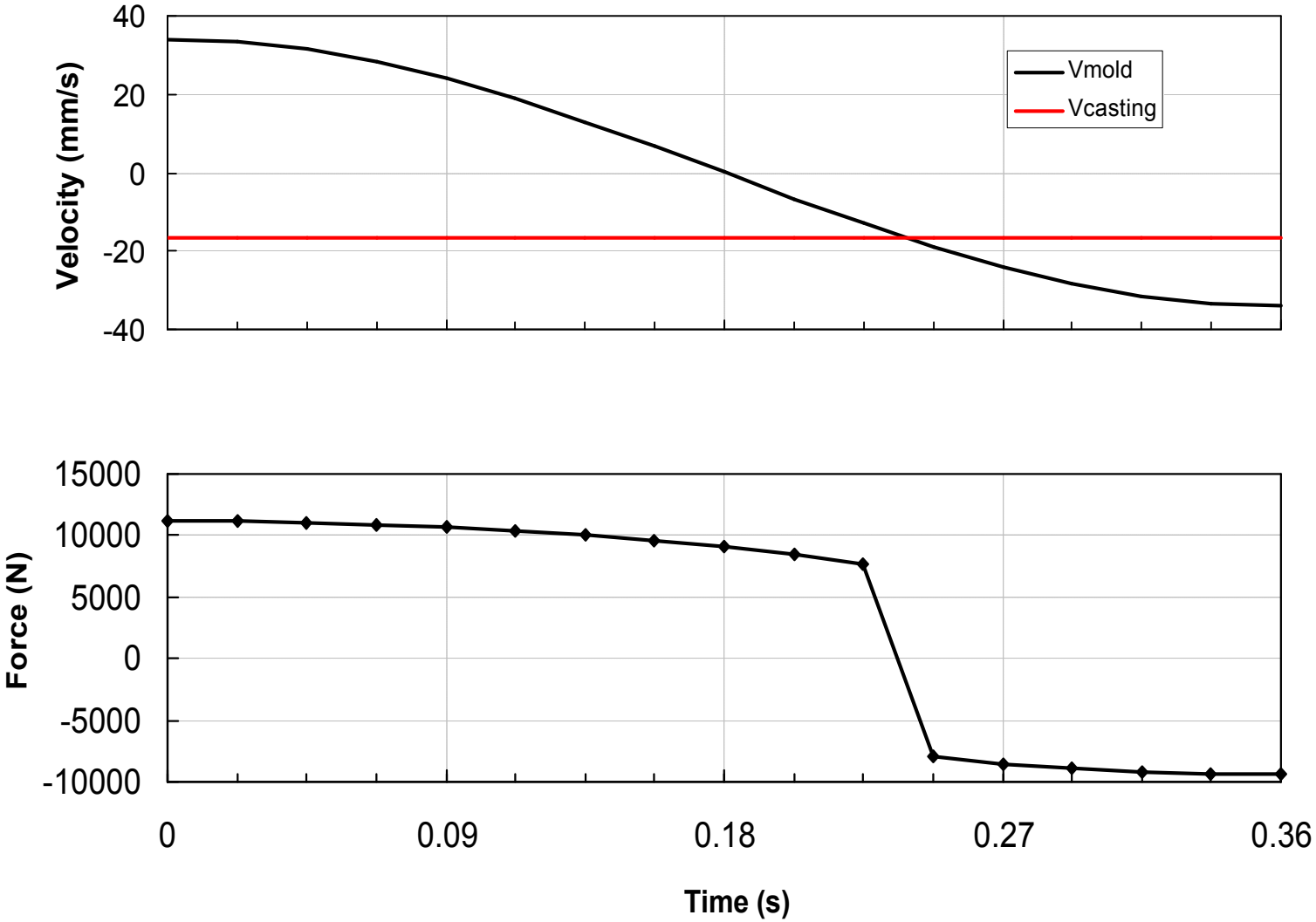
Flux Thickness : Case 1



Shear Stress down the Mold during Half Period
(Case 1)



Mold Velocity and Friction Force during Half Period
(Case 1)

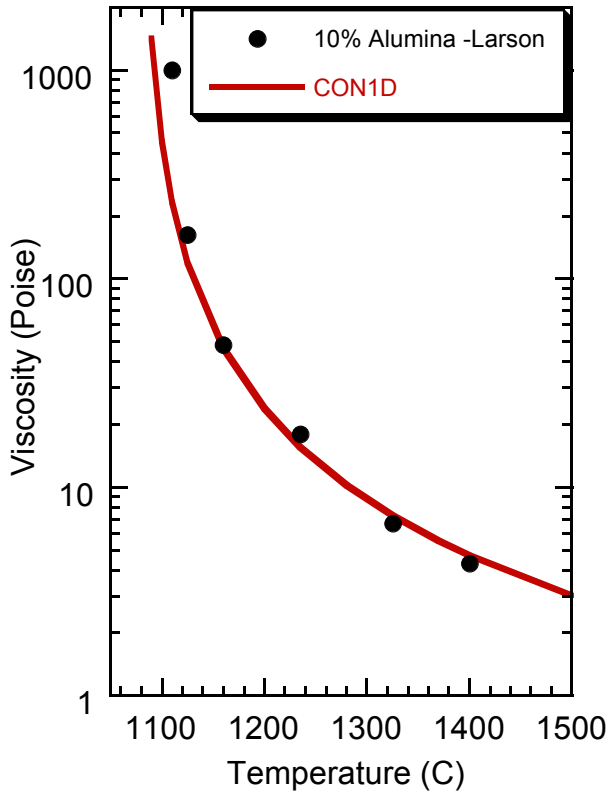


Parametric Study Parameters

	Casting Speed (m/min)	Oscillation Frequency (cpm)	Negative Strip Time (s)	Consumption Rate (kg/m^2)	Osc. Mark Geometry (mm^2)	**Friction Force Amplitude (KPa)**
Case 1	1.0	83.3	0.24	.450	.45*4.5	**17.13**
Case 2	1.3	108.3	0.19	.315	.225*2.25	**9.29**
Case 3	1.6	133.3	0.15	.230	.15*1.5	**17.64**

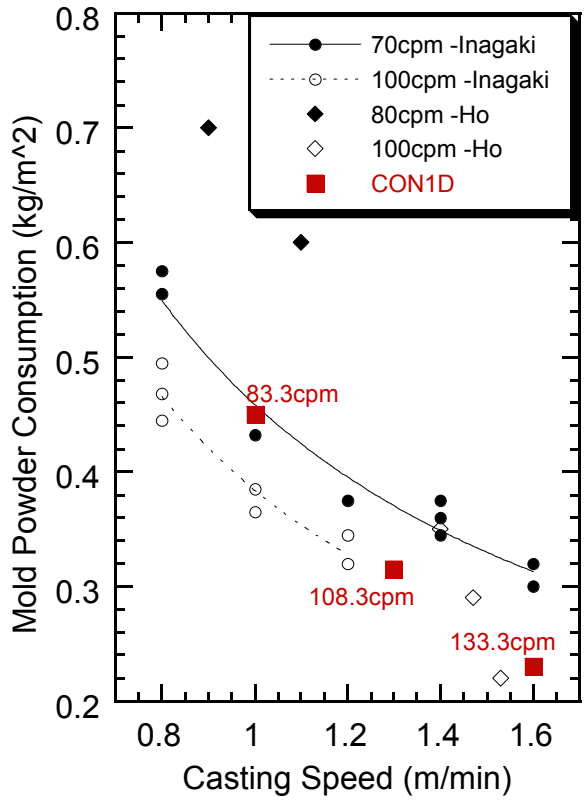
* Other conditions are same as Case 1

Parameters Chosen



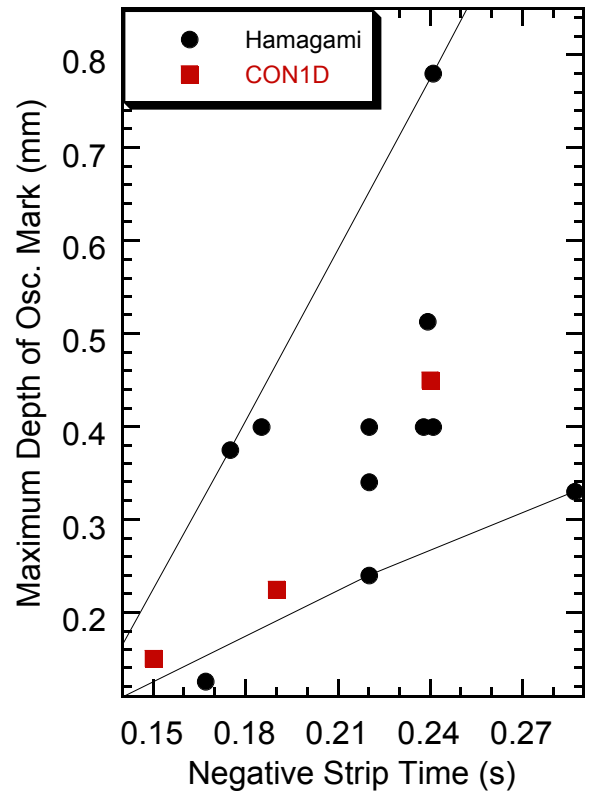
Mold powder viscosity

(D. Larson, Industrial Heating, 1986, 53, p16)



Consumption rate

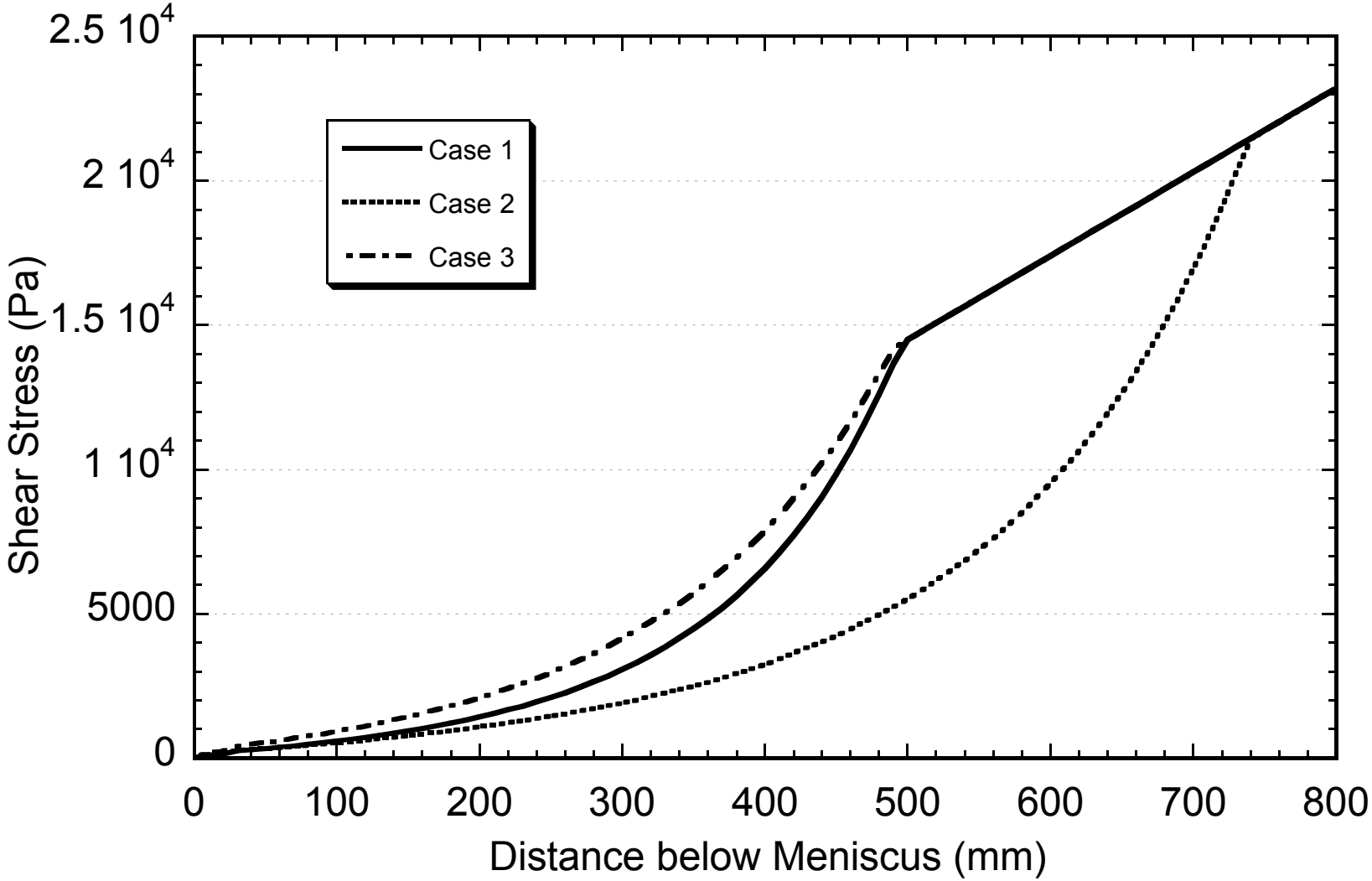
(M. Inagaki etc.,CAMP-ISIJ, 1989, 2, p309;
B. Ho, Master thesis, 1992)



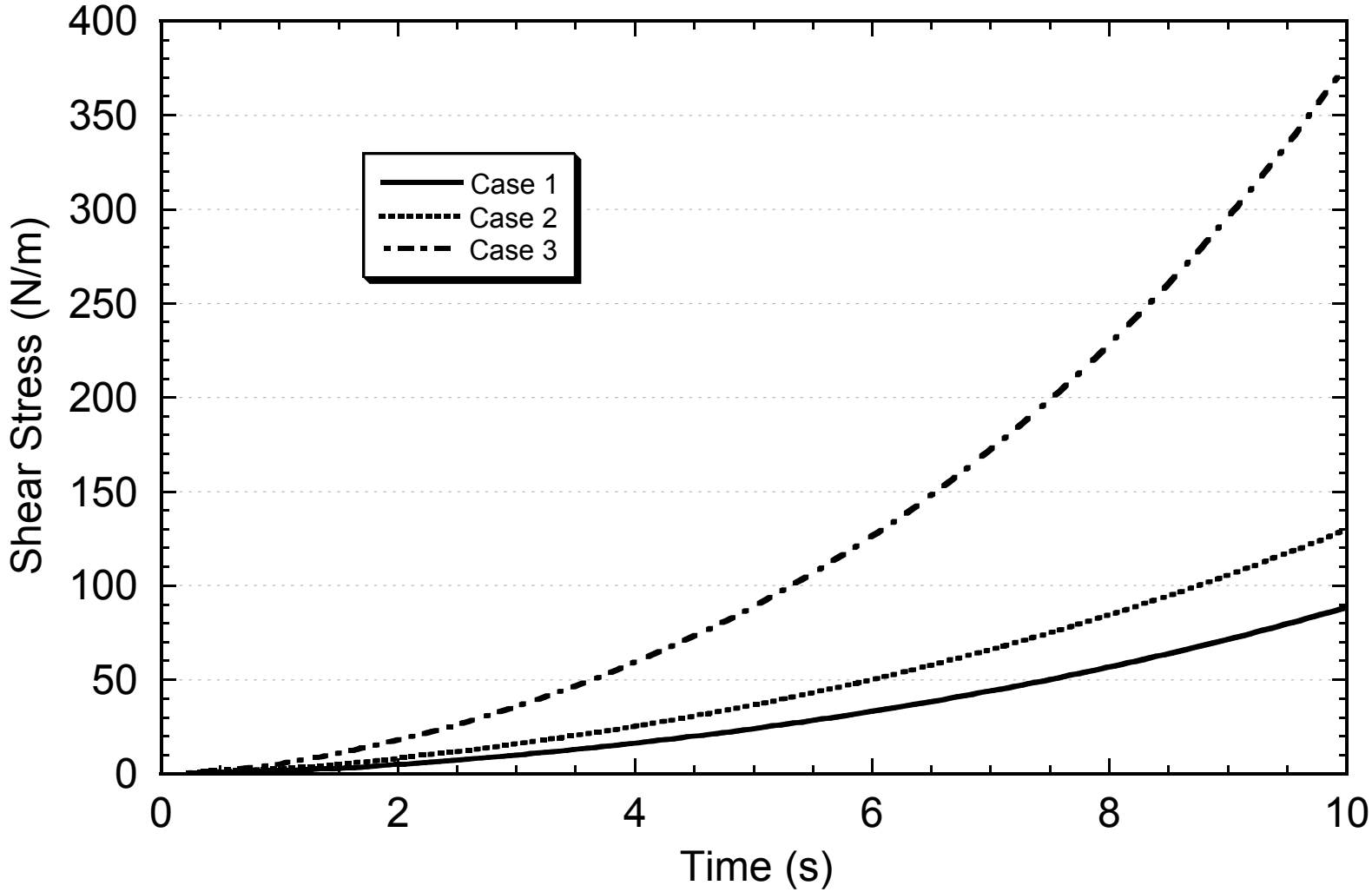
Oscillation mark depth

(K. Hamagami etc., Steelmaking Conference Proceeding, 1982, 65, p358)

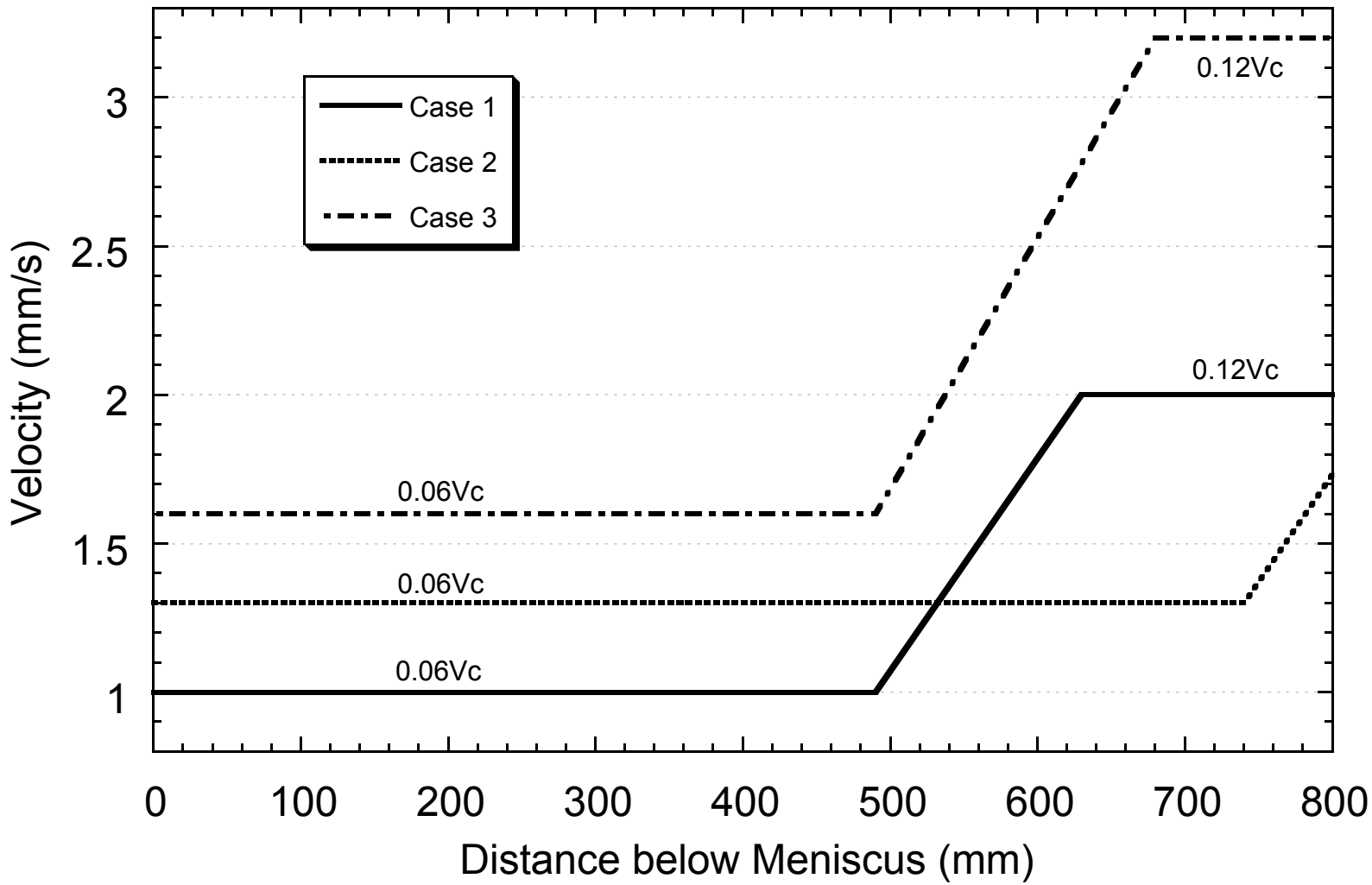
Maximum Shear Stress down the Mold Comparison



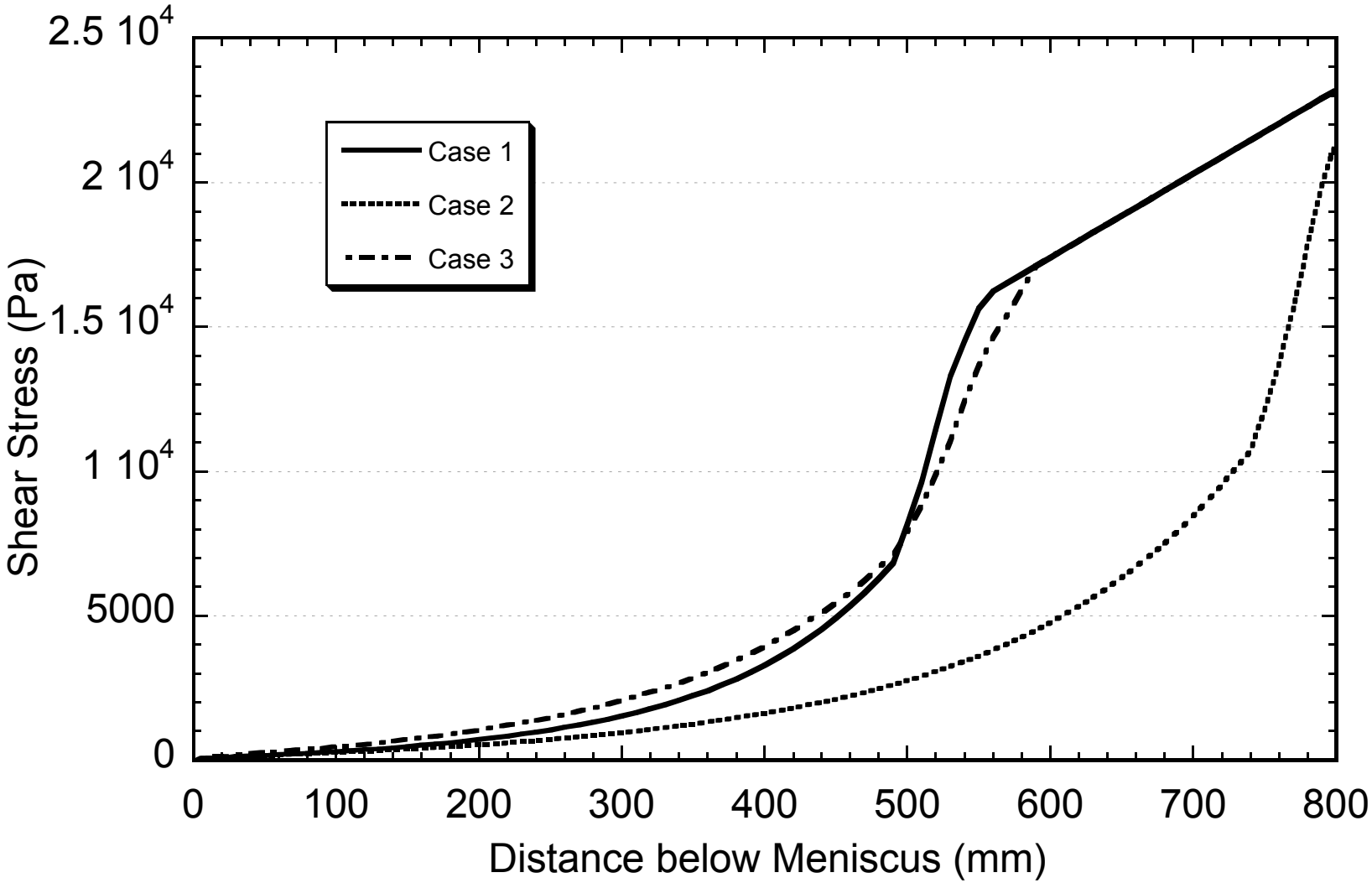
Maximum Shear Stress near Meniscus



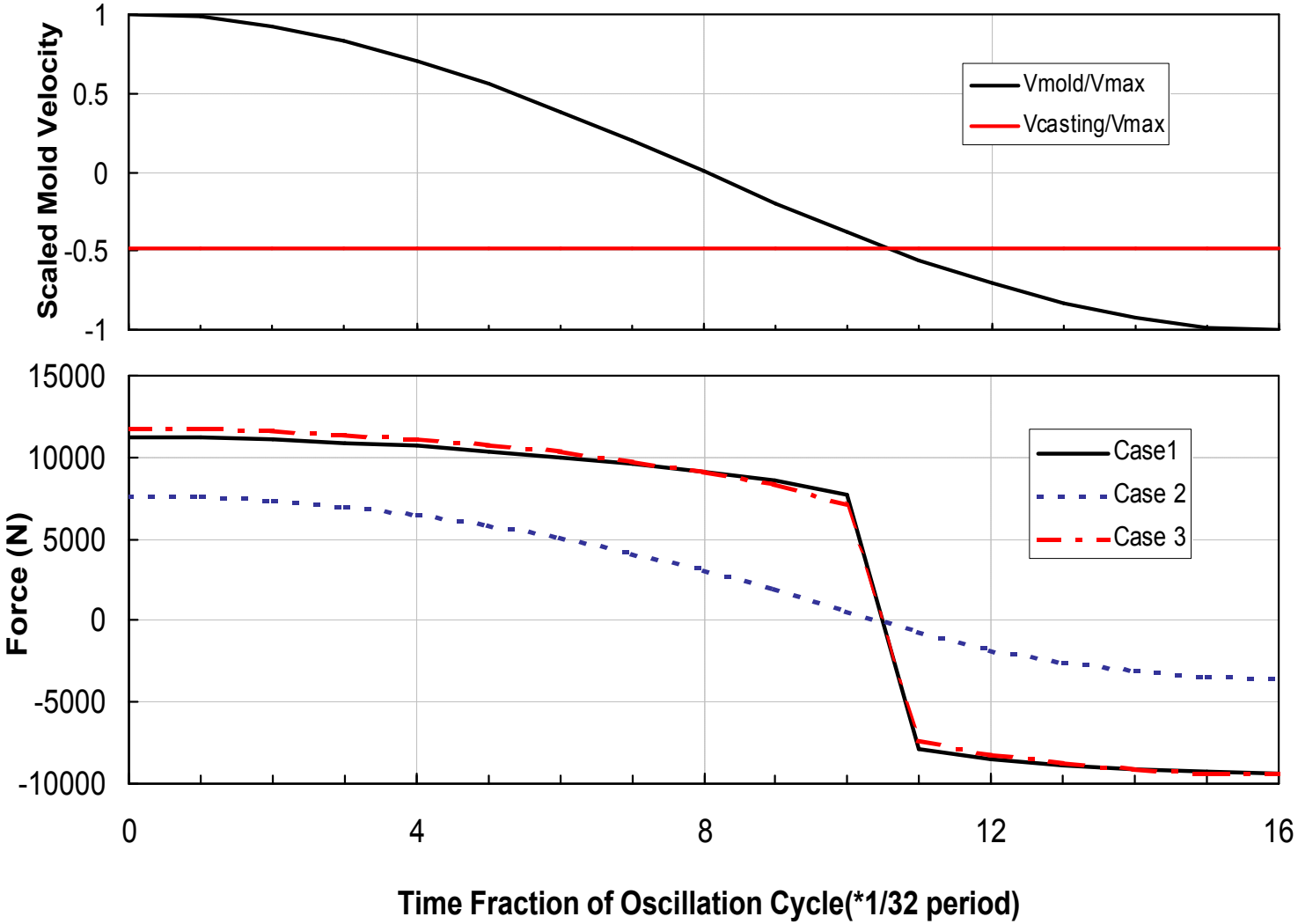
Solid Flux Layer Velocity



Average Shear Stress down the Mold Comparison

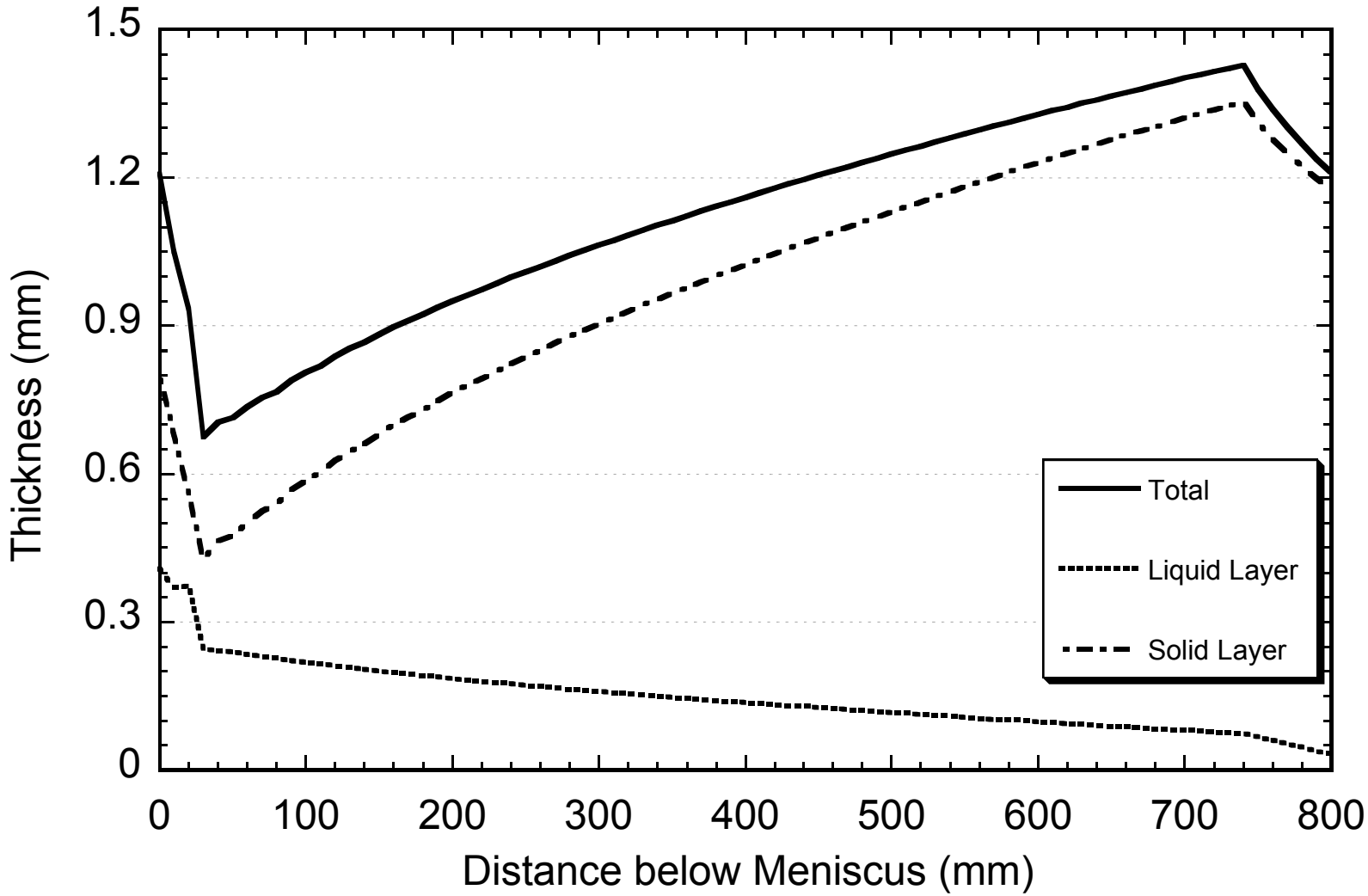


Friction Force during Half Period Comparison

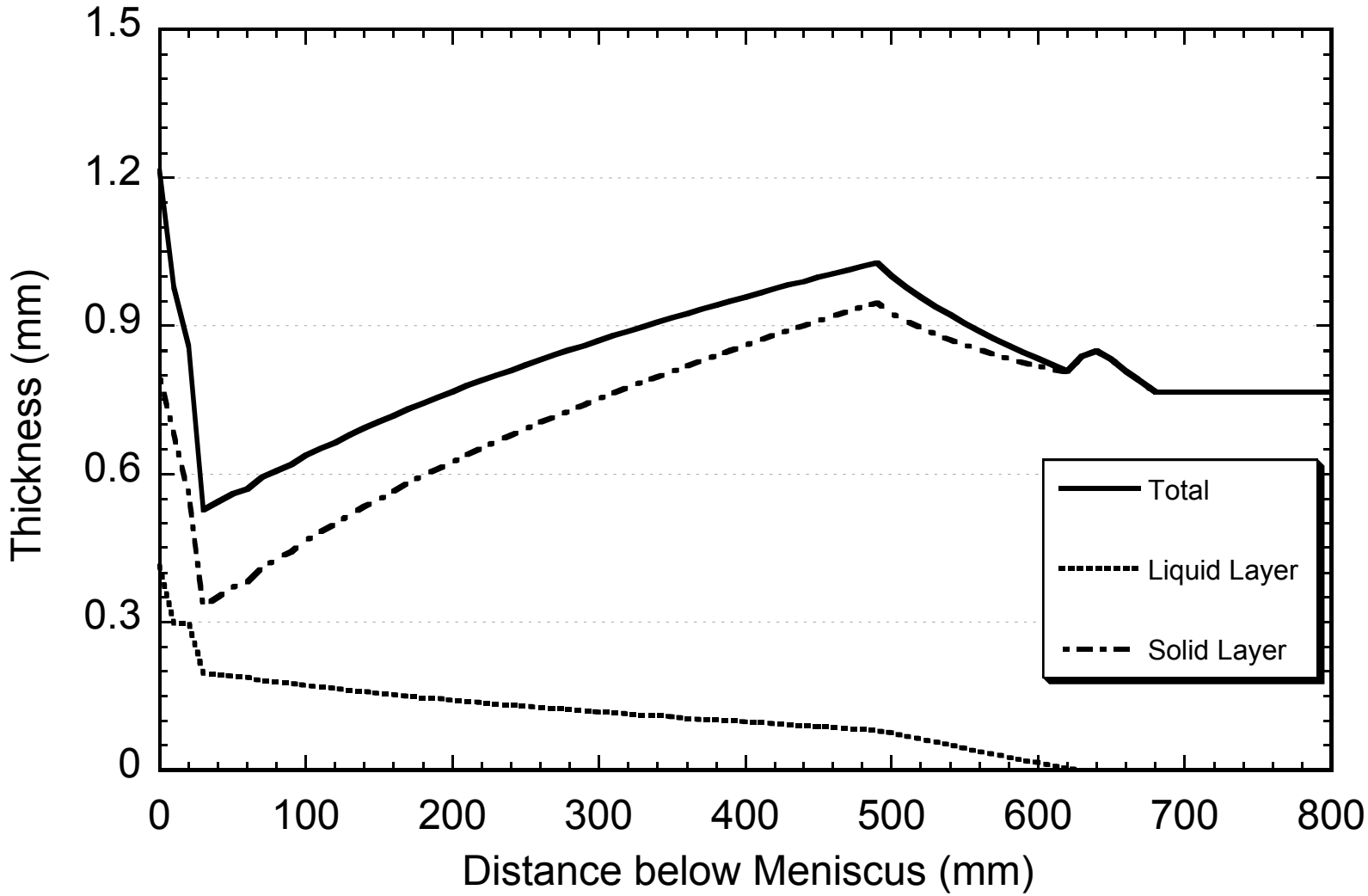


* Vmax is the amplitude velocity of mold oscillation (=π*stroke*freqency)

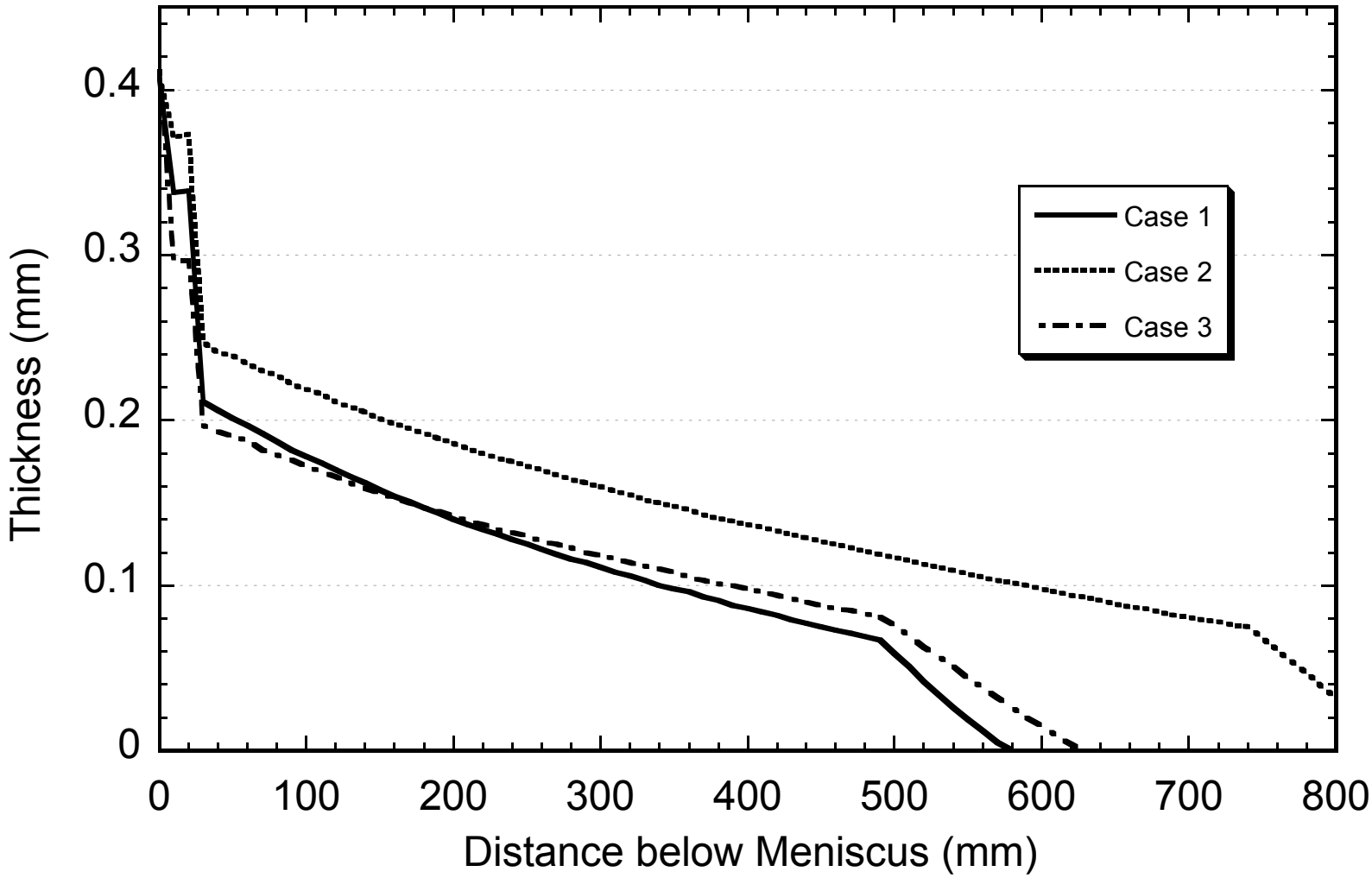
Flux Thickness : Case 2



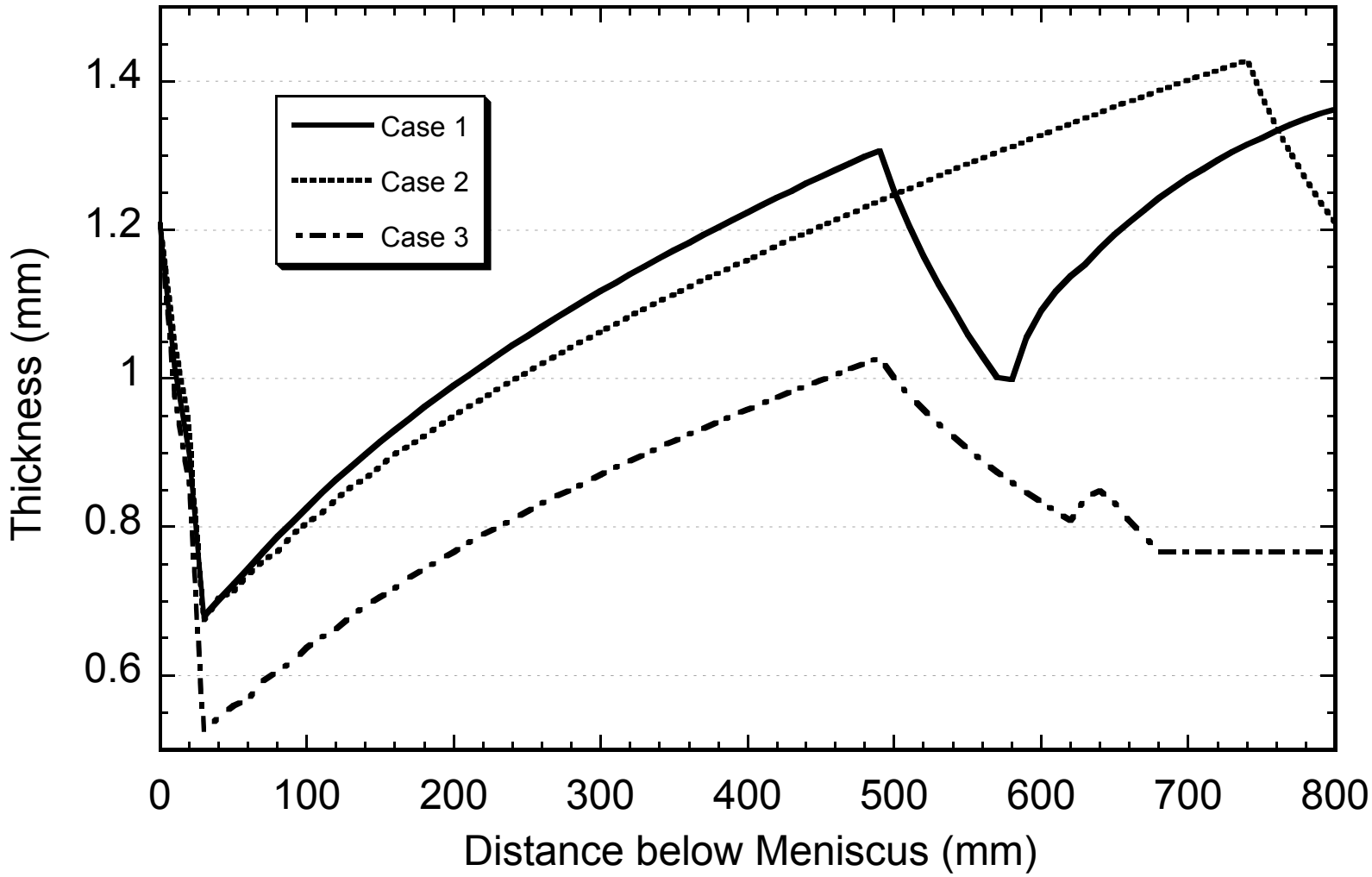
Flux Thickness : Case 3



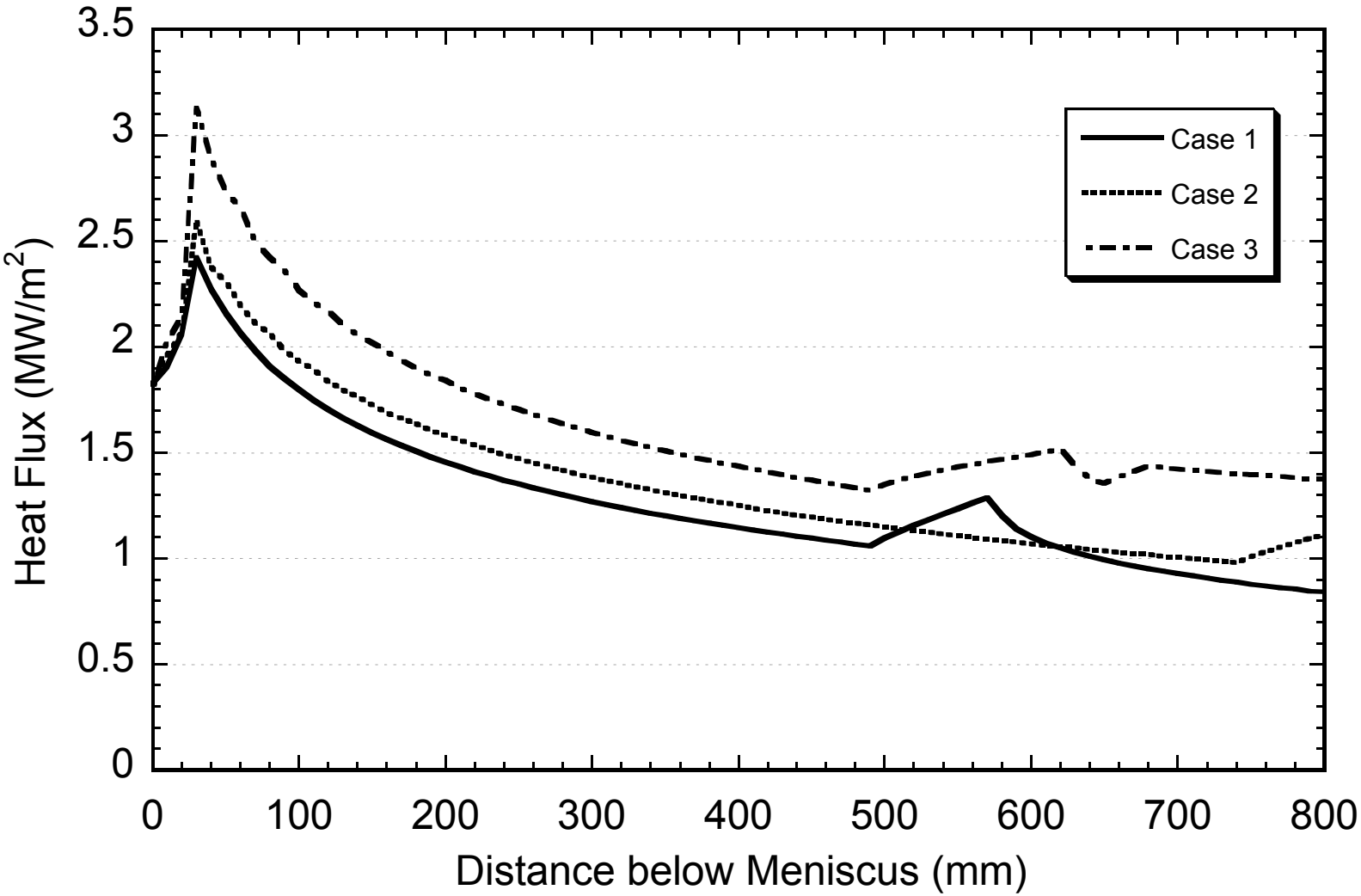
Liquid Flux Thickness Comparison



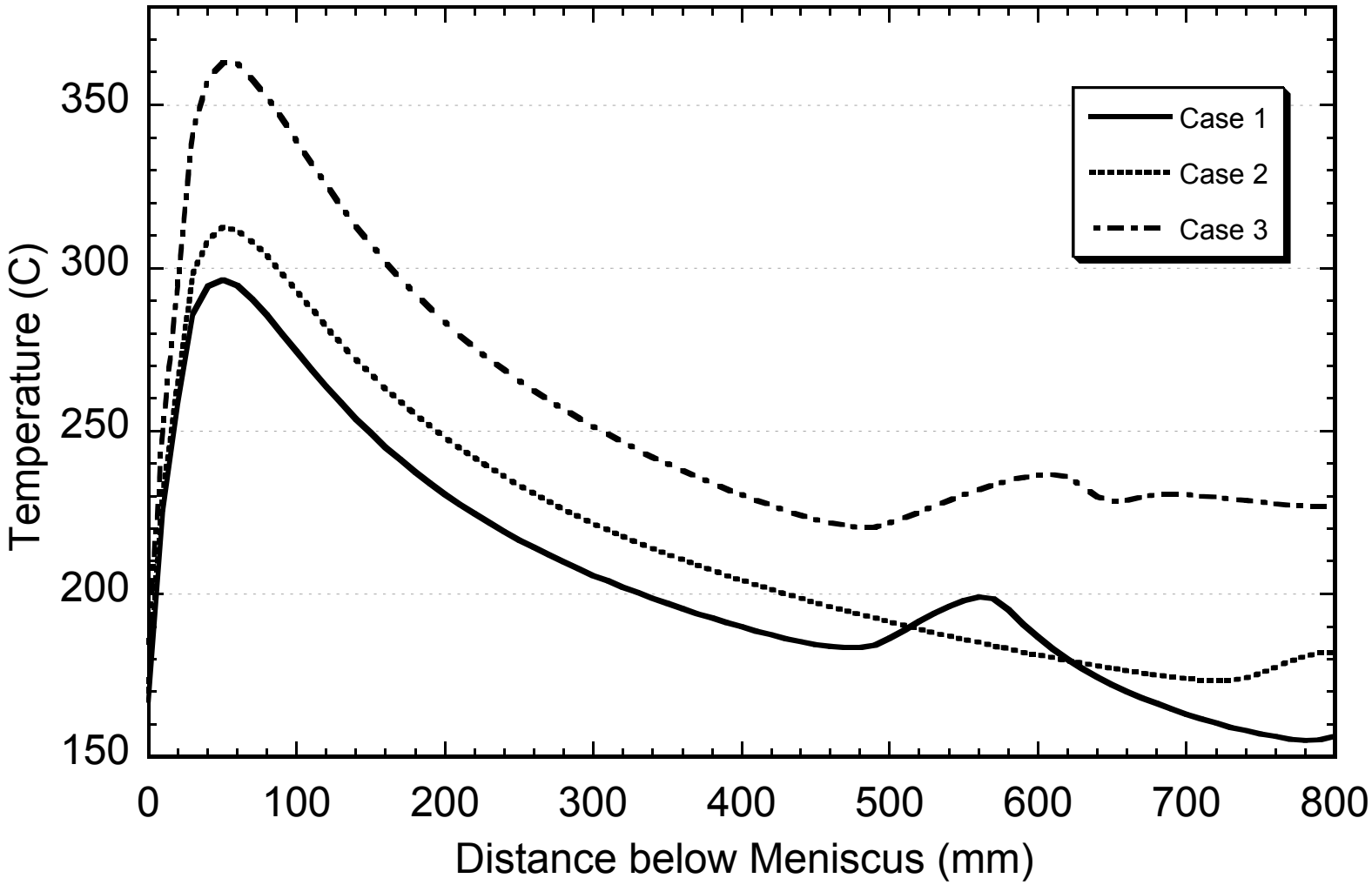
Total Flux Thickness Comparison



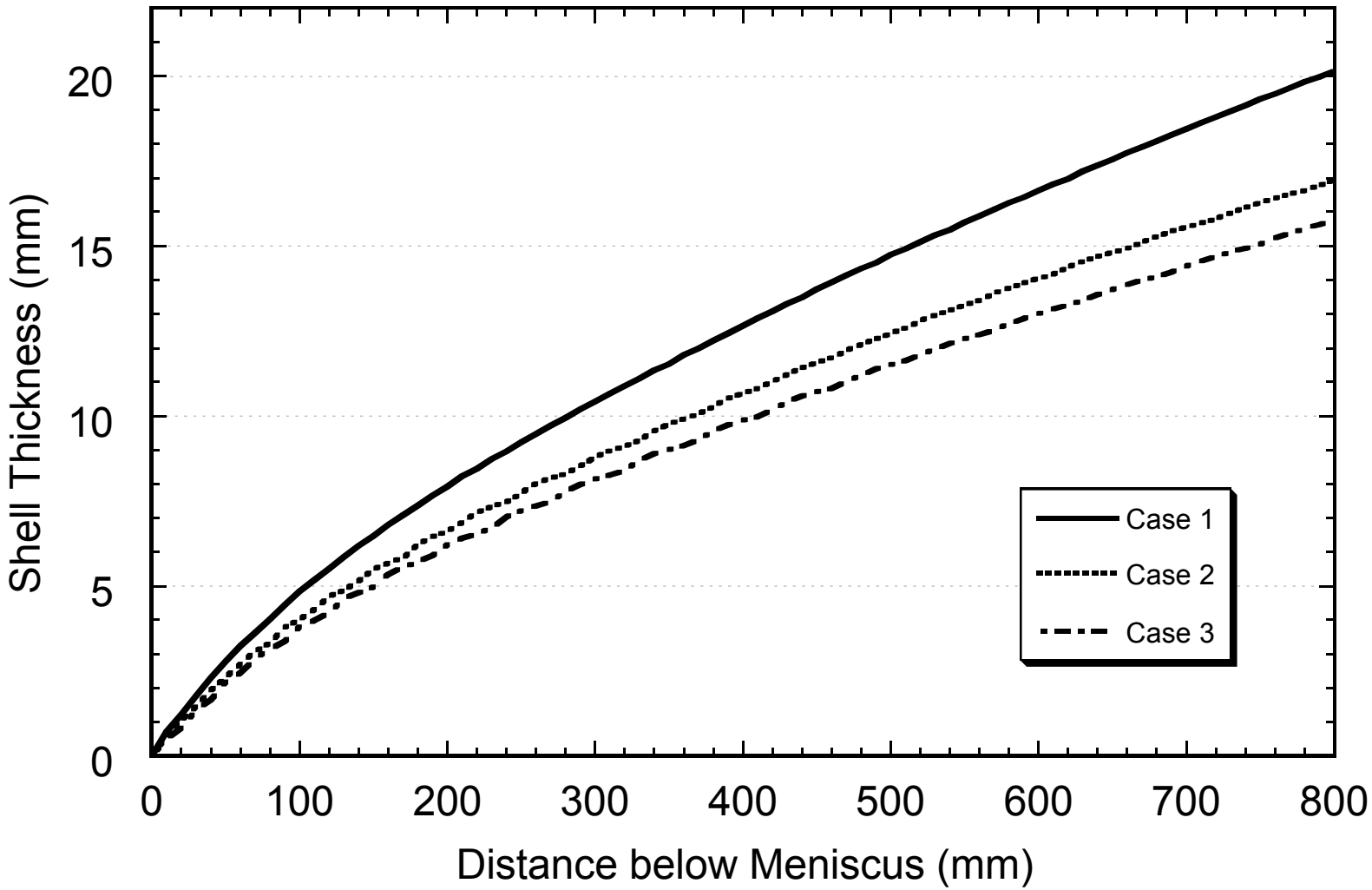
Heat Flux Comparison



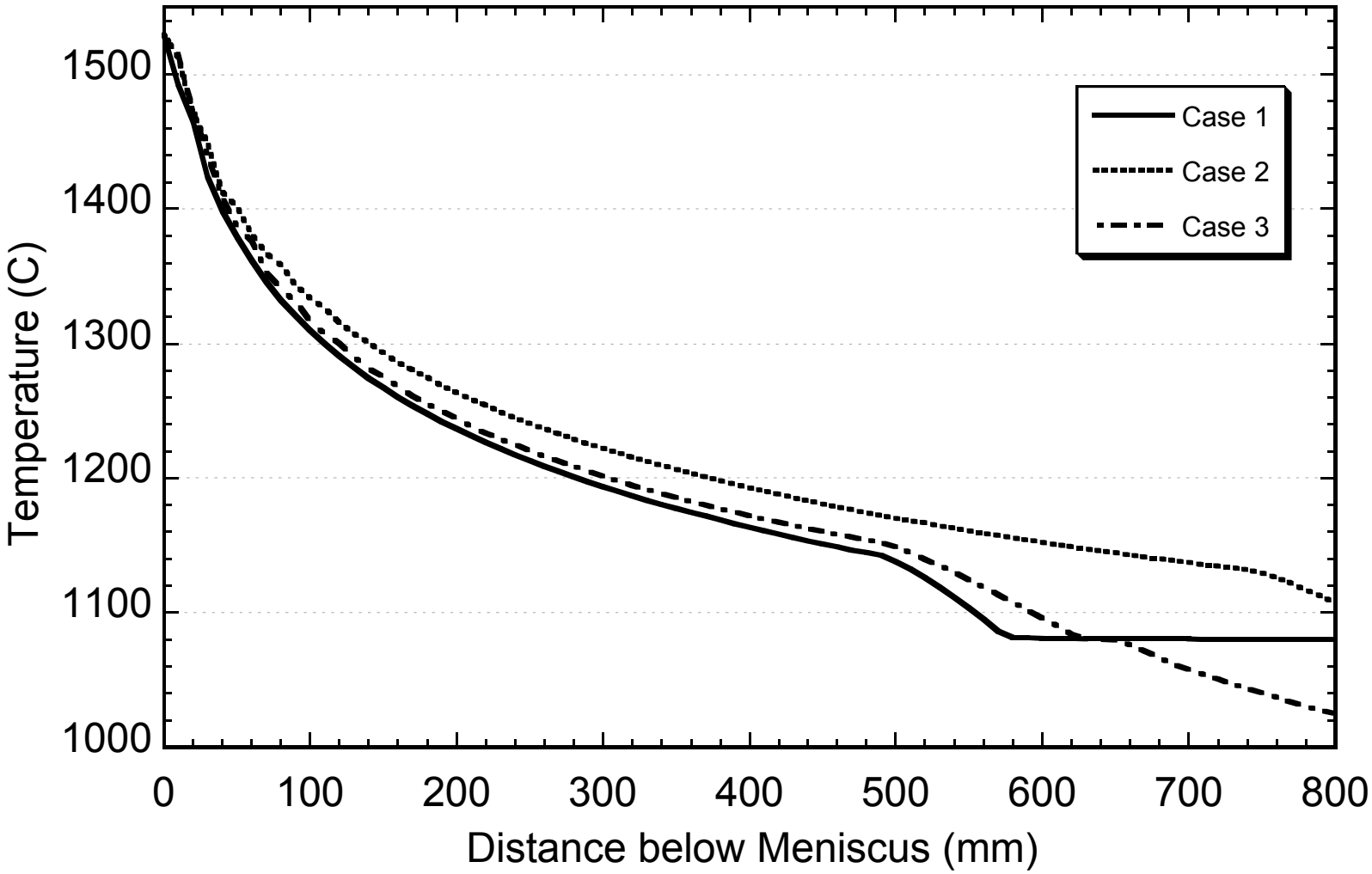
Mold Hot Face Temperature Comparison



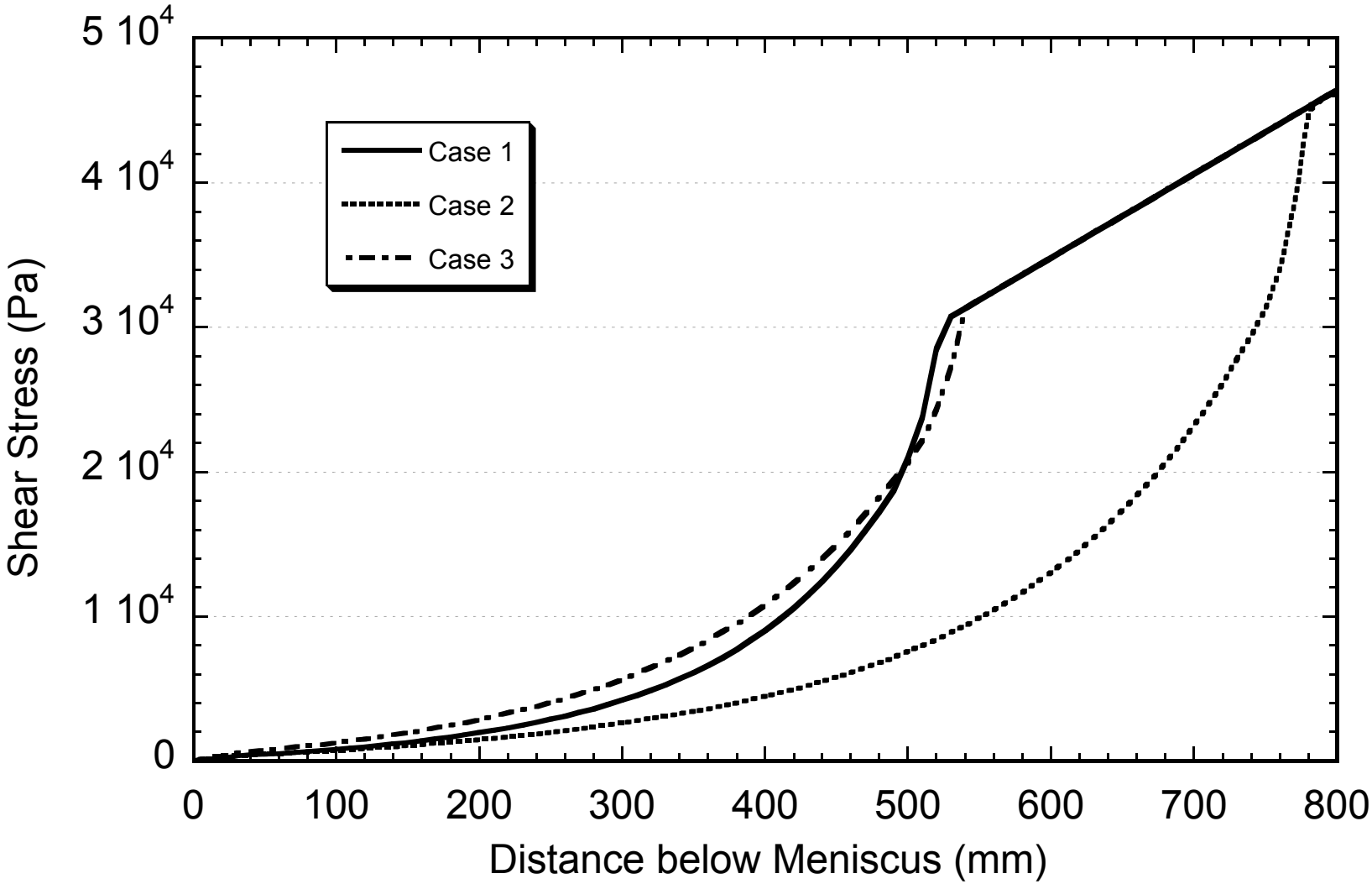
Shell Thickness Comparison



Shell Surface Temperature Comparison

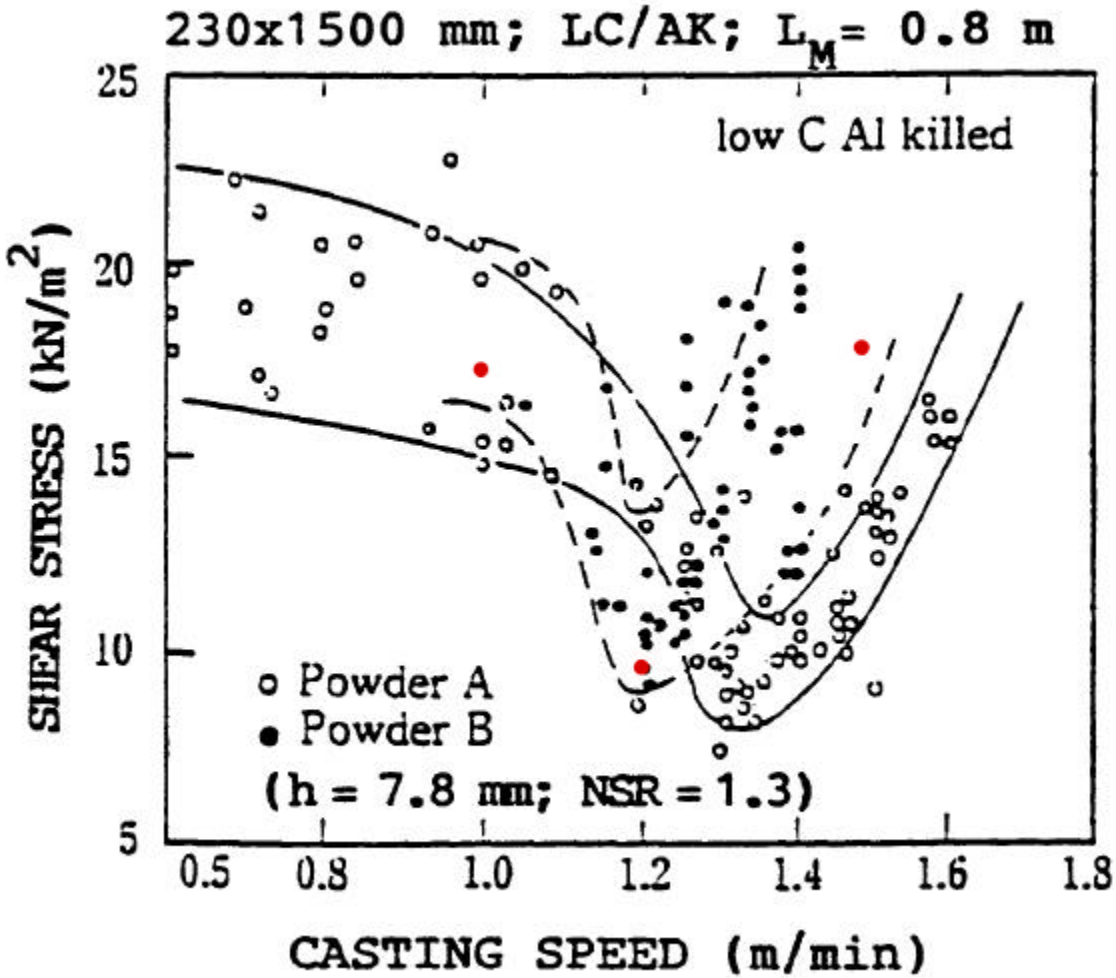


Shear Stress Amplitude down the Mold Comparison



Effect of Casting Speed on Friction Force

(From H. Nakato, S. Omiya etc., Journal of Metals. , V36 n3 Mar 1984 p44-50)



• CON1D predicted results

Consumption Rate

$CONS_{basic}$ = Consumption Rate - $\Delta CONS$

where,

$CONS_{basic}$ is the minimum consumption rate without oscillation mark

$\Delta CONS$ is the increase of consumption rate due to oscillation mark, in order to satisfy the mass balance:

$$\Delta CONS = \frac{0.5 * Osc.depth * Osc.width}{pitch} * r$$

Unit: kg/m^2	Case 1	Case 2	Case 3
$CONS_{basic}$	.239	.262	.207
$\Delta CONS$	.211	.053	.023

Conclusions

- In one oscillation cycle, the liquid flux layer has sinusoidal profile for shear stress, while the solid flux layer has square wave.
- Lower friction exists in top half of mold.
- For constant friction coefficient, solid fraction increases cause huge increase in mold friction.
- Liquid layer thickness controls the friction force in mold: thicker liquid layer has shorter solid fraction which lowers friction force.
- Total flux layer thickness affects heat transfer across gap: thicker total flux layer lowers heat flux, leading to lower mold temperature, thicker shell thickness.

Conclusions

- If friction exceeds solid flux strength, then it will fracture, and increase solid flux velocity, causing possible drop in flux layer thickness in transition region accompanied by rebound heat flux.
- Steel shell surface temperature and hence liquid layer thickness is affected by both total flux thickness and casting speed: thicker layers and higher speeds increase shell temperature.
- Higher casting speed and higher real consumption both tends to lower friction.

Conclusions

- The fraction of mold with solid flux can be identified by:

  - value of friction (more solid flux tends toward higher friction)

  - shape of cycle (more solid flux tends toward sharper transition)

- Higher casting speed with lower consumption rate has increased transverse crack risk because friction is higher in top liquid portion of mold, where shell is hotter, thinner and weaker.

Future Work

- Model calibration with plant measured data
  - mold friction
  - consumption rate
  - oscillation mark geometry
- Relate flux fracture strength to solid flux velocity transition region
- Investigate coefficient of friction as a function of flux composition
- Incorporate default empirical equations for consumption rate, oscillation mark geometry etc.
- Incorporate the effects of flux crystallization behavior