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

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October 18, 2001

Background & Objectives

- Previous Work:
  - pseudo-transient analytical model of heat flux and flow in interfacial flux layers.
  - mold friction depends on powder flux consumption rate and solid flux velocity.
- High heat flux and heat flux variation in the mold are well known to cause slab defects.
- Flux layer break-up (Ron O'malley) is known to be followed by long periods of heat flux instability (and defects frequency) before stable, steady casting resumes.
- Hypothesis: if conditions enable continuous stable solid flux layer stuck to the mold wall, it may ensure the slab quality.
- When is this possible?
  - find the critical powder consumption rate.
  - find key factors that effect critical consumption rate:

- flux Poisson's ratio, υ	- liquid flux pool depth, h_0
- fracture strength, σ	- mold thickness, d_{mold}
- casting speed, V_c	- oscillation marks geometry
- mold/flux friction coefficient, ϕ	- flux viscosity curve

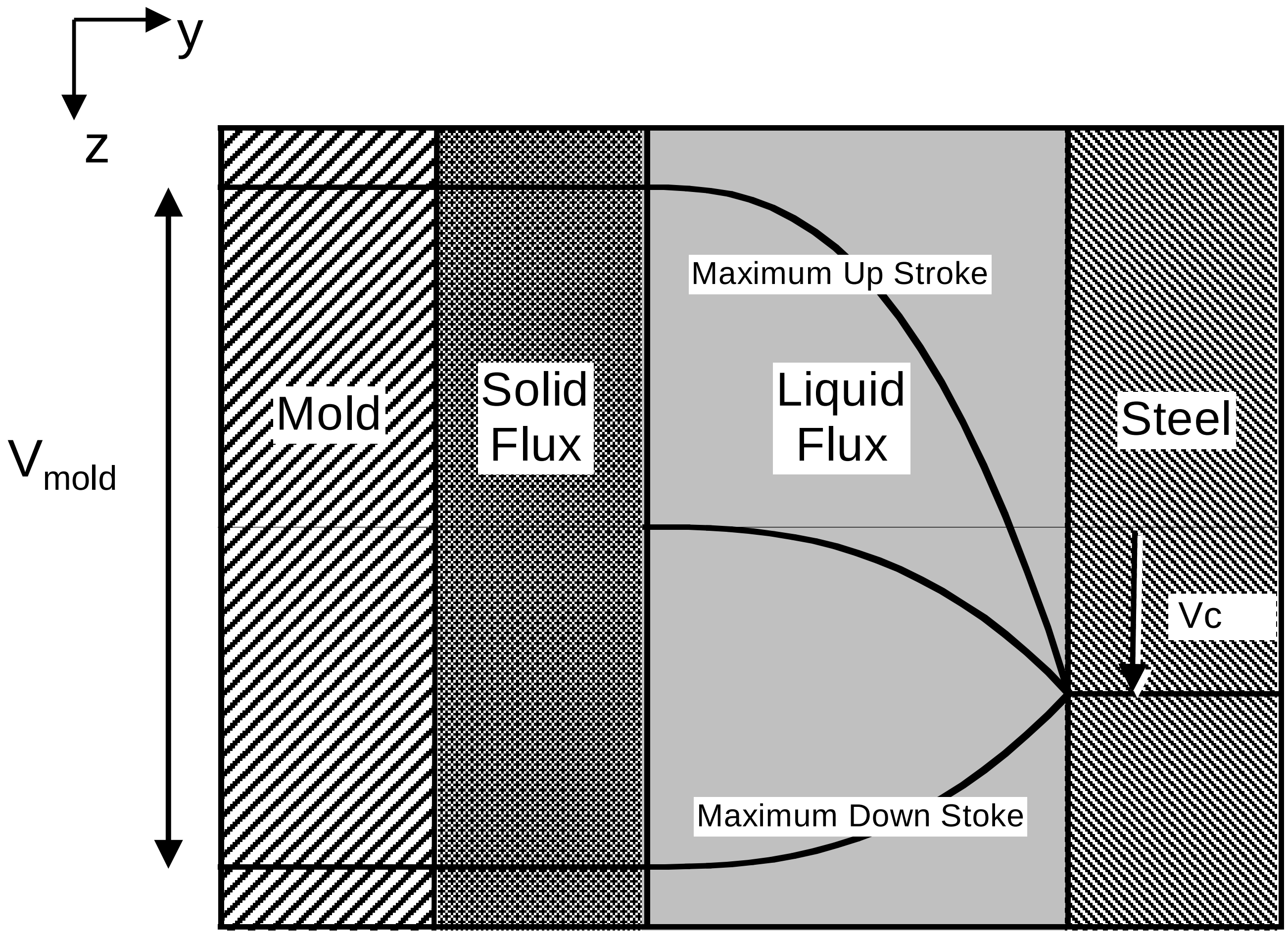
Outline

- Models Description

	Liquid Flux Layer	Solid Flux Layer
CON1D	Pseudo-transient Analytical Model	Pseudo-transient Analytical Model
Validation	Finite Difference Method (FDM)	ANSYS (Finite Element Method)

- Results
- Parametric Study

Schematic Profile of Flux Velocity



Liquid Flux Layer Flow Models

Momentum balance equation of liquid flux flow in the gap:

$$\rho\left(\frac{DV}{Dt}+V\cdot\nabla V\right)=-\nabla P+\left(\nabla\tau\right)+\rho g \qquad (1)$$

Flux flow along casting (z-) direction is:

$$\rho\cdot\left(\frac{\partial V_z}{\partial t}+V_x\cdot\frac{\partial V_z}{\partial x}+V_y\cdot\frac{\partial V_z}{\partial y}+V_z\cdot\frac{\partial V_z}{\partial z}\right)$$

$$=-\frac{\partial P}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+\rho g \qquad (2)$$

Liquid Flux Layer Flow Models

Assume:

- Ferro-static pressure, p, is transmitted directly through the steel shell

$$\frac{\partial p}{\partial z} = \rho_{steel} g$$

- No flow in width direction, $V_x \frac{\partial V_z}{\partial x} = 0, \frac{\partial \tau_{xz}}{\partial x} = 0$

- $V_y \frac{\partial V_z}{\partial y}, V_z \frac{\partial V_z}{\partial z}, \frac{\partial \tau_{zz}}{\partial z}$ are negligible (demonstrated later).

So, Eq.(2) simplifies to:

$$\rho \frac{\partial V_z}{\partial t} = \frac{\partial \tau_{yz}}{\partial y} + \left(\rho - \rho_{steel}\right) g \qquad (3)$$

Liquid Flux Layer Flow Models

Constitutive equation for shear stress-velocity gradient in liquid flux layer:

$$\tau_{yz} = \mu \frac{\partial V_z}{\partial y} \qquad (4)$$

Assume:

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

Where: μ_s is flux viscosity at the steel shell/flux interface

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:

$$\tau_{yz} = \mu_s \frac{d_l^n}{y^n} \frac{\partial V_z}{\partial y} \qquad (6)$$

Where: d_l is liquid flux thickness

FDM Liquid Flux Layer Flow Model

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

$$\rho \frac{\partial V_z}{\partial t} = \mu_s \frac{d_l^n}{y^n} \frac{\partial^2 V_z}{\partial y^2} - \mu_s \frac{n d_l^n}{y^{n+1}} \frac{\partial V_z}{\partial y} + (\rho - \rho_{steel}) g \qquad (7)$$

Boundary Conditions: (flux solid/liquid & flux liquid/steel interfaces)

$$V_z \,|_{y=0} = V_{mold} = \pi s f \cos(2\pi f t) \qquad (8)$$

$$V_z \,|_{y=d_l} = V_c \qquad (9)$$

Explicit finite-difference discretization with a central difference scheme:

$$V_i^{new} = \frac{\Delta t}{\rho} \left(\mu_s \frac{d_l^n}{y^n} \frac{V_{i+1} - 2V_i + V_{i-1}}{\Delta y^2} - \mu_s \frac{n d_l^n}{y^{n+1}} \frac{V_{i+1} - V_{i-1}}{\Delta y} + (\rho - \rho_{steel}) g \right) + V_i \qquad (10)$$

FDM Liquid Flux Layer Flow Model

Simulation Parameters and Results

Casting Conditions:

Casting Speed, V_c	**16.67 mm/s**
Mold Oscillation Stroke, s	**7.8 mm**
Mold Oscillation Frequency, f	**1.389 cps**
Steel Density, ρ_{steel}	**7400 kg/m^3**

Flux Properties:

Density, ρ	**2500 kg/m^3**
Temperature Dependent Index for Viscosity, n	**1.65**
Viscosity at Shell Surface Side, μ_s	**0.54/0.55 Pas***
Liquid Layer Thickness, d_l	**0.2 mm ***

Simulation Parameters:

Δt: 5.0e-7 s **Δy: 0.04 mm**

***: From CON1D output followed by FDM model runs at z=53mm and at z=54mm**

negligible

$\rho \cdot \frac{\partial V_z}{\partial t}$	$\cancel{\rho \cdot V_y \cdot \frac{\partial V_z}{\partial y}}$	$\cancel{\rho \cdot V_z \cdot \frac{\partial V_z}{\partial z}}$	$(\rho - \rho_{steel}) \cdot g$	$\frac{\partial \tau_{yz}}{\partial y}$	$\cancel{\frac{\partial \tau_{zz}}{\partial z}}$	
-337	**0.034**	**0.0431**	**-48020**	**47683**	**-1.0624**	**N/m^3**

Pseudo-transient Liquid Flux Layer Flow Model
(used in CON1D)

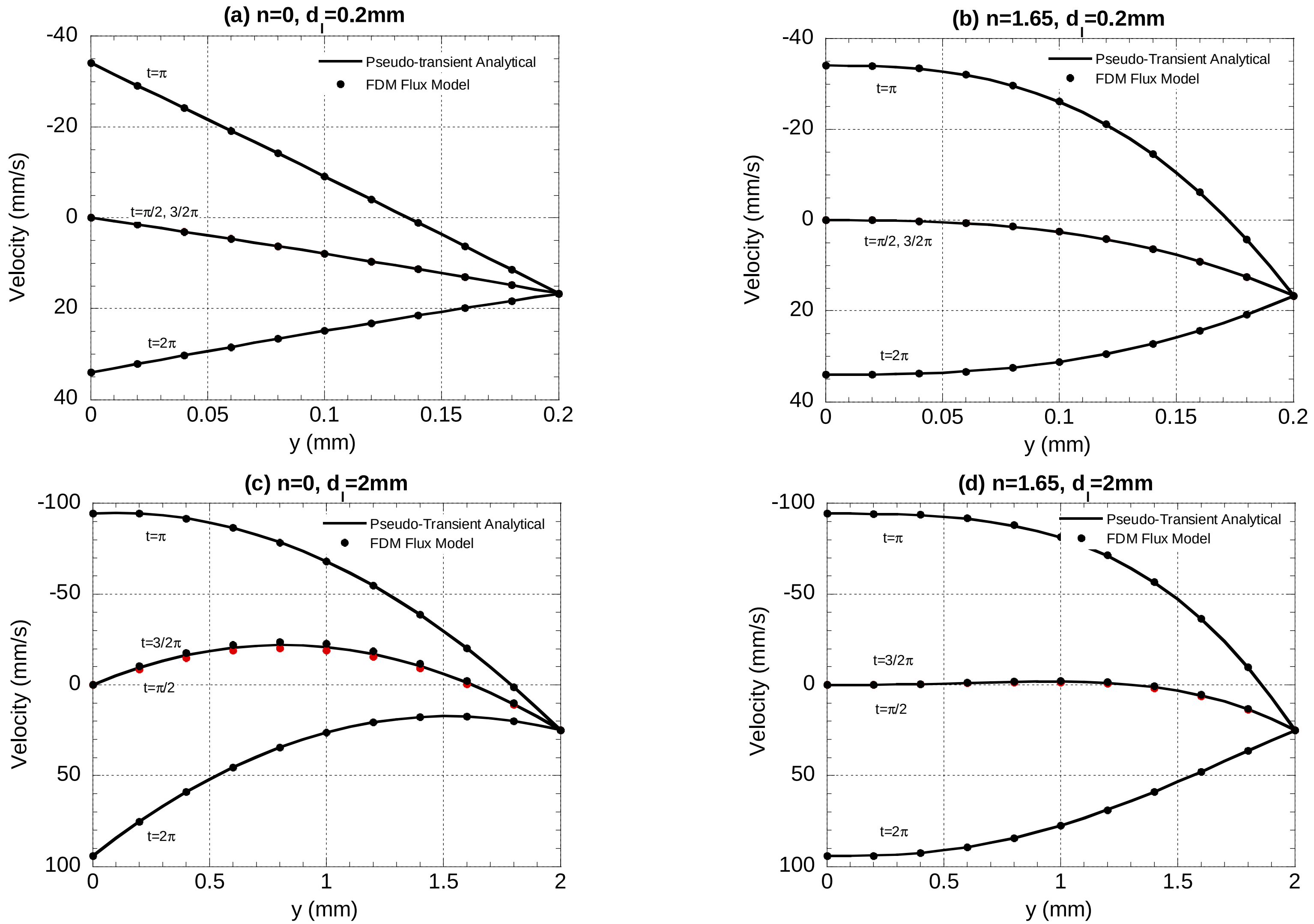
- The transient term, $\rho \frac{\partial V_z}{\partial t}$, is proportional to s*f^2.
- For this typical case: s=7.8mm, f=83.3cpm, $\rho \frac{\partial V_z}{\partial t} < 1.5\%$
- Therefore, neglecting this transient term yields a pseudo-transient analytical solution:

$$V_z = \frac{-(\rho - \rho_{steel}) g y^{n+2}}{\mu_s (n+2) d_l^n} + \left(\frac{(V_c - V_m)}{d_l} + \frac{(\rho - \rho_{steel}) g d_l}{\mu_s (n+2)} \right) \frac{y^{n+1}}{d_l^n} + V_m \qquad (11)$$

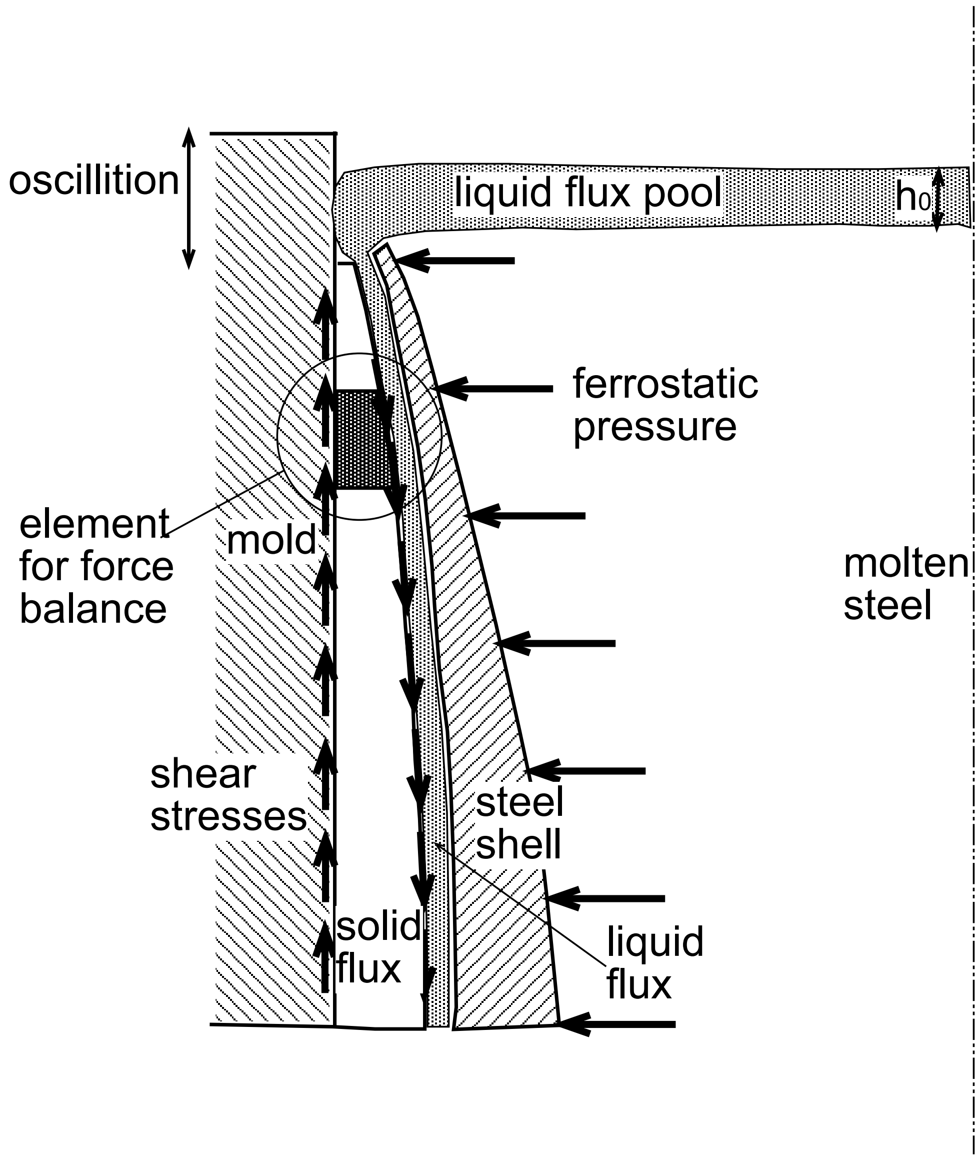
$$\tau_{yz} = \frac{(n+1)\mu_s (V_c - V_m)}{d_l} + \frac{(\rho - \rho_{steel}) g \left((n+1) d_l - (n+2) y \right)}{n+2} \qquad (12)$$

Velocity Distribution in Liquid Flux Layers

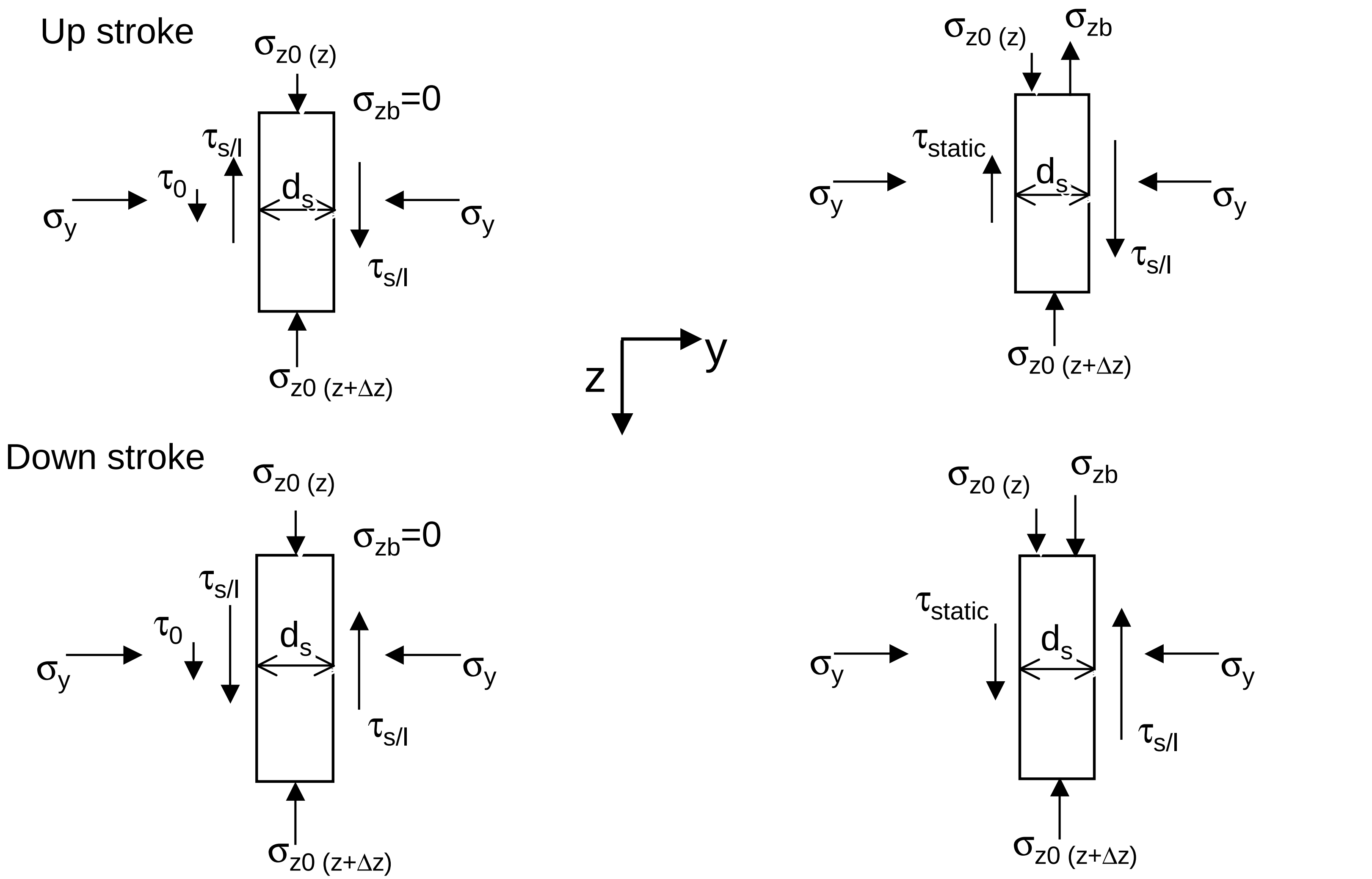
(comparing pseudo-transient analytical solution in CON1D with FDM flux model)



Schematic of Solid Flux Stress



Force Balance in Solid Flux Layer



liquid shear stress limits stress

friction coefficient limits stress

Analytical Solid Flux Stress Model (used in CON1D)

Assume: solid flux stuck to the mold wall

Shear stress at flux solid/liquid interface (evaluating τ_{yz} at y=0 in Eqn (12)):

$$\tau_{s/l} = \mu_s \frac{(n+1)(V_c - V_{mold})}{d_l} + \frac{(n+1)}{(n+2)}(\rho - \rho_{steel})gd_l$$

Maximum static solid friction due to mold/shell relative motion:

$$\tau_{static} = \phi \cdot \rho_{steel} gz$$ ϕ, friction coefficient

Normal stress: $\sigma_y = -(\rho_{flux} g h_0 + \rho_{steel} gz)$ h_0, liquid flux pool depth

Axial stress component due to ferro-static pressure (ignoring mold/shell relative motion):

$$\sigma_{z0} = \frac{\nu}{(1-\nu)}\sigma_y$$ υ, Poisson's ratio

Shear stress component due to ferro-static pressure(ignoring mold/shell relative motion):

$$\tau_0 = \left(\sigma_{z0(z+\Delta z)} - \sigma_{z0(z)}\right) \cdot d_s / \Delta z$$ d_s, solid flux layer thickness

Analytical Solid Flux Stress Model (used in CON1D)

Shear stress at mold/solid flux layer interface:

$$\tau_{m/s} = Min\left(\tau_{s/l} + \tau_0, \tau_{static}\right)$$

Axial stress component due to imbalance in shear stresses of flux layer interfaces:

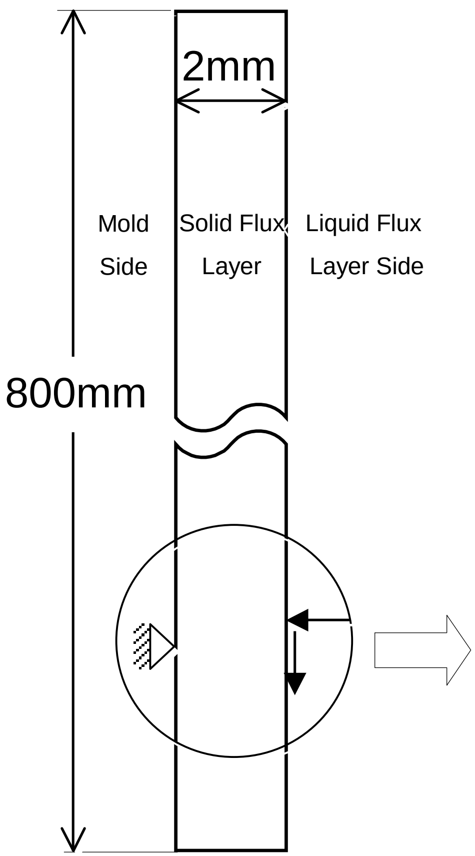
$$\sigma_{zb} = \left(\tau_{s/l} - \left(\tau_{m/s} - \tau_0\right)\right) \cdot \Delta z / d_s$$

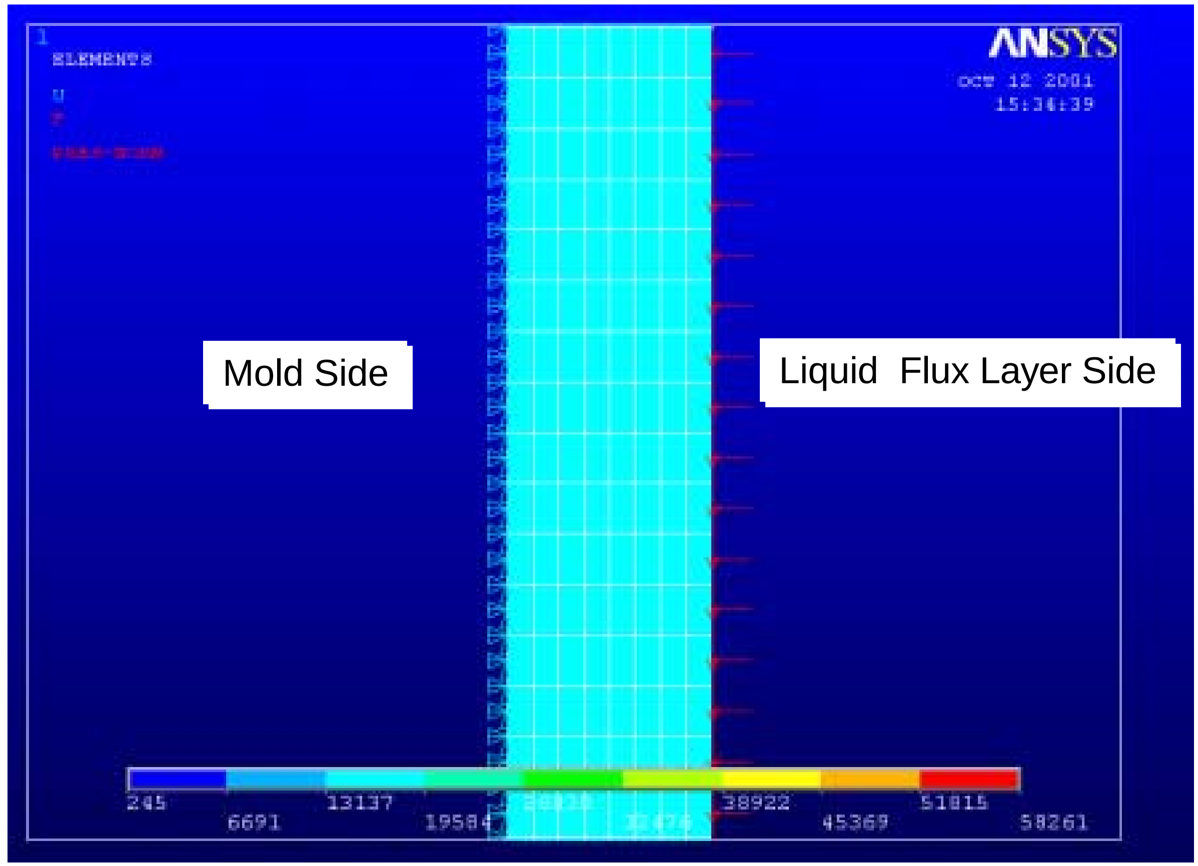
Total axial stress in solid flux layer:

$$\sigma_z = \sigma_{zb} + \left(\sigma_{z0(z+\Delta z)} - \sigma_{z0(z)}\right)$$

ANSYS Solid Flux Stress Model

Domain & Boundary Conditions





Test problem for CON1D model validation – no relative movement of mold and steel shell

Boundary Conditions:

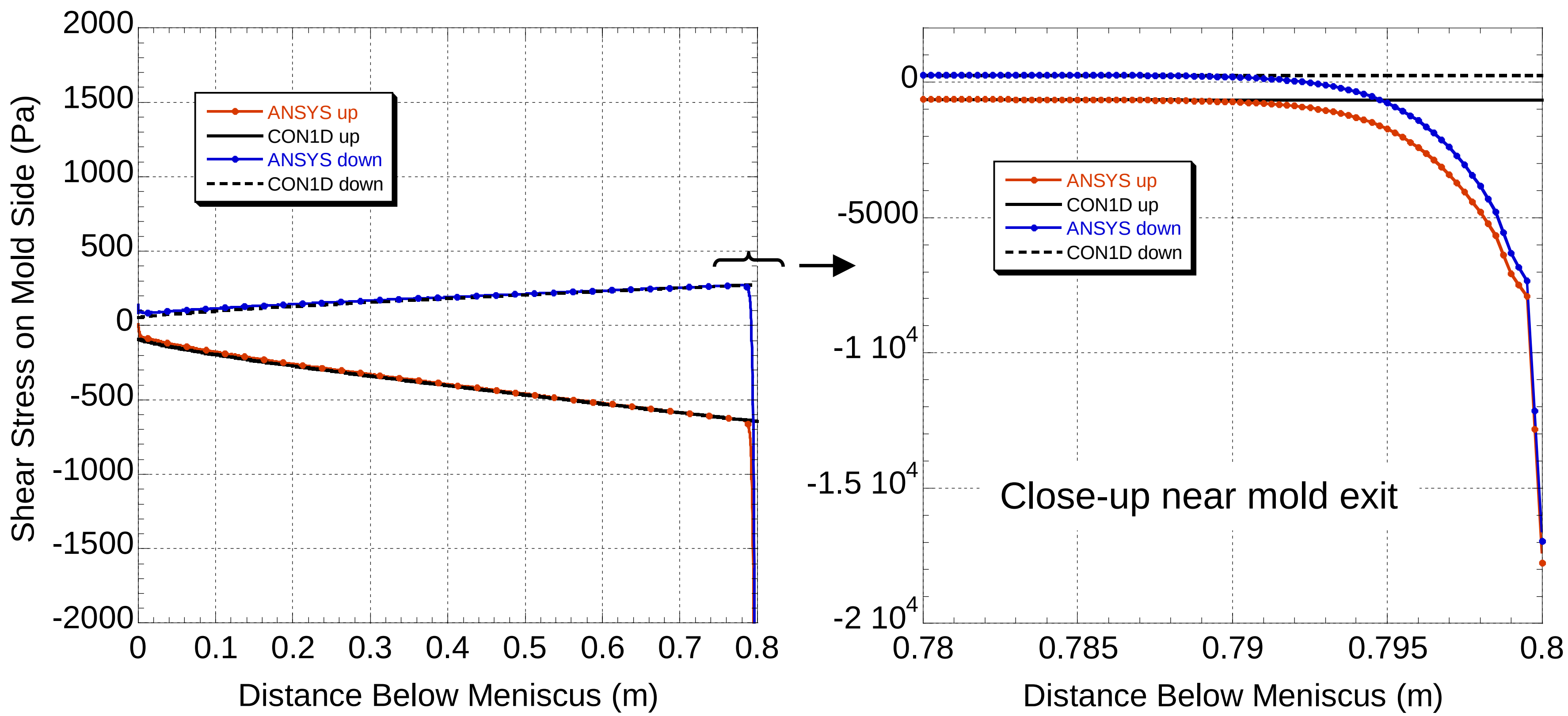
Mold Side: Fixed displacement

Liquid Flux Layer Side: Gradient ferro-static pressure and shear stress (from CON1D)

Example Application: Case 1 &1a &2b
Input Conditions

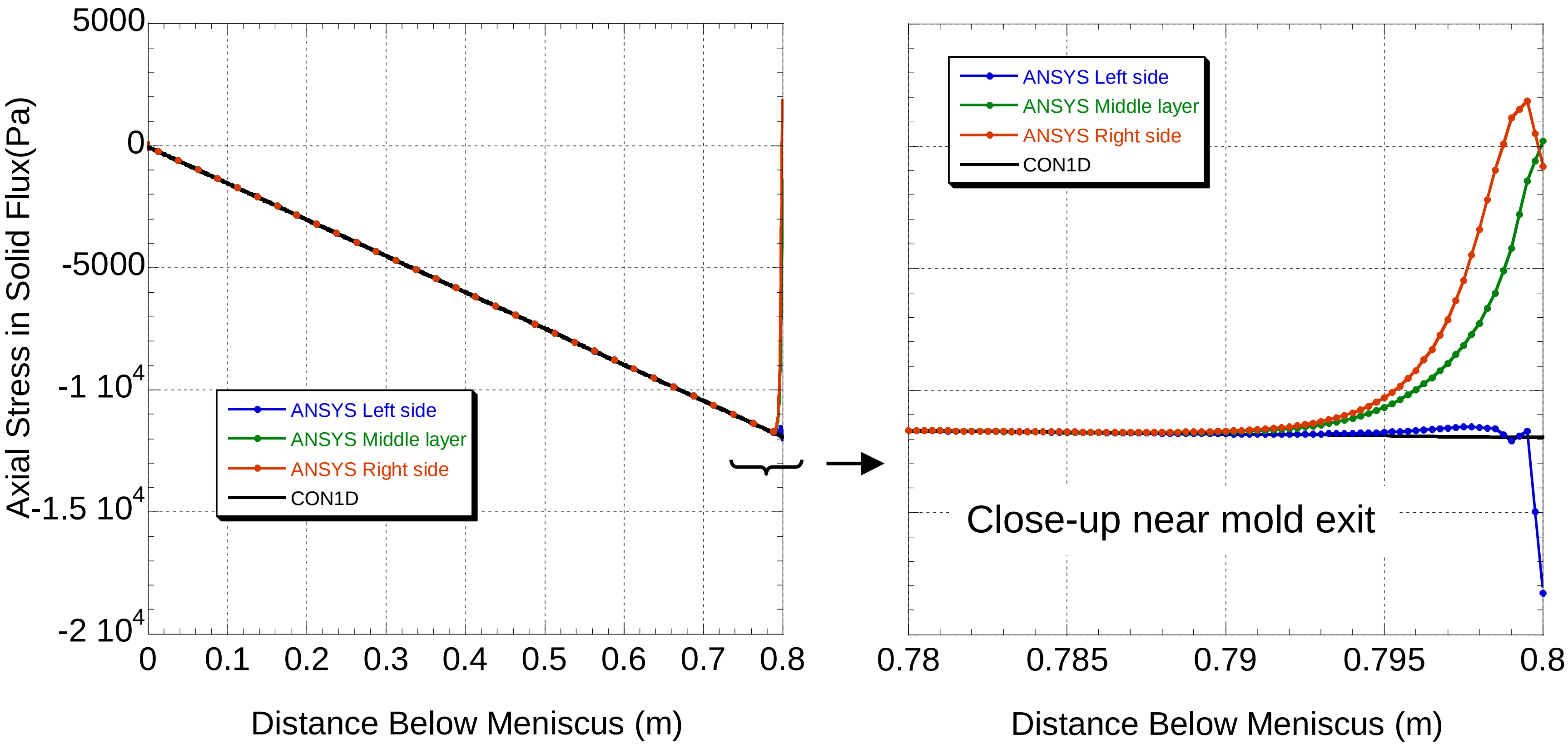
	Case 1&1a	Case2b	Unit
• Casting Speed:	1.0		m/min
• Pour Temperature:	1550		^oC
• Slab Geometry:	1500*230		mm^2
• Nozzle Submergence depth:	265		mm
• Working Mold Length:	800		mm
• Time Step:	dt=0.001		s
• Mesh Size:	dx=0.5		mm
• Fraction Solid for Shell Thickness location:	0.3		
• Carbon Content:	0.05		%
• Mold Powder Solidification Temperature:	1080		^oC
• Mold Powder Conductivity (solid/liquid):	1.5/1.5		W/mK
• Mold Powder Density:	2500	**2700**	kg/m^3
• Mold Powder Viscosity at 1300 ^oC:	8.72	**1.06**	poise
• Exponent for temperature dependency of viscosity:	1.65	**5**	
• Mold Powder Consumption Rate:	0.45/0.27 (1/1a)	**0.287**	kg/m^2
• Solid Flux Velocity:	0		(stuck to mold wall)
• Oscillation Mark Geometry (depth*width):	0.45*4.5		mm^2
• Mold Oscillation Frequency:	83.3		cpm
• Oscillation Stroke:	7.8		mm
• Mold Thickness (including water channel):	51		mm
• Initial Cooling Water Temperature:	30		^oC
• Water Channel Geometry (depth*width*distance):	25*5*29		mm^3
• Cooling Water Flow rate:	7.8		m/s

Comparison of CON1D & ANSYS:
Shear Stress on Mold Side (Case 1)



- CON1D model matches ANSYS (except within 10mm near mold exit).

Comparison of CON1D & ANSYS:
Axial Stress in Solid Flux

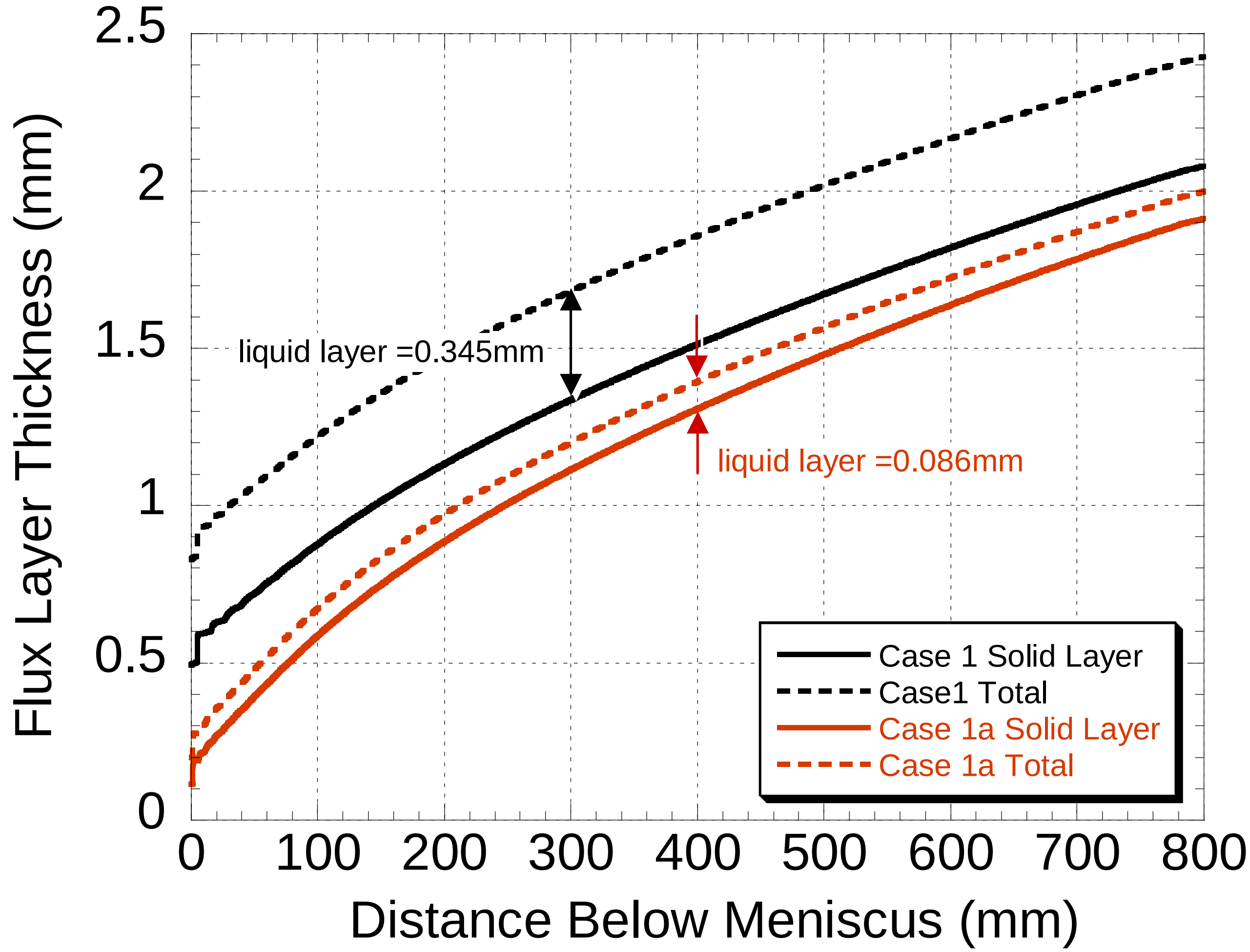


- Case1 at maximum up stroke.
- CON1D model matches ANSYS (except within 10mm near mold exit).
- Solid flux layer is in compression almost everywhere so a stable solid flux layer is present, no failure is possible.

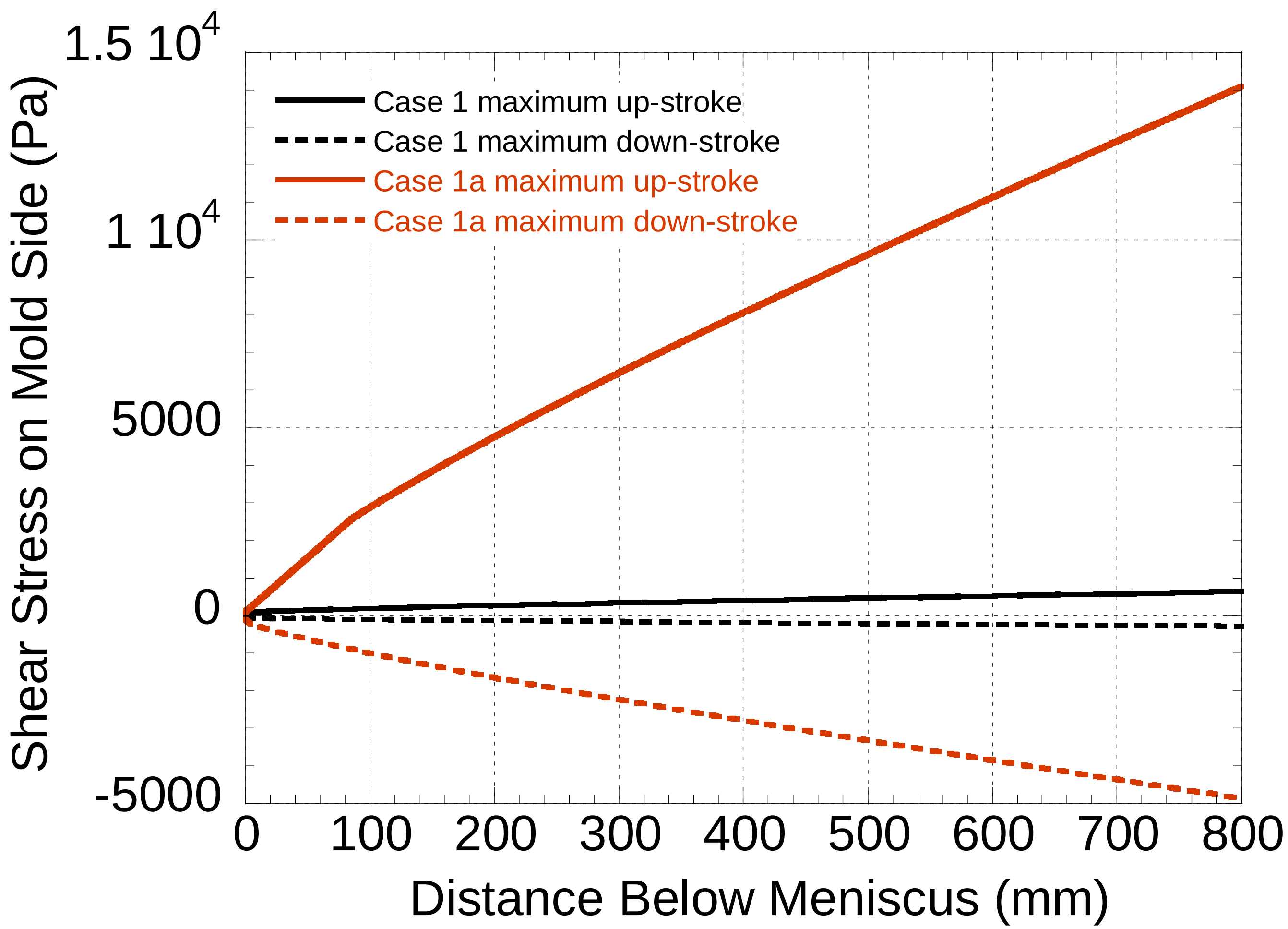
Example Application: Case 1 & 1a & 2b
Output Results

	Case1	Case1a	Case2b	Unit
• Liquidus Temperature:	1529	1529	1529	^oC
• Solidus Temperature:	1509	1509	1509	^oC
• Negative Strip Time:	0.24	0.24	0.24	s
• Positive Strip Time:	0.48	0.48	0.48	s
• Negative Strip Ratio of Velocity:	0.3	0.3	0.3	-
• Velocity Amplitude of Mold Oscillation:	34.03	34.03	34.03	mm/s
• Pitch (spacing between oscillation marks):	12	12	12	mm
• Maximum Mold Hot Face Temperature:	248.03	406.99	338.81	^oC
• Maximum Mold Cold Face Temperature:	114.16	175.38	148.73	^oC
• Mold Cooling Water Temperature Increase:	4.90	6.19	5.73	^oC
• Mean Heat Flux in Mold:	1.0159	1.2816	1.1895	MW/m^2
• Basic Consumption Rate, $CONS_{basic}$:	0.23906	0.05914	0.07599	kg/m^2
• Shear Stress in Mold at Maximum Up-stroke:	0.3943	7.8437	8.0472	KPa
• Shear Stress in Mold at Maximum Down-stroke:	-0.1803	-2.7254	-2.8659	KPa
Variables Calculated at Mold Exit:				
• Shell Surface Temperature:	1223.18	1133.24	1163.02	^oC
• Mold Hot Face Temperature:	144.12	153.74	151.31	^oC
• Shell Thickness:	17.67	20.84	19.77	mm
• Liquid Flux Film Thickness:	0.3469	0.0863	0.1531	mm
• Solid Flux Film Thickness:	2.0795	1.9129	1.9508	mm
• Heat Flux:	0.6751	0.7263	0.7141	MW/m^2

Flux Layers Thickness

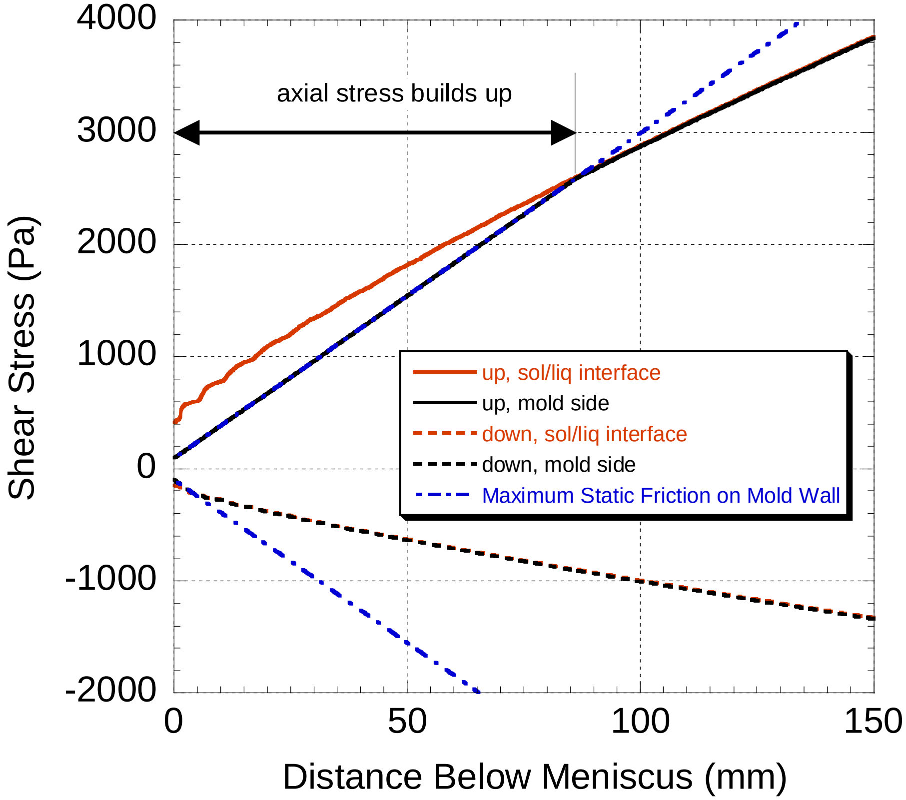


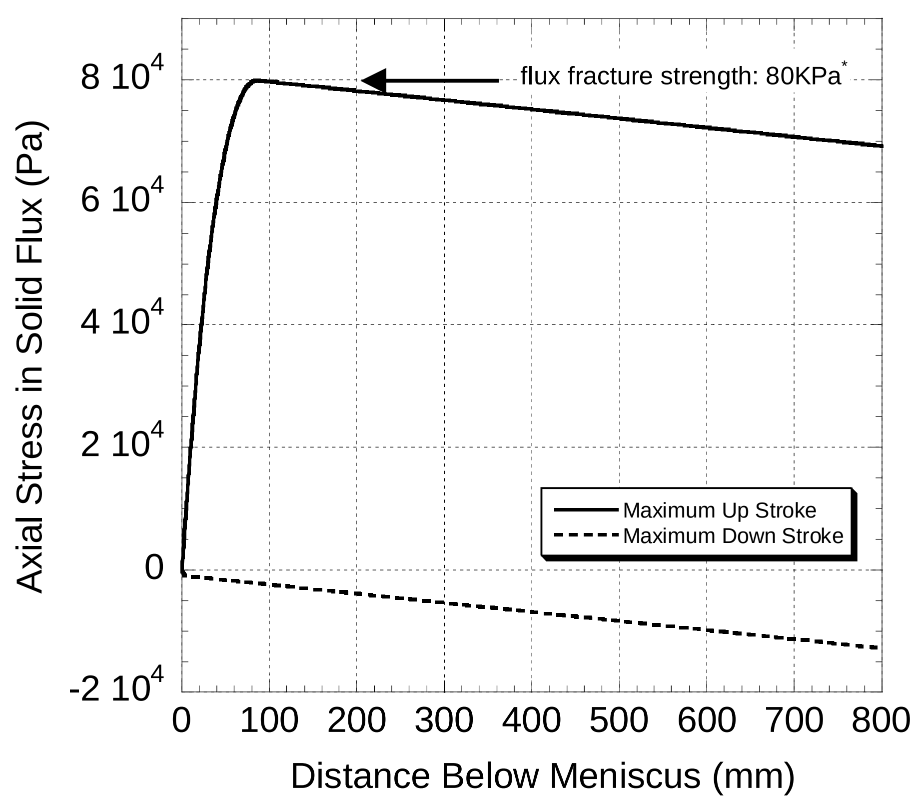
Shear Stress on Mold Side



- Decreasing flux consumption rate → thinner flux layers thickness → higher shear stress

How Does Axial Stress Build up near Meniscus? (Case 1a)





- Only when liquid shear stress exceeds maximum static solid friction, does axial stress build up

* Akira Yamauchi, *Heat Transfer Phenomena and Mold Flux Lubrication in Continuous Casting of Steel*, Doctoral Thesis, Royal Institute of Technology, Sweden, March 2001

Powder Flux Consumption Rate

$CONS_{basic}$ = Total Consumption Rate – ΔCONS (kg/m^2)

where,

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

ΔCONS is the component of consumption rate due to filling the oscillation marks:

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

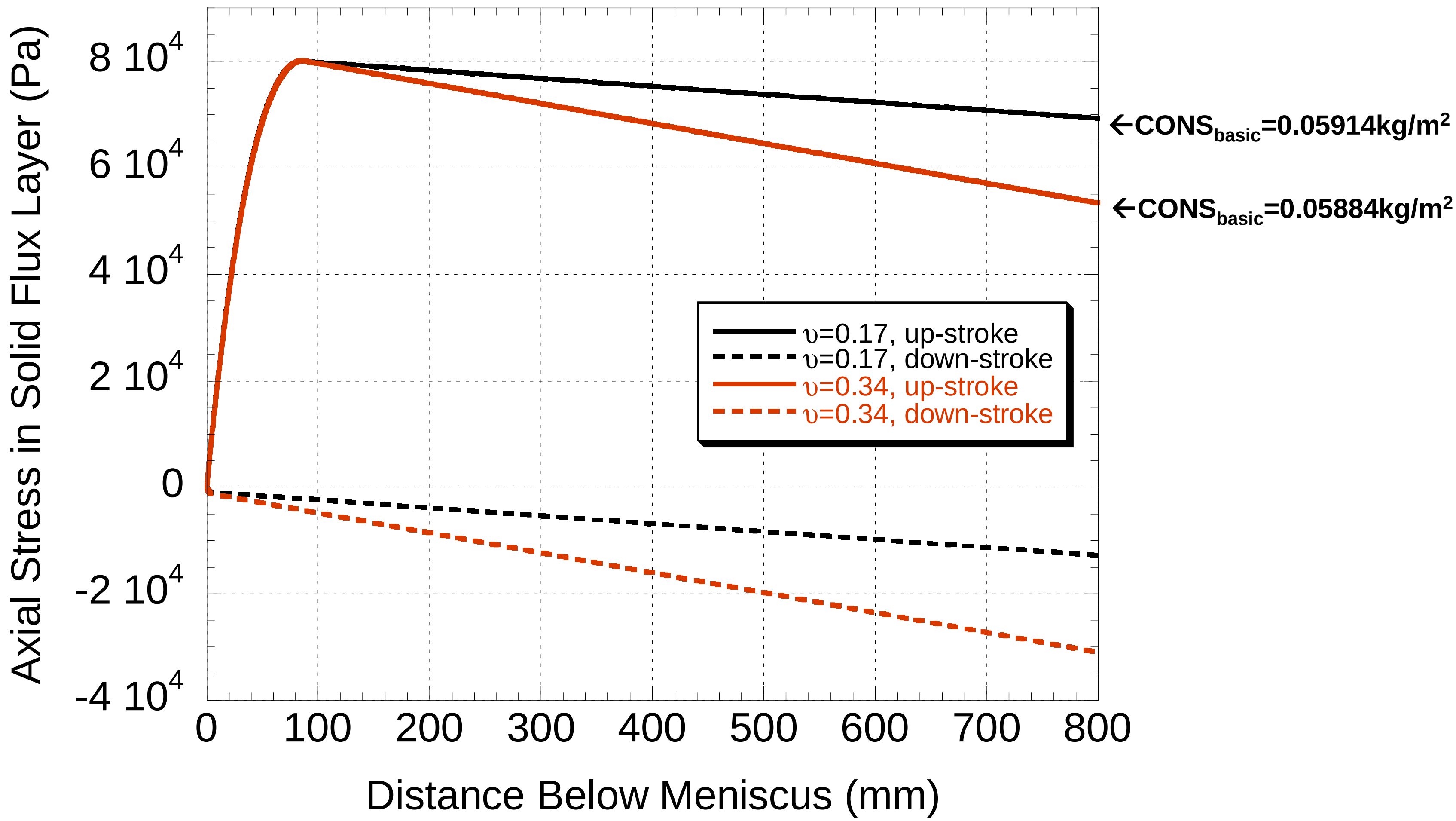
Critical $CONS_{basic}$: The minimum basic consumption rate to keep solid flux attached to mold wall

Parametric Study

- Lower flux consumption rate leads to higher shear stress in liquid/solid flux interface.
- If friction on mold side can not compensate the shear stress on solid/liquid interface, tensile axial stress builds up in solid flux layer.
- When axial stress in solid flux exceeds the flux fracture strength, solid flux breaks and is dragged down the mold wall.

- Find the critical powder consumption rate, $CONS_{basic}$.
- What effect critical $CONS_{basic}$?
  - flux Poisson's ratio, υ
  - fracture strength, σ
  - casting speed, V_c
  - mold/flux friction coefficient, ϕ
  - liquid flux pool depth, h_0
  - mold thickness, d_{mold}
  - oscillation marks geometry
  - flux viscosity curve

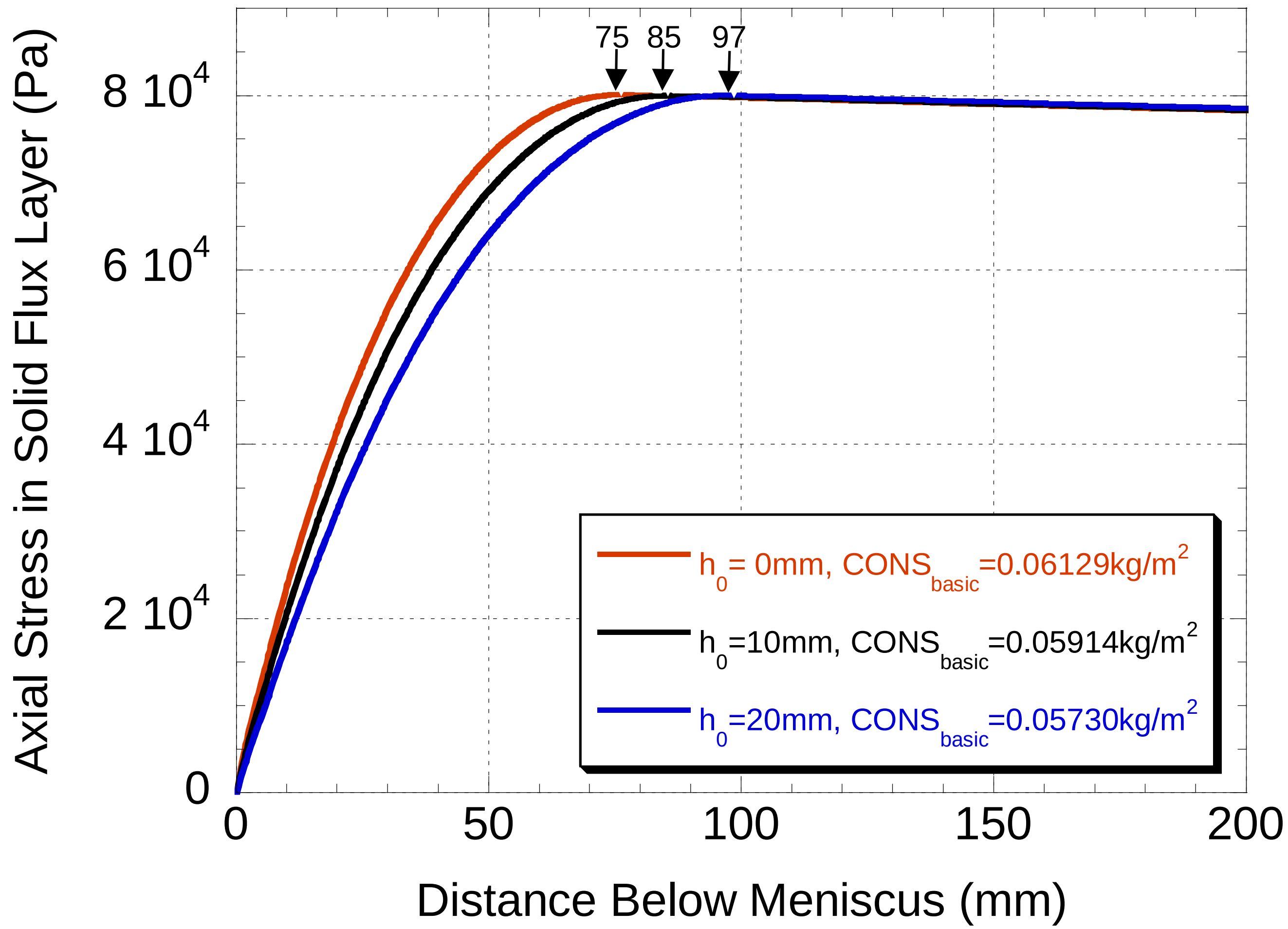
Effect of Poisson's Ratio, υ



- For υ=0.34, critical $CONS_{basic}$ decreases 0.5% (comparing to υ=0.17)

→ Poisson's ratio is not important on critical $CONS_{basic}$

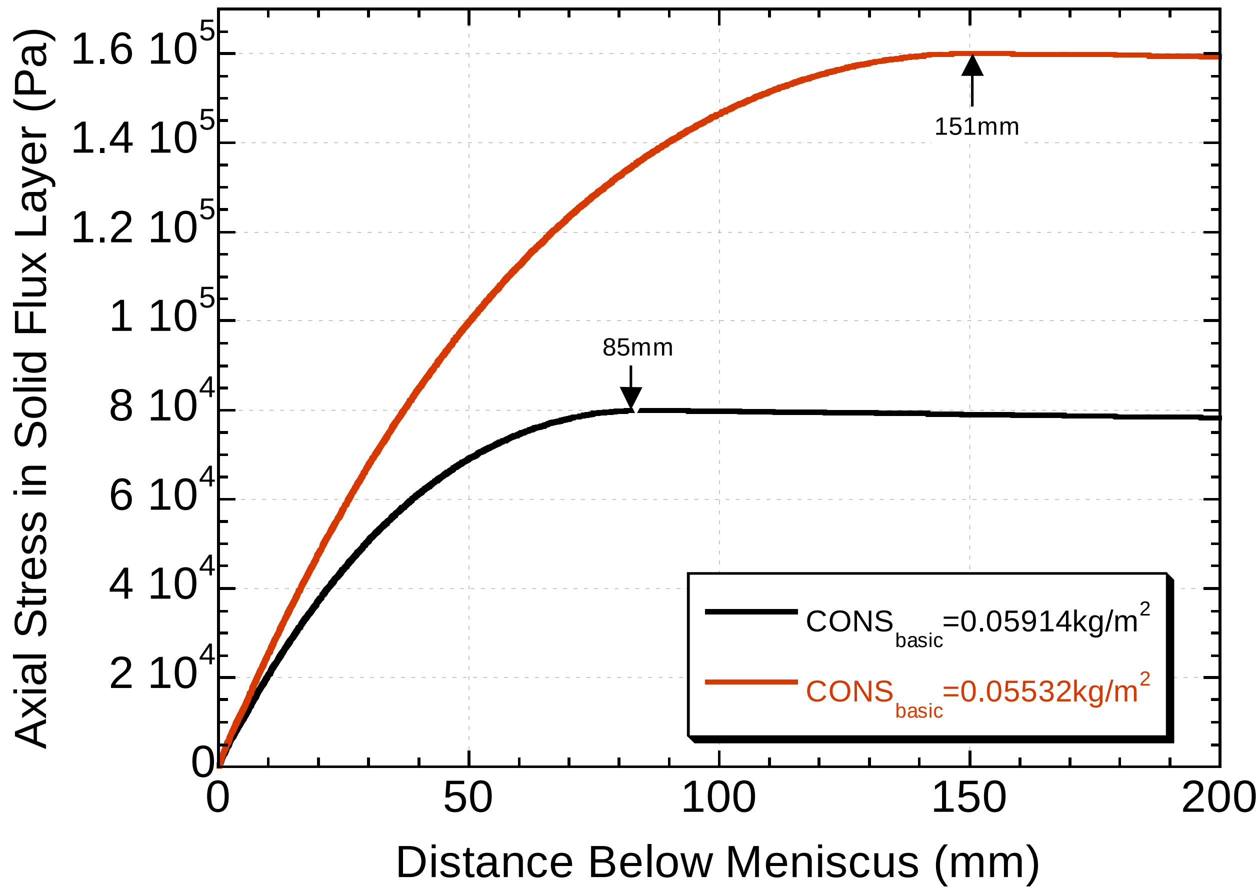
Effect of Liquid Flux Pool Depth, h_0



- Decreasing 10mm h_0, the critical $CONS_{basic}$ increases 3.5% and the maximum axial stress position shifts to the meniscus about 10mm; vice versa.

→Liquid flux pool depth is not important on critical $CONS_{basic}$

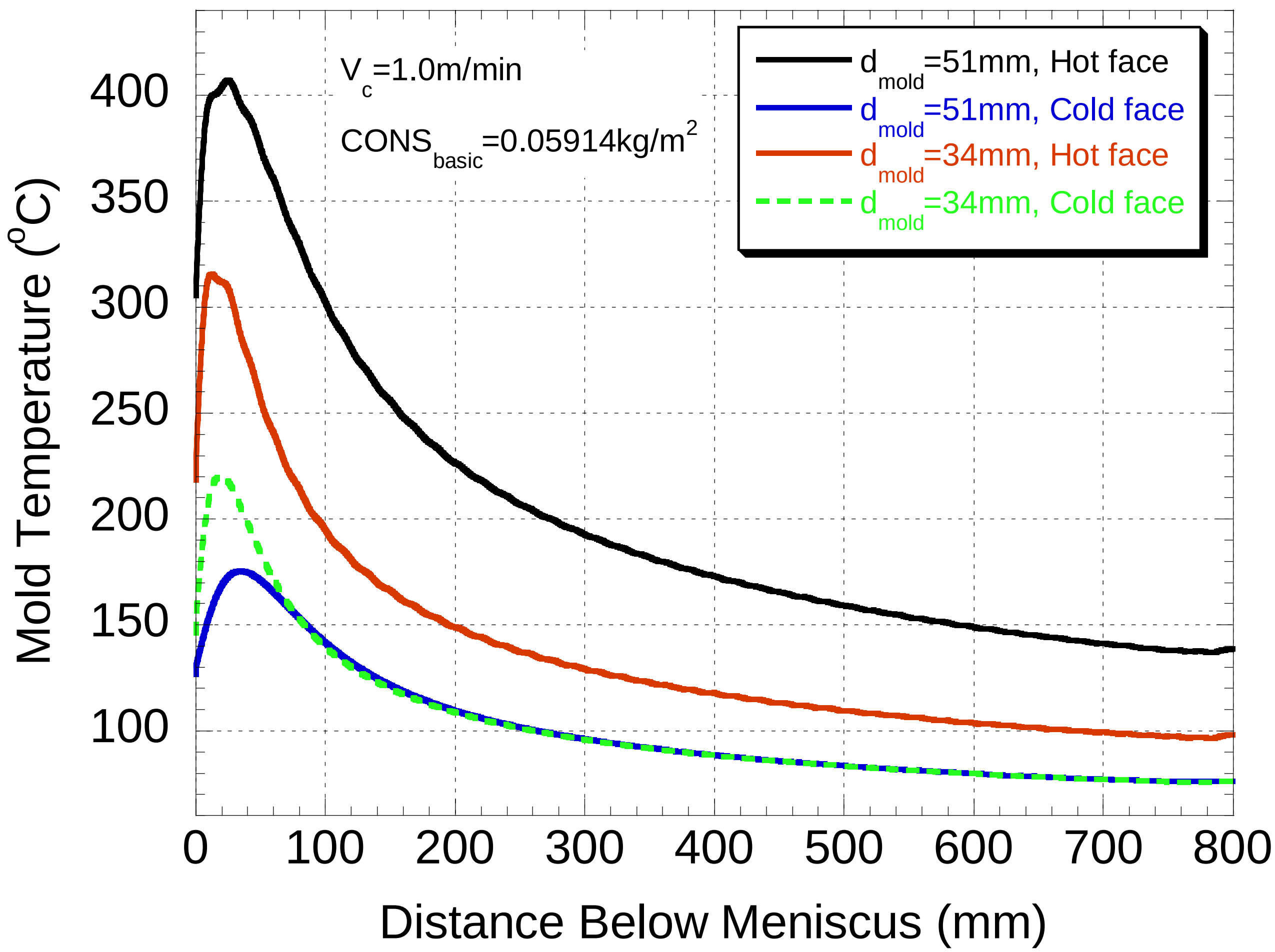
Effect of Fracture Strength, σ



Doubling flux fracture strength, σ:

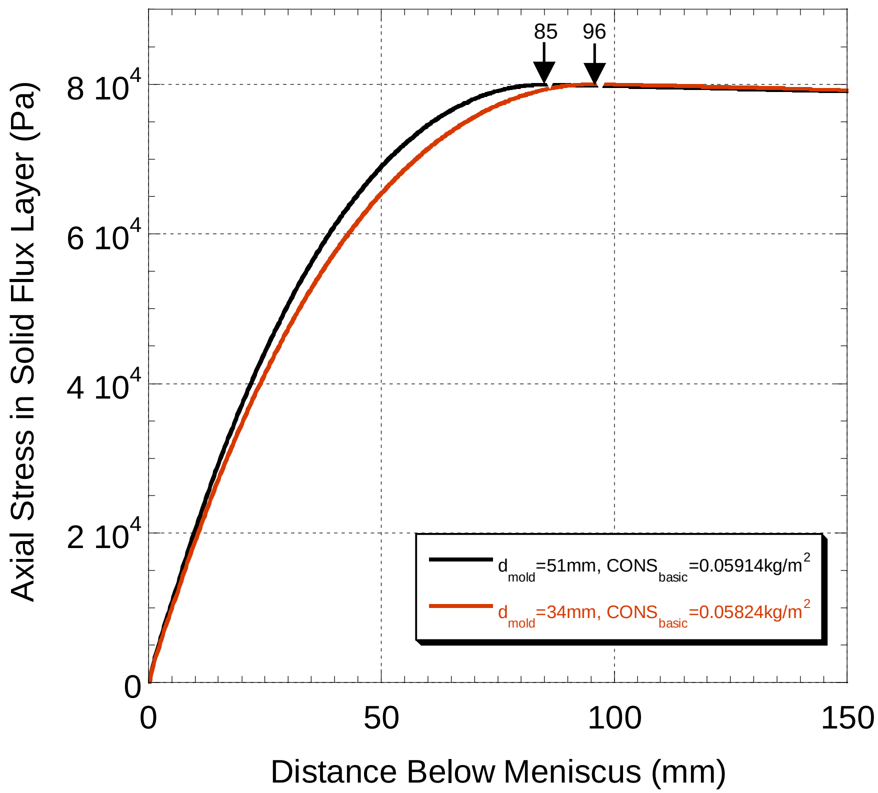
- allows critical $CONS_{basic}$ to decrease by 6.8%,
- moves the critical fracture position from 85mm to 151mm below meniscus.

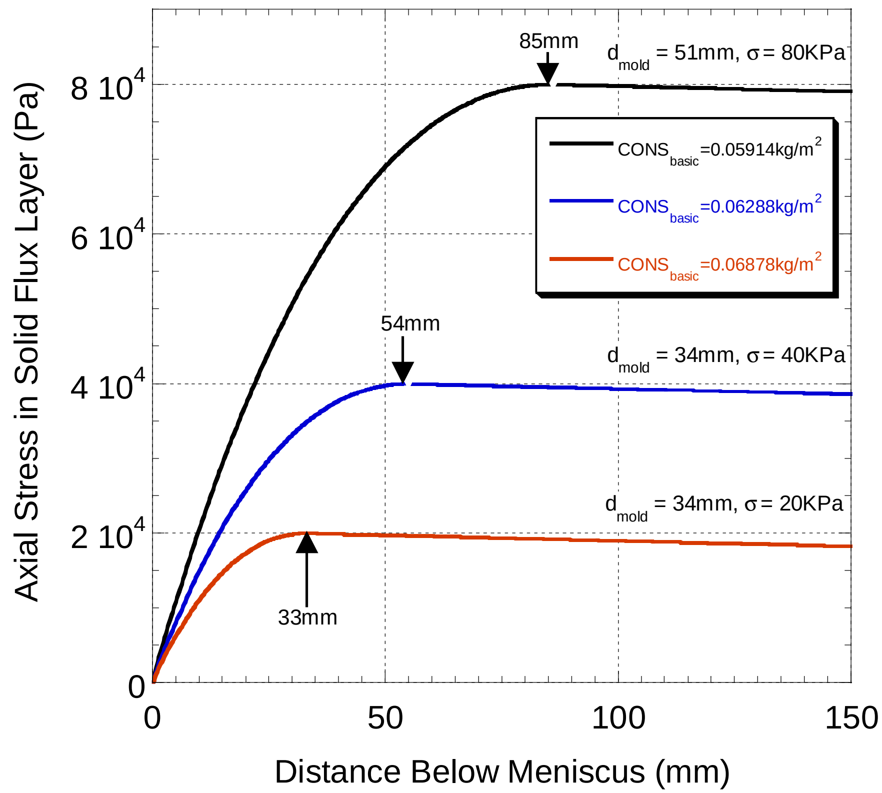
Effect of Mold Thickness on Mold Temperature



- Decreasing mold thickness decreases mold hot face temperature.

Effect of Mold Thickness

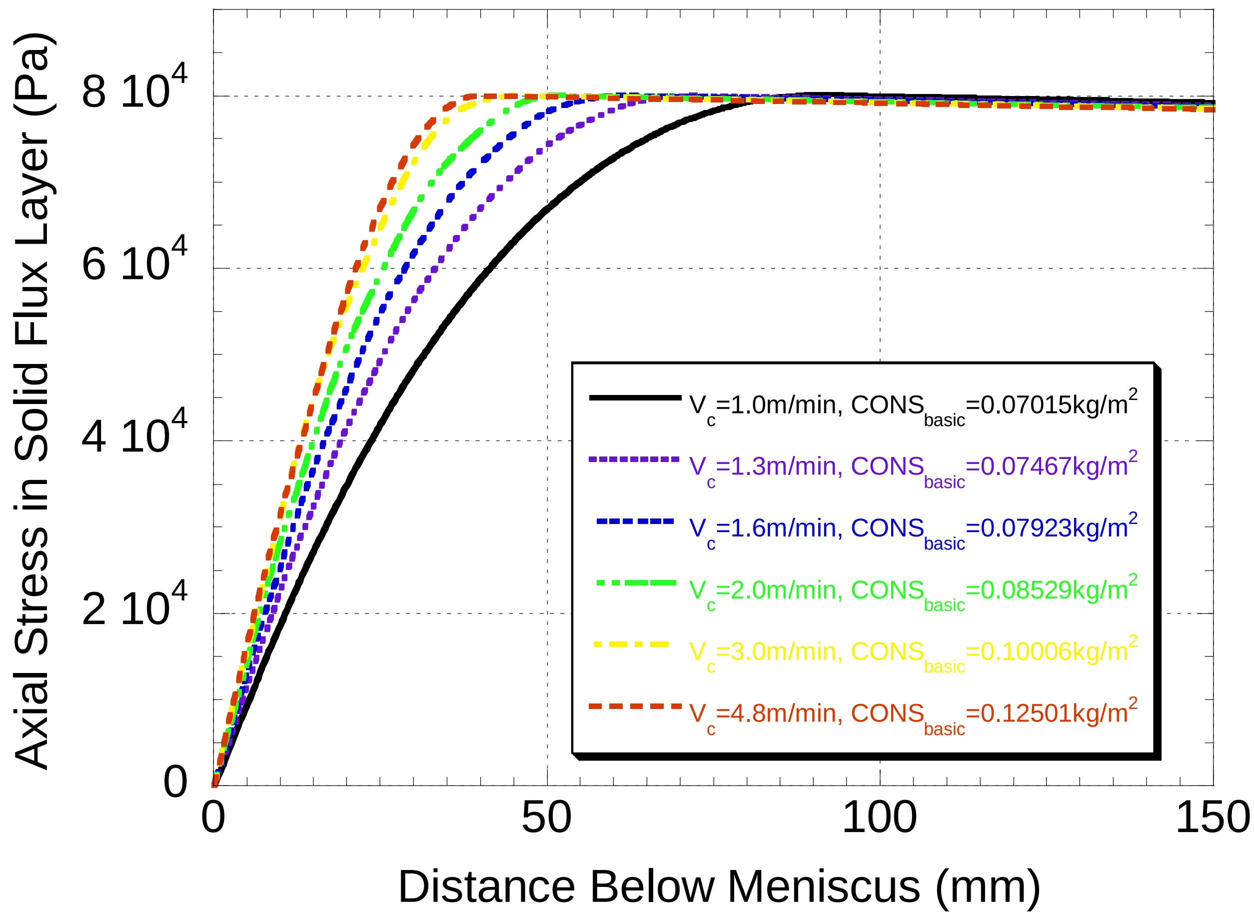




- Decreasing mold thickness by 33% decreases $CONS_{basic}$ by 1.5%, which is negligible

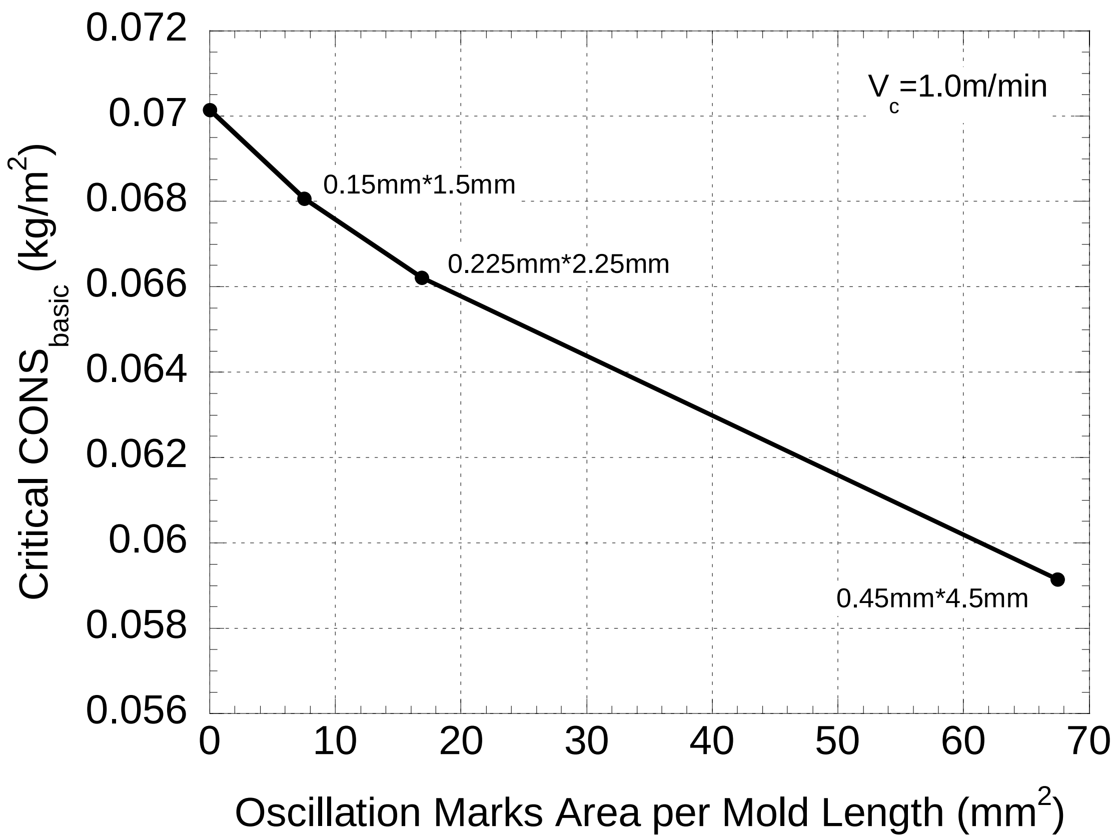
- Lower mold temperature may cause glass transition in solid flux → lower fracture strength, higher possibility of flux fracture → increase critical $CONS_{basic}$

Effect of Casting Speed, V_c
(no oscillation marks)



- Assume constant pitch (increasing mold oscillation frequency proportionally)
- Increasing casting speed, V_c, from 1.0 to 1.6m/min:
  - requires that critical $CONS_{basic}$ increases by 12.9%
  - moves the critical fracture position from 91mm to 51mm.

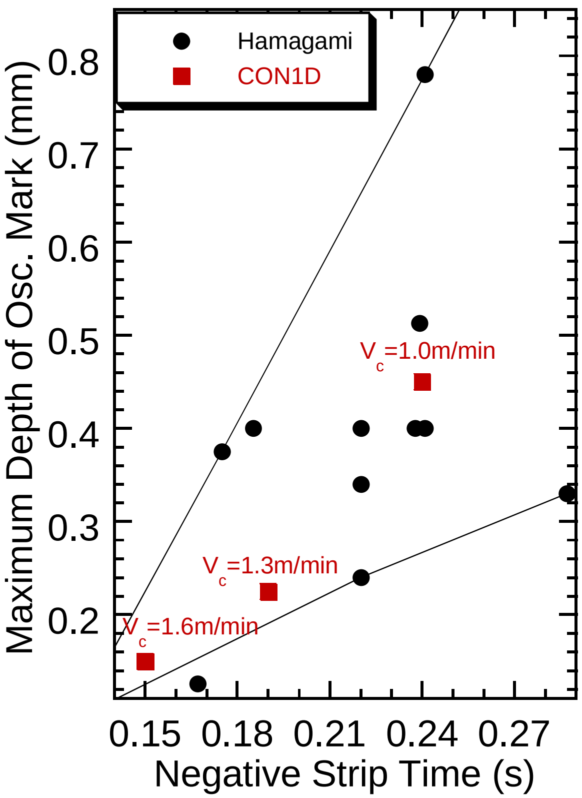
Effect of Oscillation Marks

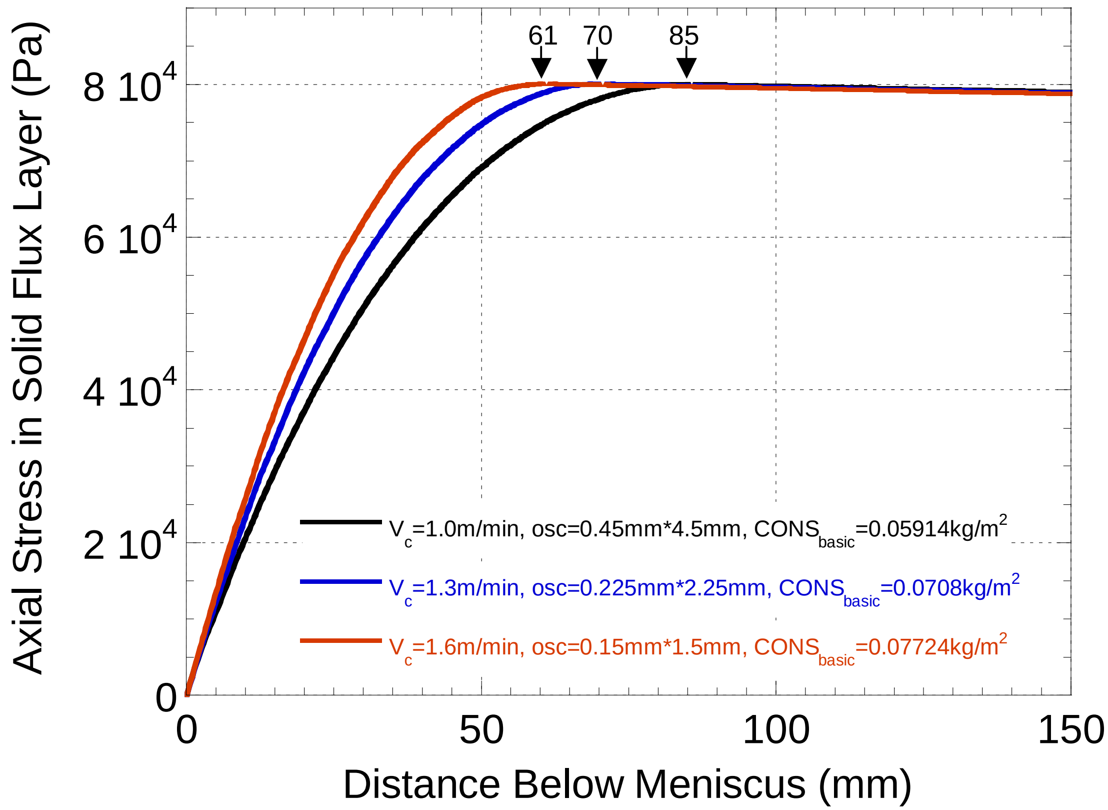


- Decreasing oscillation marks area → less resistance in gap → higher heat flux, lower shell surface temperature → higher flux viscosity → higher shear stress → higher possibility of flux fracture → increasing critical CONS$_{basic}$

- The 0.45*4.5mm oscillation marks decreases CONS$_{basic}$ by 18.6% relative to no oscillation marks.

Effect of Casting Speed, V_c
(with oscillation marks)





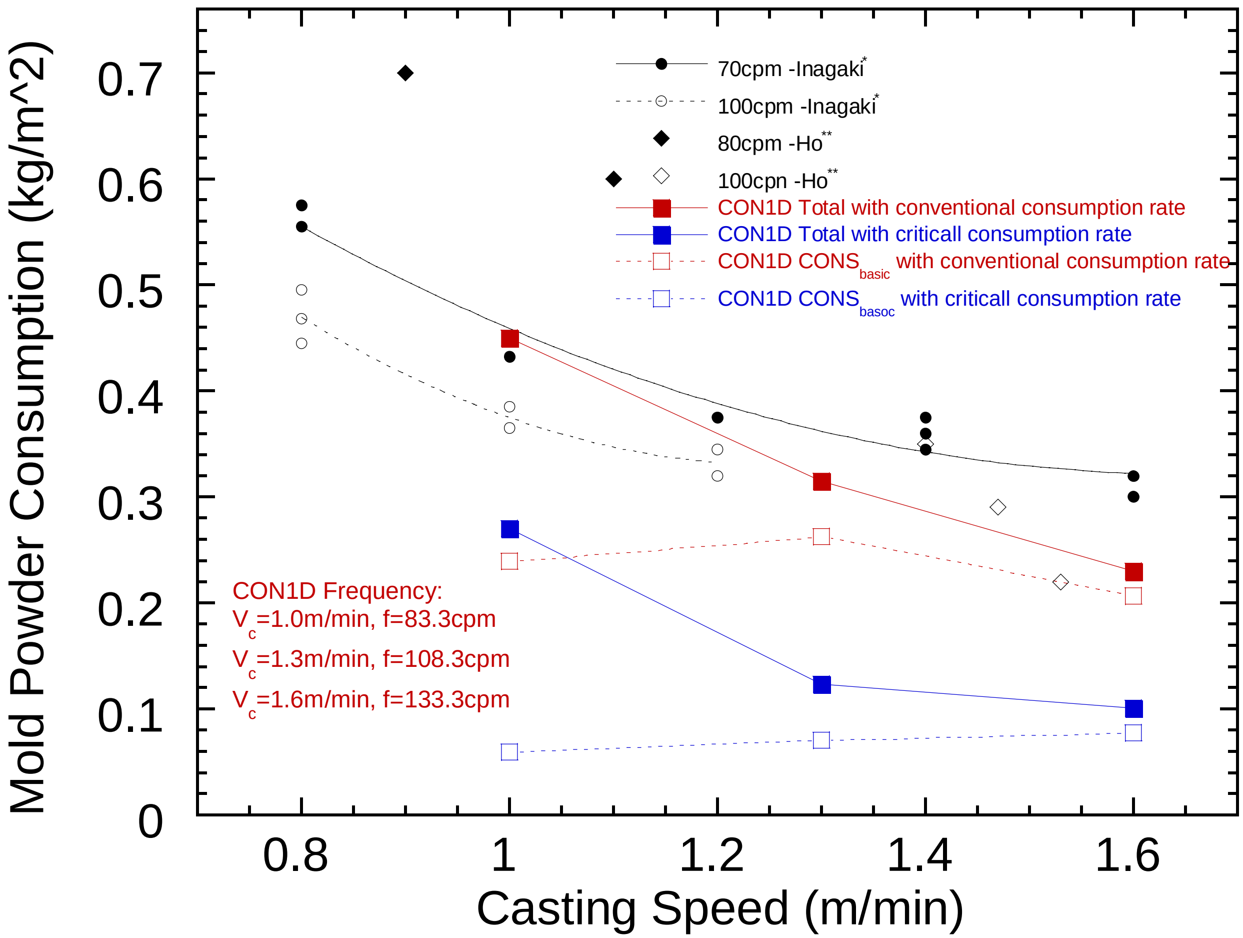
Oscillation mark depth chosen

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

Increasing casting speed from 1.0 to 1.6m/min (constant pitch, higher frequency, lower negative strip time, shallower oscillation marks, higher heat flux):

- increases $CONS_{basic}$ by 30.6%,
- moves critical fracture position from 85mm to 61mm.

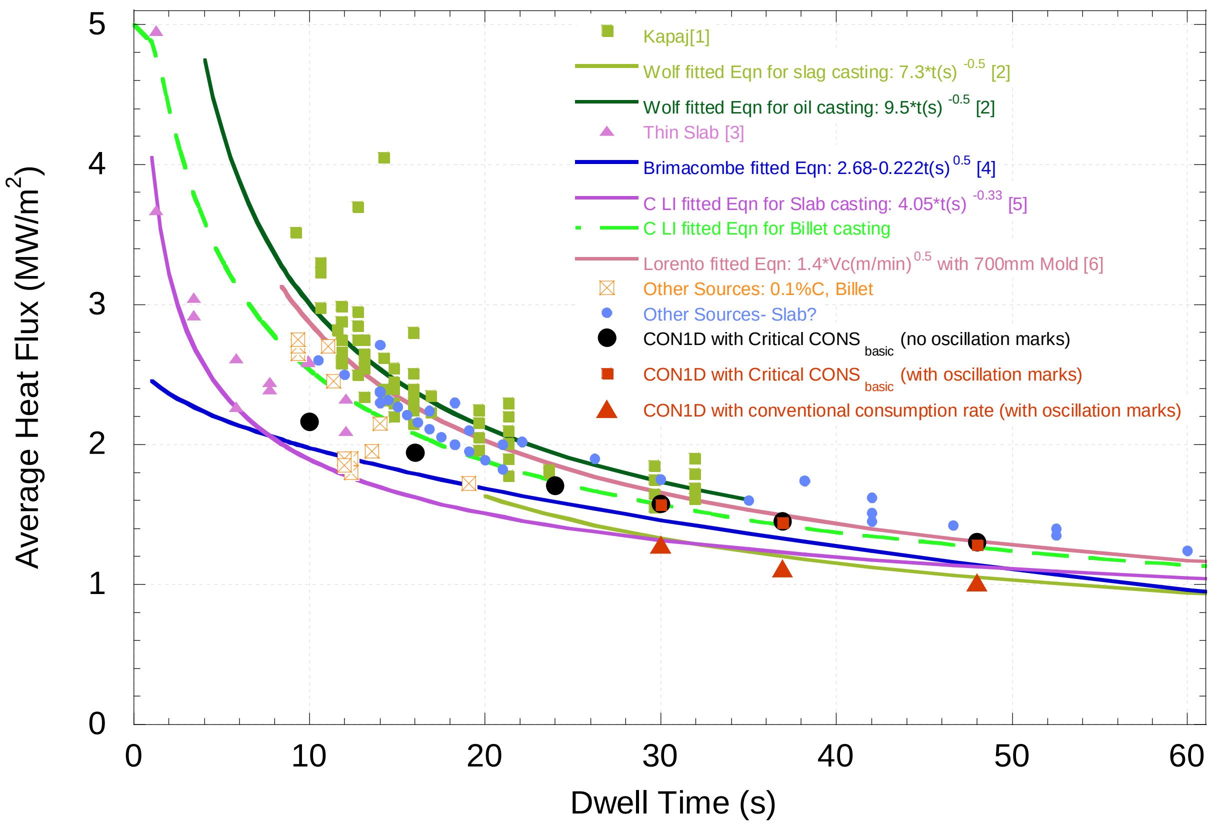
Powder Consumption Rate
(with oscillation marks)



* M. Inagaki etc.,CAMP-ISIJ, 1989, 2, p309

** B. Ho, Master thesis, University of Illinois,1992

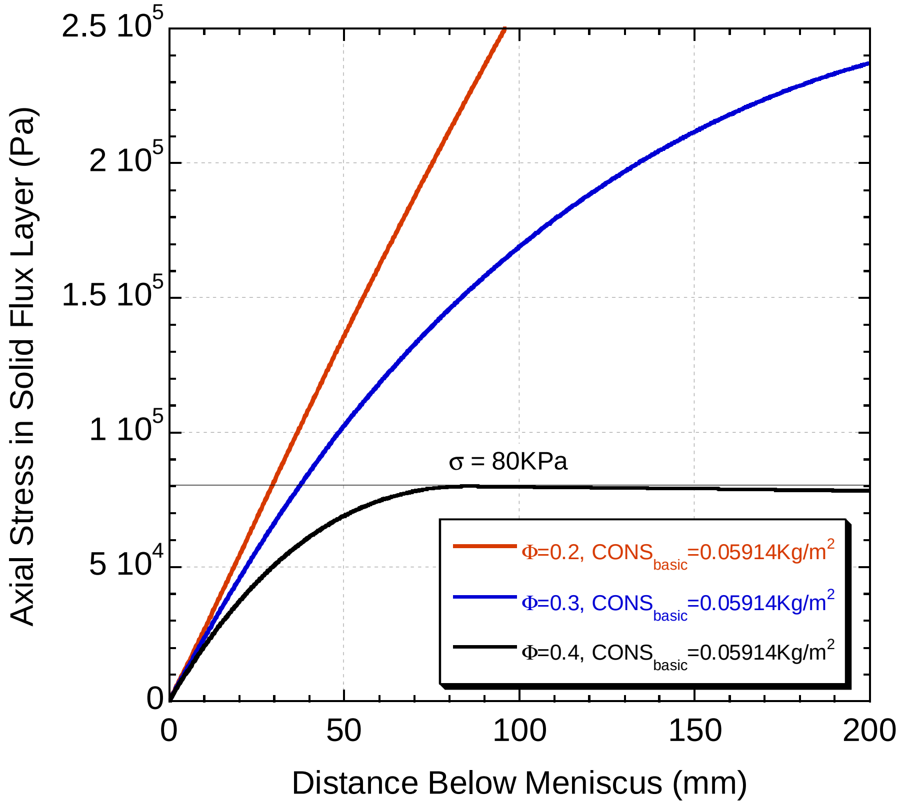
Average Heat Flux with Casting Speed

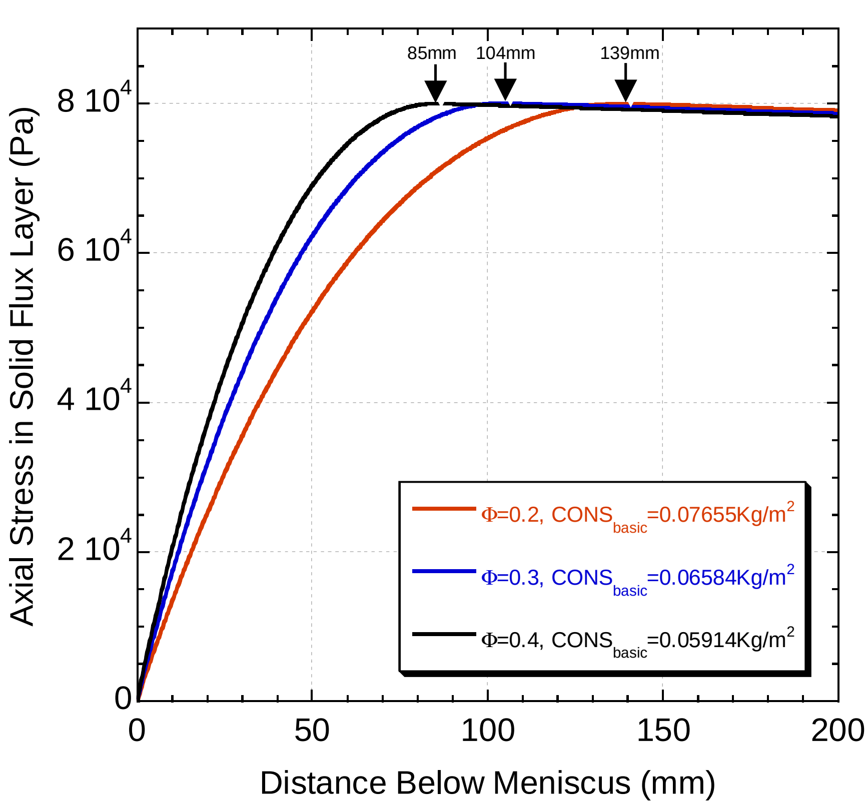


[1] Kapaj N., Pavlicevic M. and Poloni A., 84th Steelmaking Conf. Proc., Baltimore, MD, ISS, p67
[2] Wolf M.M., I&SM, V.23, Feb., 1996, p47
[3] Park J.K., Samarasekera I.V., and Thomas B.G. et al, 83th Steelmaking Conf. Proc., Warrendale, PA, ISS, p13
[4] Brimacombe J.K., Canadian Metallurgical Quarterly, V.15, N.2, 1976, p17
[5] Li C. and Thomas B.G. Brimacombe Memorial Symposium, Vancouver, Canada, 2000, p17
[6] Lorento D.P. unpublished paper

- Average heat flux in mold increases with casting speed
- Casting with low consumption rate (approaching critical $CONS_{basic}$) leads to higher average heat flux in mold

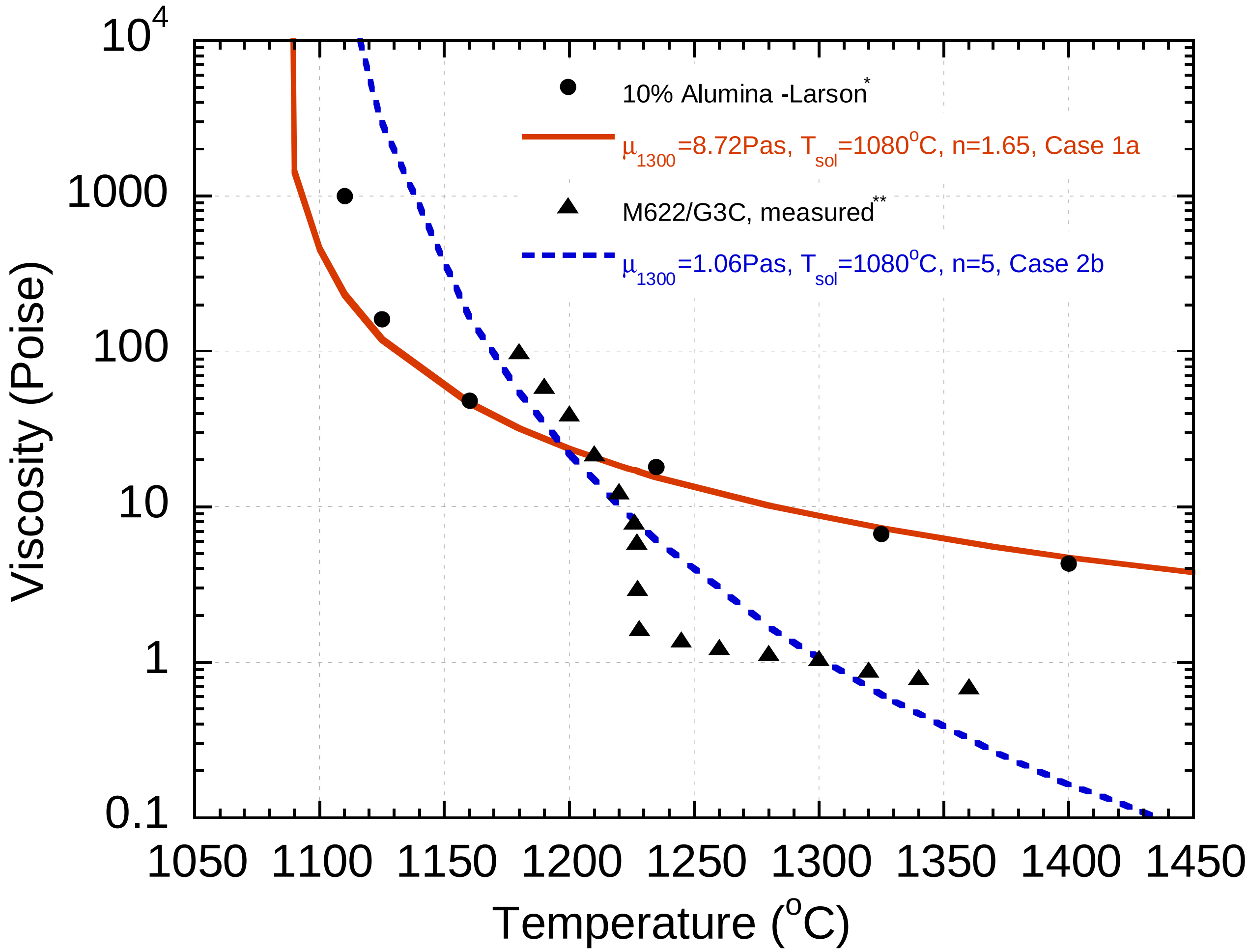
Effect of Friction Coefficient, ϕ





- Keep same $CONS_{basic}$, ϕ=0.2 case will break at 29mm, ϕ=0.3 case will break at 37mm.
- Decreasing friction coefficient, ϕ, from 0.4 to 0.2:
  - increases critical $CONS_{basic}$ by 29.4%,
  - moves the critical fracture position from 85mm to 139mm below meniscus.
- Maintaining high friction coefficient is important to keep solid flux attached to mold wall

Viscosity of Flux

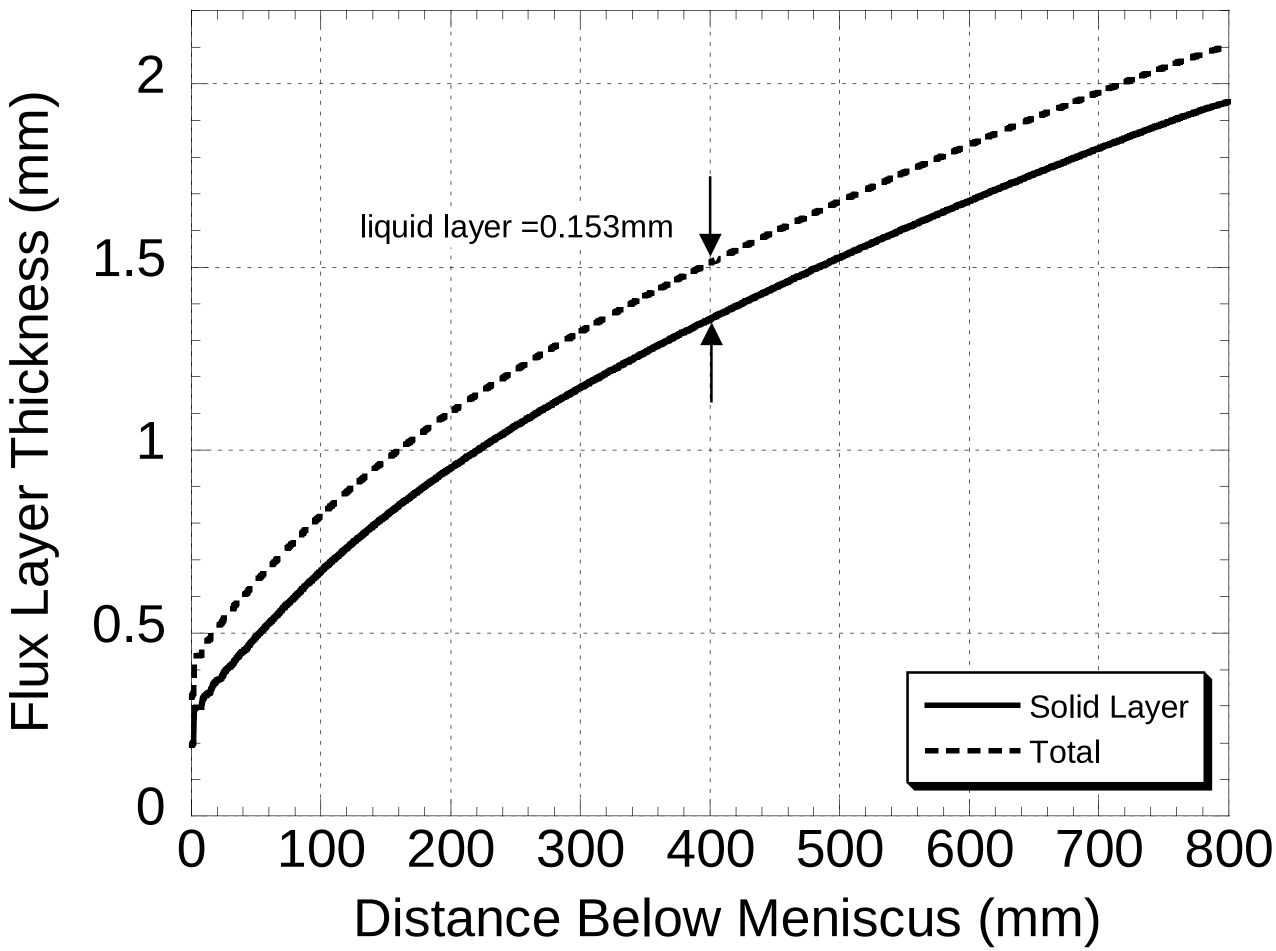


* D. Larson, Industrial Heating, 1986, 53, p16

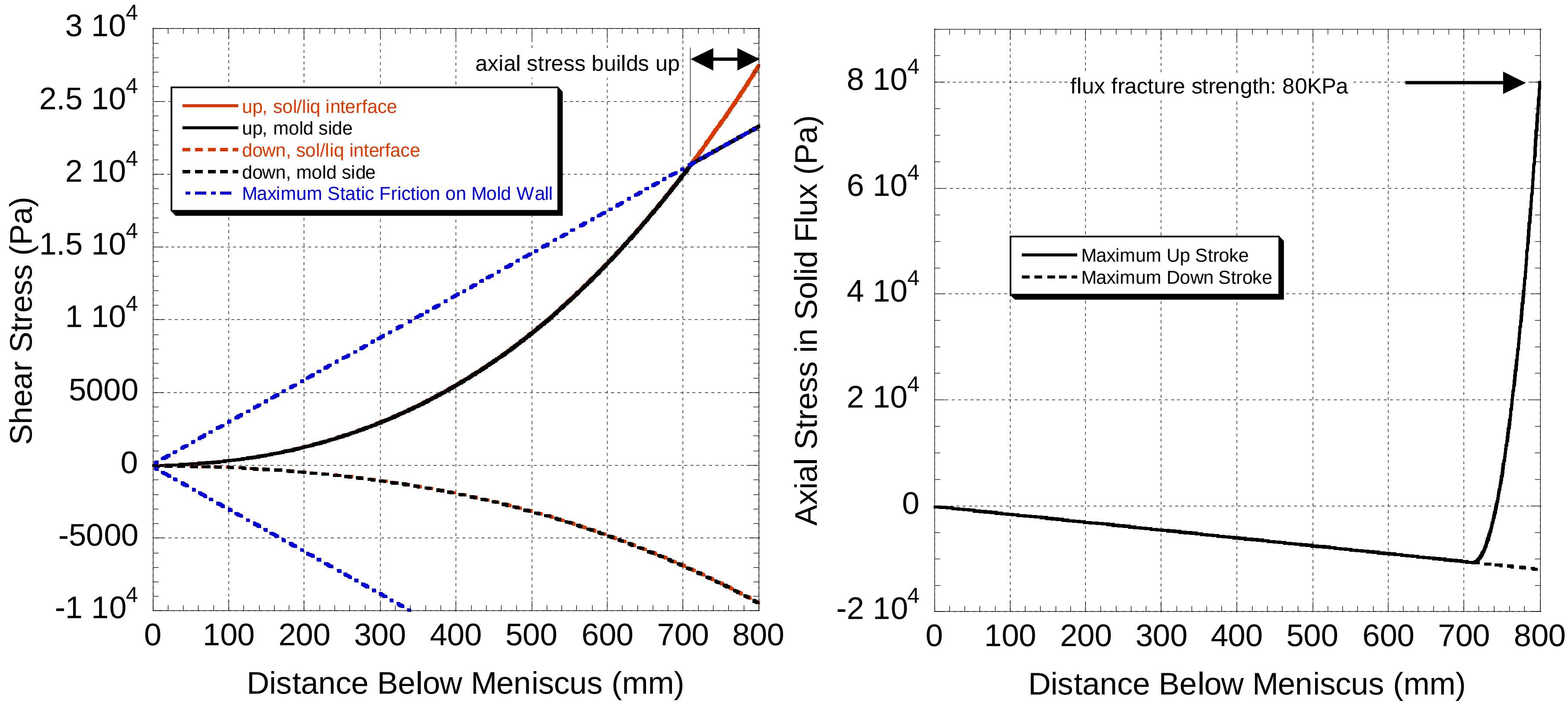
** From Amoco Inc., measured in Germany

Flux Layer Thickness

(Case 2b, $CONS_{basic}$=0.07599kg/m^2)

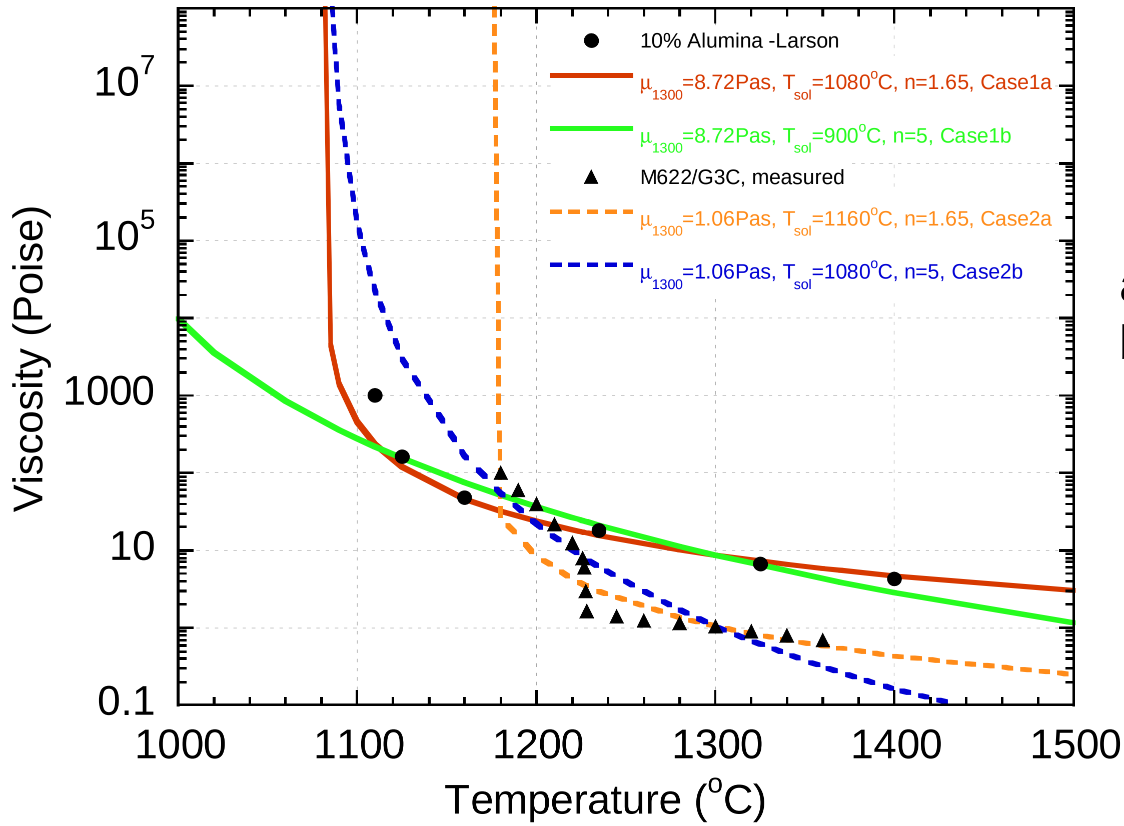


How Does Axial Stress Build up near Mold Exit? (Case 2b)



- Case 2b: using M622/G3C flux, critical $CONS_{basic}$=0.07599kg/m^2.
- Only when liquid shear stress exceeds maximum static solid friction, does axial stress build up.
- Critical fracture position is near to the mold exit.

Flux Viscosity Curve



a: “crystalline” shape
b: “glassy” shape

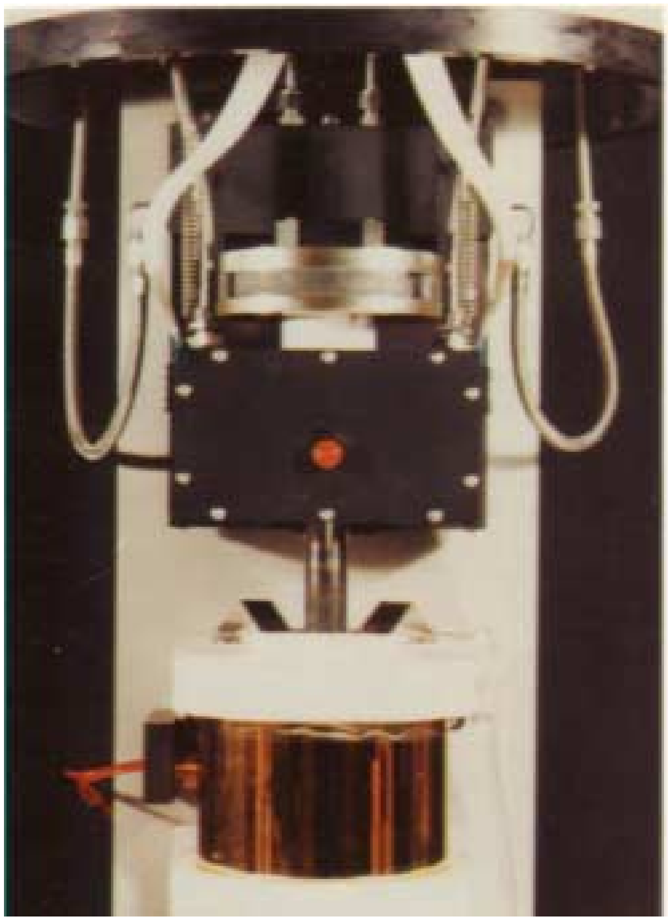
Case1a: Critical $CONS_{basic}$=0.05914kg/m^2, $Z_{fracture}$ near meniscus

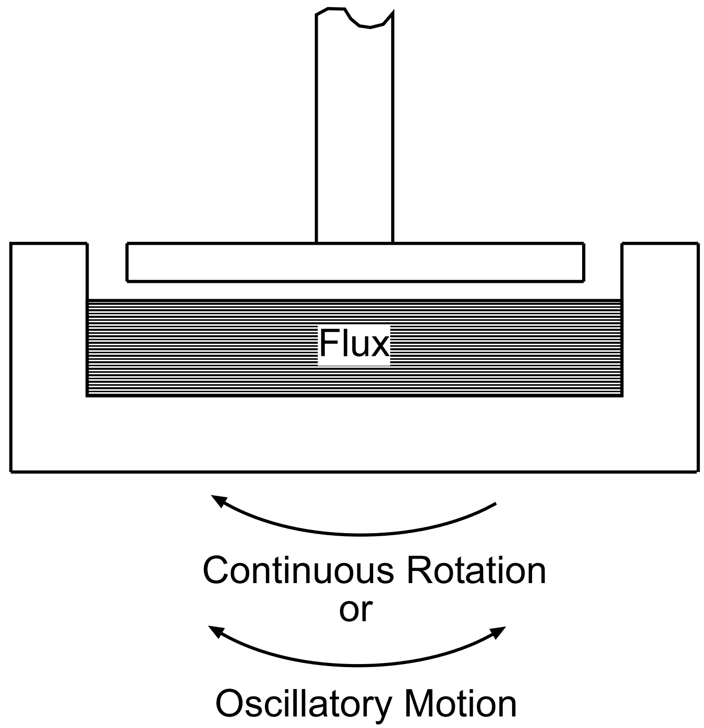
Case1b: Critical $CONS_{basic}$=0.15473kg/m^2, $Z_{fracture}$ near mold exit

Case2a: Critical $CONS_{basic}$<0.04877kg/m^2, $Z_{fracture}$ near meniscus

Case2b: Critical $CONS_{basic}$=0.07599kg/m^2, $Z_{fracture}$ near mold exit

High Temperature Tribometer (HTT)





Measure detailed friction data on material test specimens up to 1000°C

Conclusions

- When friction on mold side can not compensate the shear stress on flux solid/liquid interface, axial stress builds up in solid flux layer. If the axial stress exceeds the flux fracture strength, solid flux breaks and moves from the mold wall.
- Parametric study reveals the variables which increases the difference of shear stresses between both sides of solid flux, increases axial stress and critical $CONS_{basic}$, and also increases the likelihood of fracture, the effect of:
  - Flux Poisson's ratio, υ is negligible (doubling υ decreases $CONS_{basic}$ by 0.5%).
  - Liquid flux pool depth, h_0 is not important (decreasing h_0 10mm increases $CONS_{basic}$ by 3.5%).
  - Doubling fracture strength, σ, decreases $CONS_{basic}$ 6.8%.
  - Mold thickness d_{mold} is negligible, but thinner mold with lower mold temperature may make flux more brittle, therefore increases the possibility of fracture.
  - Increasing casting speed V_c from 1.0 to 1.6m/min increases $CONS_{basic}$ 30%, in which 18% is due to the shallower oscillation marks.
  - Maintaining high mold/flux coefficient, ϕ, is important (decreasing ϕ from 0.4 to 0.2 increases $CONS_{basic}$ by 29.4%).

Conclusions

- Flux temperature-viscosity curve decides the shear stress along mold wall and affects both the critical consumption rate and the possible position where solid flux breaks.
- Glassy fluxes 1b & 2b (with low low-temperature viscosity) tend to fracture near mold exit easily (higher critical $CONS_{basic}$).
- Crystalline fluxes 1a & 2a (with sharp viscosity curve) tend to fracture near meniscus, but less easily (lower critical $CONS_{basic}$) and these fluxes also likely have higher friction coefficient.
- Comparing two crystalline fluxes (Case 1a & 2a), higher melting temperature and lower high-temperature viscosity flux (Case 2a) has lower critical $CONS_{basic}$ and is less easily fractured.

Future Work

- Measure flux viscosity and friction coefficient at low temperature using HTT.
- Study flux behavior after it breaks.
- Calculate friction force due to mismatch taper using normal stress calculation from CON2D.