CCC Annual Report

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Effect of Non-Newtonian Slag Behavior on Gap Flow and Friction in CC

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Introduction

Observation: Mold shear stress and mold friction are not equal during the oscillation upstroke and downstroke.

Goal: Develop a new model for the slag layer for this phenomena.

Use computational tools (eg CON1D) to interpret these signals

Approach:

This project will determine the effect of the non-Newtonian behavior of the slag fluid on the mold stress and friction, in 2 steps:

1: mold movement ⟹ slag velocity profile

2: slag velocity profile ⟹ mold friction

UPSTROKE (lower)

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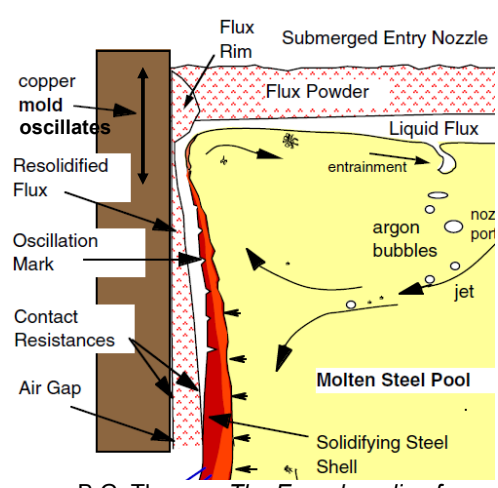
DOWNSTROKE (higher)



B.G. Thomas, *The Encyclopedia of Advanced Materials*, 2001,.

Introduction – CON1D

- CON1D: a finite-difference model for heat transfer and solidification in the mold region of a continuous caster.

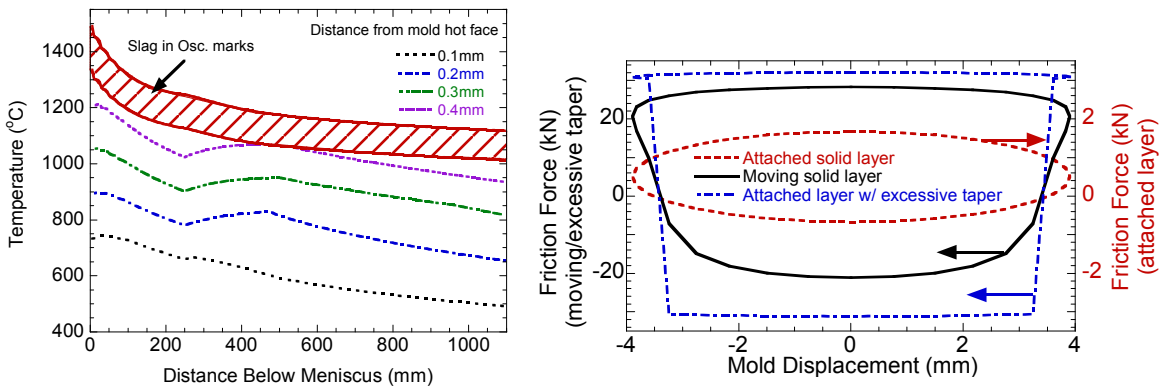
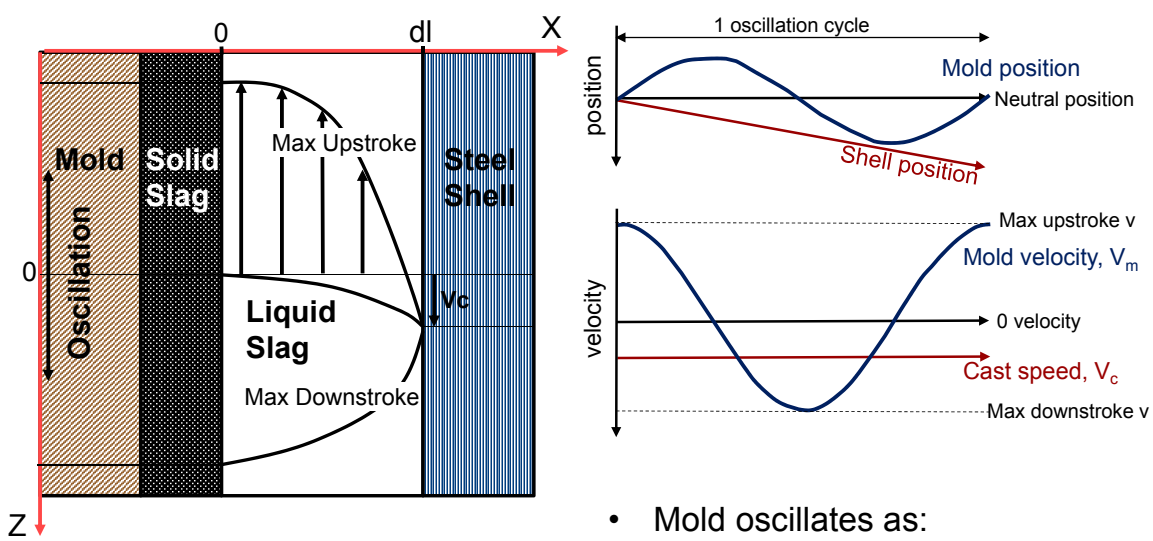


Figure: examples of temperature of the slag, and mold friction from CON1D model[1]

CON1D considers the liquid slag as Newtonian fluid with temperature dependency. This project will take into consideration of non-Newtonian behavior of slag fluid

[1]: Y. Meng and B.G. Thomas, *METALLURGICAL AND MATERIALS TRANSACTIONS B*, 2003

Problem Schematic

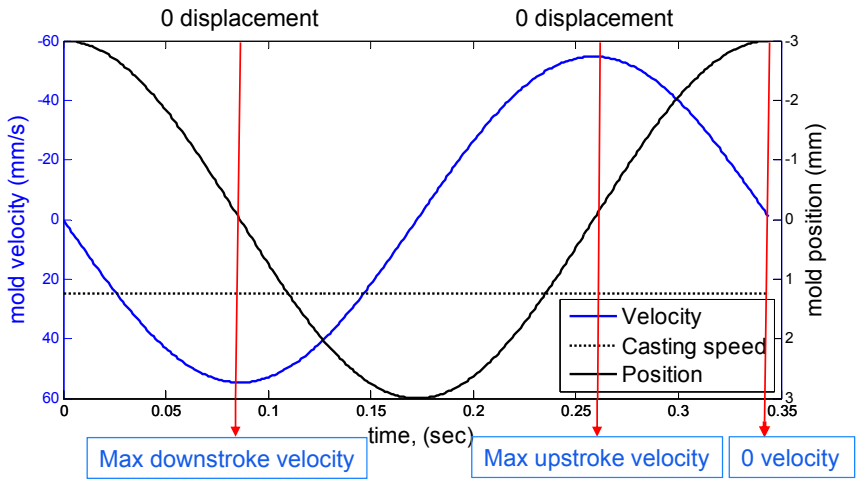


- Mold oscillates as: $V_m = \varphi\omega\sin(\omega t)$
- Casting speed as: V_c

Particular mold velocity definition

s	Stroke	6.0 mm
φ	Amplitude(stroke/2)	3.0 mm

ω	Frequency	2.9 Hz
V_c	casting speed	1.488 m/min



Momentum balance for fluid

Assuming incompressible flow with constant density and no velocity across slab width:

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_z}{\partial z} = 0$$

The momentum balance on z-direction (vertically):

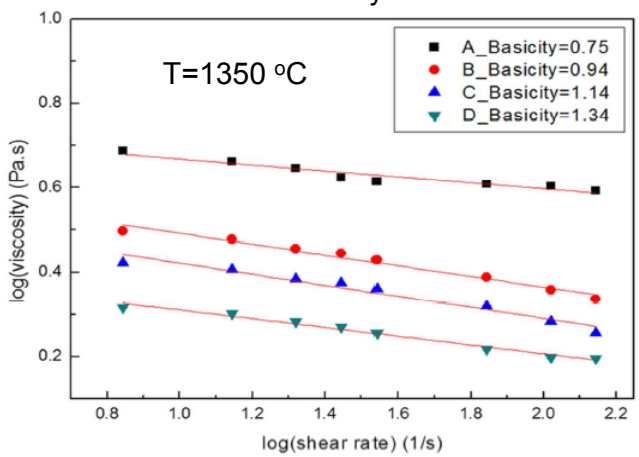
$$\rho \bullet \left(\frac{\partial V_z}{\partial t} + V_x \bullet \frac{\partial V_z}{\partial x} + V_y \bullet \frac{\partial V_z}{\partial y} + V_z \bullet \frac{\partial V_z}{\partial z} \right) = -\frac{\partial P}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho g_z$$

With $\frac{\partial P}{\partial z} = \rho_{steel}\, g_z$, this simplifies to:

$$\boxed{\rho \bullet \frac{\partial V_z}{\partial t} = \frac{\partial \tau_{xz}}{\partial x} + \left(\rho - \rho_{steel}\right) g_z}$$

Non-Newtonian slag fluid data

Recent work shows viscosity as a function of shear rate for slags:



Sample	CaO/SiO_2	SiO_2	CaO	MgO	Al_2O_3	Na_2O	F
A	0.75	44.8	36	0.9	4.8	7	7.4
B	0.94	40.1	40.2	1	4.9	7.1	7.5
C	1.14	36.4	43.6	1.1	5	7.3	7.6
D	1.34	33.4	44.8	0.8	5.4	7.6	7.6

S. Shina, J. Chob, S. Kim, J. Am. Ceram. Soc., pp 3263–3269 (2014)

- Slag fluid:
  shear thinning behavior

  $\tau = m \cdot (\dot{\gamma})^n$ with 0<n<1

  $\mu_{eff} = m \cdot (\dot{\gamma})^{n-1}$ with 0<n<1

  From the fitting of the figure:

  $\log(\mu_{eff}) = \log(m) + (n-1)log(\dot{\gamma})$

- Example with Basicity=0.94 (=CaO/SiO_2):

  n=0.874, m=0.616

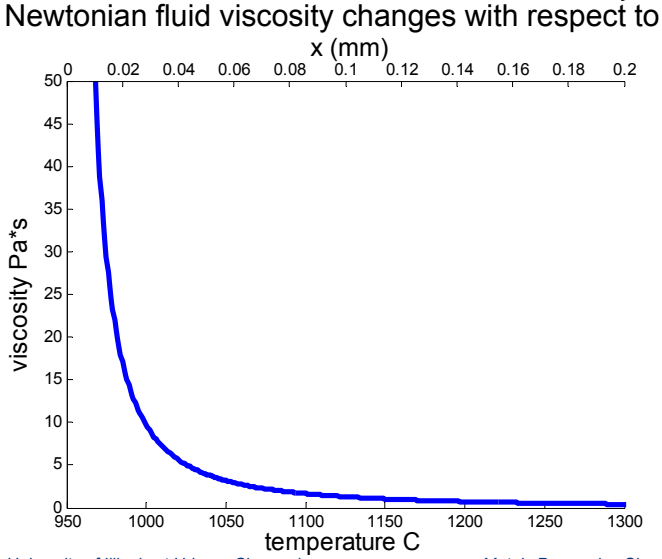
  $\tau = 0.616 \cdot (\dot{\gamma})^{0.874}$

Newtonian Viscosity for fluid

The viscosity – temperature relationship fits into:

$$\mu = \mu_0 \left(\frac{T_0 - T_{fsol}}{T - T_{fsol}} \right)^a$$

Newtonian fluid viscosity changes with respect to temperature within the slag layer:



parameters		value
μ_0	ref. viscosity	0.43 Pa*s
T_0	ref. temperature	1300 °C
T_{fsol}	mold solidification temperature	950 °C
a	exponent	1.6
T	temperature at a pt.	
μ	viscosity at a pt.	

(assume T is linear across fluid layer)

Shear thinning slag fluid expression

For shear thinning fluid, shear stress with respect to temperature and shear rate is then :

$$\tau = m \cdot |\dot{\gamma}|^{n-1} \left(\frac{T_0 - T_{fsol}}{T - T_{fsol}}\right)^a (\dot{\gamma}) \,, \qquad \text{viscosity } \mu_{eff} = m \cdot |\dot{\gamma}|^{n-1} \left(\frac{T_0 - T_{fsol}}{T - T_{fsol}}\right)^a$$

Assume T is linear across the fluid layer: $T = \frac{x}{d_l}\left(T_0 - T_{fsol}\right) + T_{fsol}$

$$\boxed{\tau_{xz} = m \cdot |\dot{\gamma}|^{n-1} \left(\frac{d_l}{x}\right)^a (\dot{\gamma})}$$

Viscosity:

$$\mu_{eff} = m \cdot |\dot{\gamma}|^{n-1} \left(\frac{d_l}{x}\right)^a$$

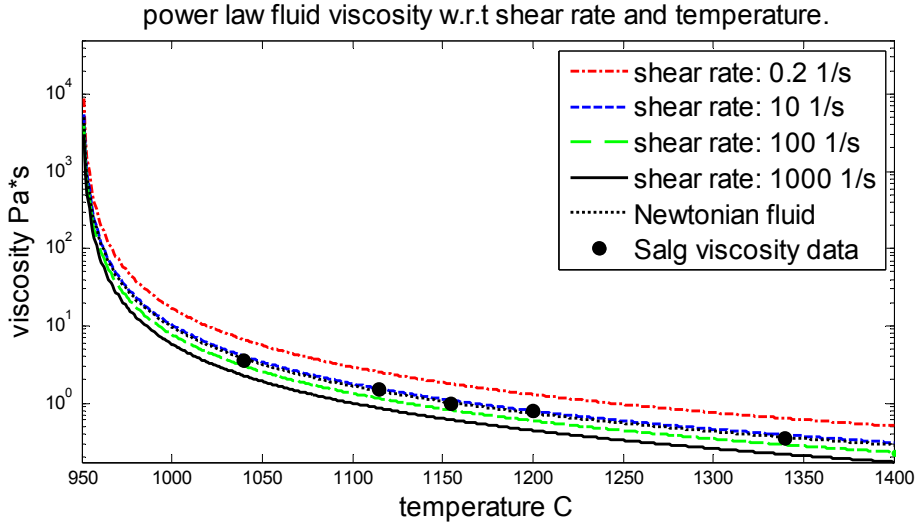
m	fluid parameter	0.616
n	fluid parameter	0.874
V_s	mold velocity,	±3.3, 0 m/min

$\dot{\gamma}$	shear rate	dV_z/dx
dl	liquid thickness	0.2 mm
V_c	cast velocity	1.488 m/min

Effective viscosity for slag fluid

Viscosity changes with respect to temperature and shear rate within the slag layer is shown in the figure. Assume T is linear across fluid layer, different color lines represent different shear rate.

power law fluid viscosity w.r.t shear rate and temperature.



Velocity Solution

Substitute the shear stress into the momentum equation:

$$\rho\left(\frac{\partial V_z}{\partial t}\right) = \frac{\partial}{\partial x}\left[m\left(\frac{\partial V_z}{\partial x}\right)^{n-1}\left(\frac{d_l}{x}\right)^{a}(\dot{\gamma})\right] + (\rho - \rho_{steel})g \qquad \text{with BC: } \begin{cases} V_z|_{x=0} = \varphi\omega\sin(\omega t) \\ V_z|_{x=dl} = V_c \end{cases}$$

Solution is:

$$Vz = \frac{nx}{a+n}\cdot\left(\frac{(\rho_{steel}-\rho)gx}{C_1}+1\right)^{-\frac{1}{n}}\cdot 2F1\left(-\frac{1}{n},\frac{a+n}{n};\frac{a}{n}+2;\frac{g(\rho_{steel}-\rho)x}{C_1}\right)\cdot\left(\frac{x^a(C_1+(\rho_{steel}-\rho)gx)}{m(dl)^a}\right)^{\frac{1}{n}}+C_2$$

Validation:

The existing model[1] treat the fluid as Newtonian fluid, which means n=1 in the power fluid model. When n=1:

$$Vz = \frac{g(\rho_{steel}-\rho)x^{a+2}}{m(a+2)(dl)^a} + \left(\frac{(V_c - V_s)}{dl} - \frac{g(\rho_{steel}-\rho)dl}{m(a+2)}\right)\cdot\left(\frac{x^{a+1}}{dl^a}\right) + V_s$$

And this is an exact match with the Newtonian fluid solution from the existing model.

[1]: Y. Meng and B.G. Thomas, *METALLURGICAL AND MATERIALS TRANSACTIONS B*, 2003

Test problem casting conditions

The following additional properties are used to evaluate the solution[1][2]:

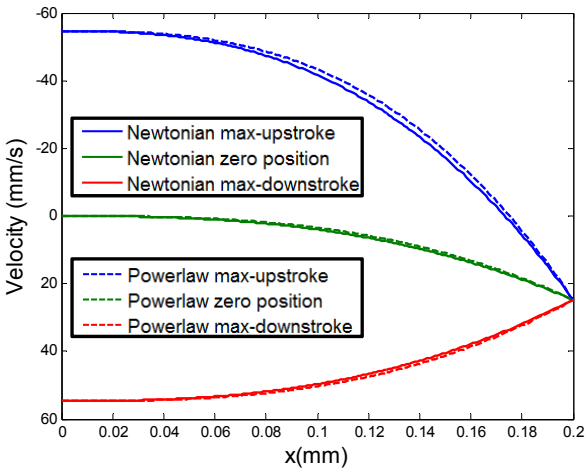
symbol	description	value
ρ_{steel}	steel density	7400 kg/m^3
ρ_{slag}	slag density	2600 kg/m^3
$s(=2\varphi)$	stroke	6.0 mm
ω	frequency	2.9 Hz
m	fluid parameter	0.616
n	fluid parameter	0.874
V_s	mold velocity	$\varphi\omega\sin(\omega t)$
V_c	cast velocity	1.488 m/min

symbol	description	value
$\dot{\gamma}$	shear rate	dV_z/dx
dl	liquid thickness	0.2 & 0.6 mm
a	exponent	1.6
μ_0	ref. viscosity	0.43 Pa*s
T_0	ref. temperature	1300 ^{o}C
T_{fsol}	mold solidification temperature	950 ^{o}C
W	slab width	1500 mm
N	slab thickness	230 mm

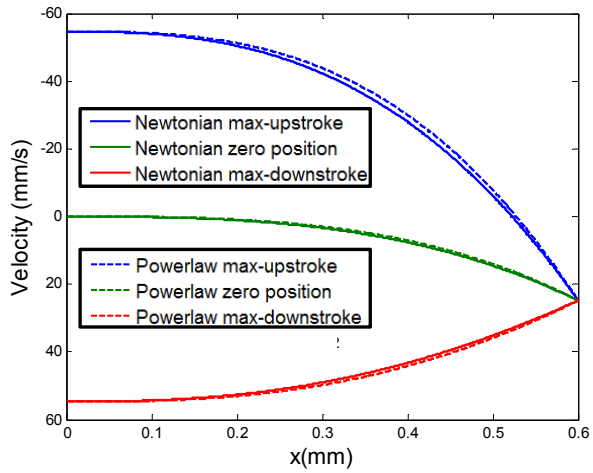
[1]: Y. Meng and B.G. Thomas, *METALLURGICAL AND MATERIALS TRANSACTIONS B*, 2003
[2]: H.Shin, S.Kim, B.G. Thomas, G. Lee, J.Park, J. Sengupta, *ISIJ International*, 2006

Velocity Solution profile

Velocity profile:



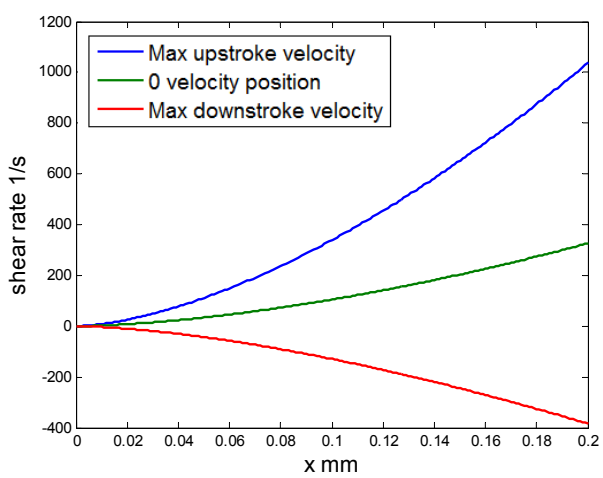
Case a, 0.2mm film thickness



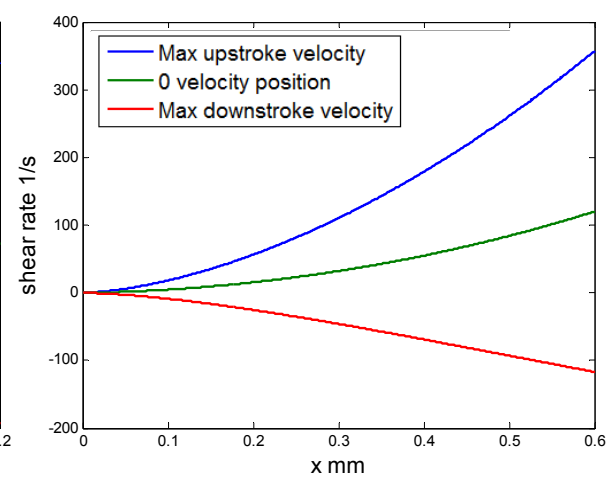
Case b, 0.6mm film thickness

Shear rate range in interfacial gap

Shear rate (dV_z/dx) from velocity solution:



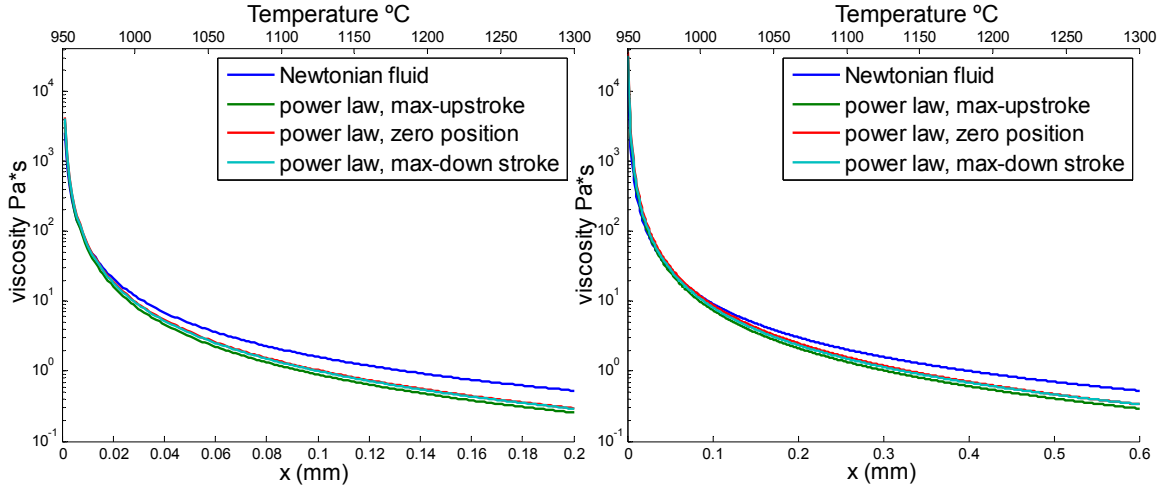
Case a, 0.2mm film thickness



Case b, 0.6mm film thickness

Effective Viscosity result

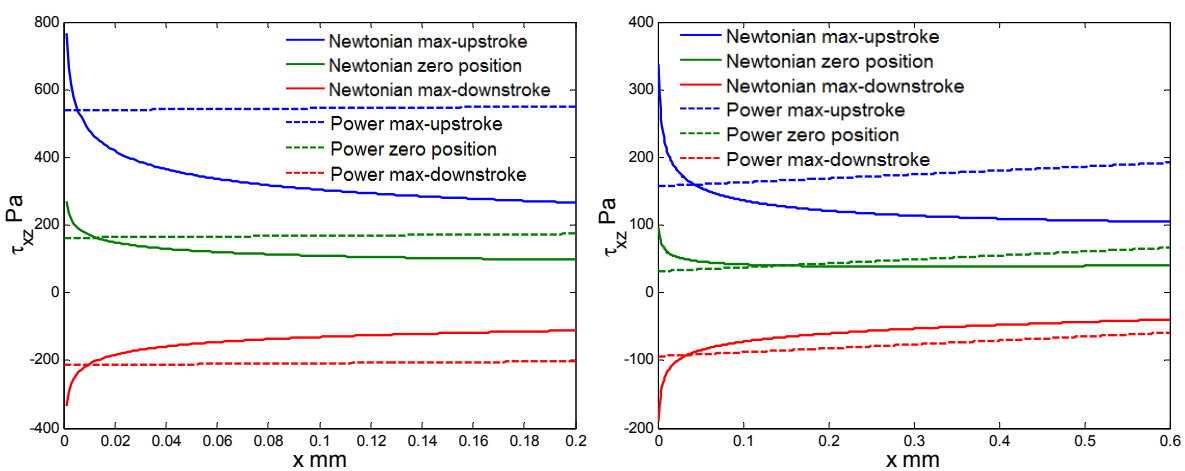
A viscosity plot using the power law fluid velocity solution:



Case a, 0.2mm film thickness *Case b, 0.6mm film thickness*

Shear stress result

Shear stress: $\tau_{xz} = m \cdot |\dot{\gamma}|^{n-1} \left(\frac{d_l}{x}\right)^a (\dot{\gamma})$

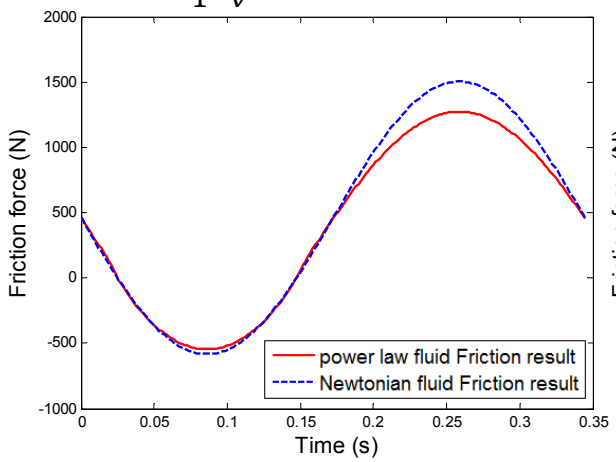


Case a, 0.2mm film thickness *Case b, 0.6mm film thickness*

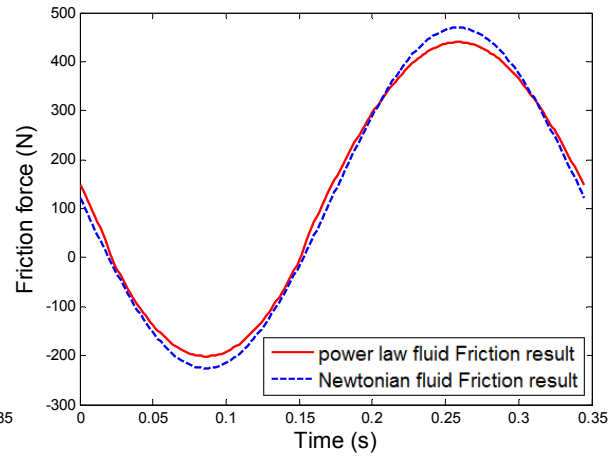
Mold friction vs. time result (with liquid only)

Integrate the shear stress at the solid/liquid slag interface gives the mold friction due to the liquid shear stress :

$$\tau_{mold} = \frac{\nu}{1-\nu}\rho_{steel} g d_s \qquad F_{contact} = \int_0^{Z_{mold}} \tau_{mold} \cdot 2(\underbrace{W}_{\text{Thickness}} + \underbrace{N}_{\text{Width}}) \cdot dz$$



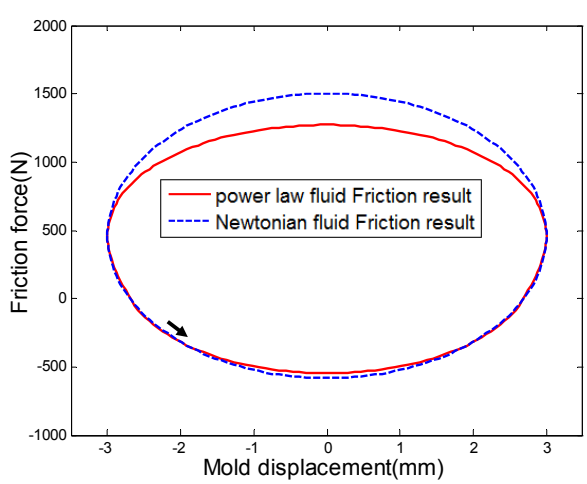
Case a, 0.2mm film thickness



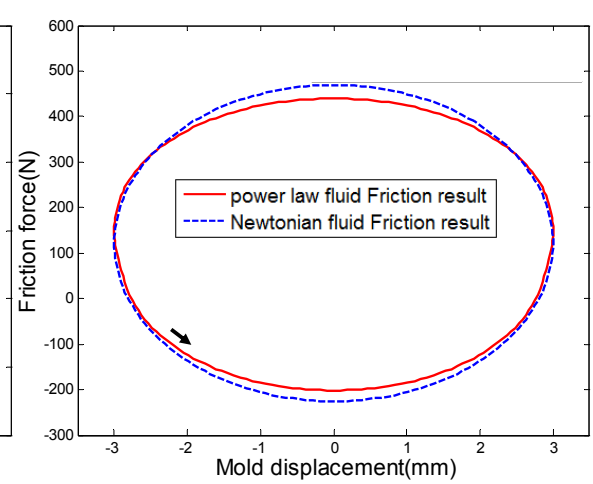
Case b, 0.6mm film thickness

Mold friction vs. position result (with liquid only)

The following friction vs. mold displacement figures predict the mold friction (due to the liquid shear stress) at a certain mold position.



Case a, 0.2mm film thickness



Case b, 0.6mm film thickness

- <u>Note that actual mold friction includes solid layer friction and other factors</u>

Conclusions & Future work

- CON1D model of heat transfer in the shell and mold, liquid slag flow, solid slag stress are used and being improved with addition of non-Newtonian fluid behavior.
- Non-Newtonian (shear-thinning) behavior of molten slag has little effect on velocity, or uneven mold friction during up/down stroke. However it does affect shear stress and liquid friction, especially when liquid layer is thin.

Future Work:

- Consider friction from solid slag layer.
  - Current work includes friction from liquid
  - Friction from solid slag layer is more important
- Examine non-Newtonian behavior of more slags

Acknowledgments

- Continuous Casting Consortium Members (ABB, AK Steel, ArcelorMittal, Baosteel, JFE Steel Corp., Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, SSAB, ANSYS/ Fluent)