CCC Annual Report

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Validation of Modeling Methodology for Slag Entrainment

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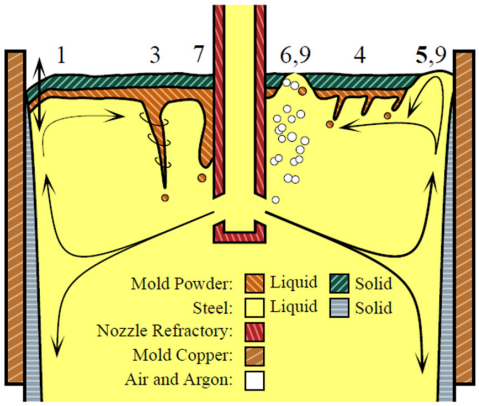
Introduction

- Mold slag entrainment is a challenge to the production of clean steel
- This work develops a numerical model to predict slag entrainment

<u>9 mechanisms of slag entrainment:</u>

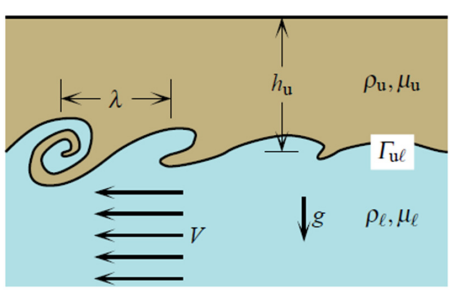
1. Top surface fluctuations
2. Meniscus freezing/hook formation
3. Vortex formation in the wake of the SEN
4. Shear-layer instability
5. **Upward flow impinging upon the top surface**
6. Argon bubble interactions/slag foaming
7. Slag crawling down the SEN
8. Top surface stationary wave instability
9. Top surface "balding"



Hibbeler and Thomas, *Iron and Steel Tech.*, 2013

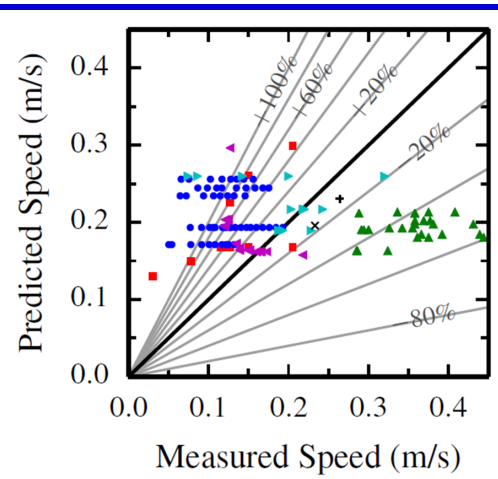
Evaluation of Previous Work

Previous Theoretical Work
Shear Instability Criterion



$$V_{crit} = \sqrt[4]{4\Gamma_{u\ell} g \left(\rho_\ell - \rho_u\right)\left(\frac{1}{\rho_u} + \frac{1}{\rho_\ell}\right)^2}$$

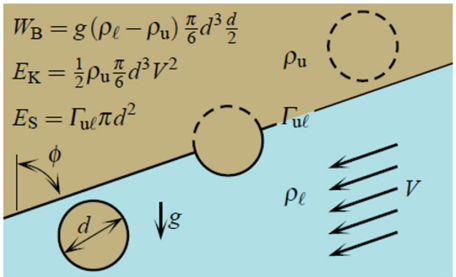
Kelvin, *Phil. Mag.*, 1871
Helmholtz, *Preuss. Akad. Berlin*, 1868



- Feldbauer, PhD Thesis, 1995
- Harman and Cramb, *Steelmaking Conf.*, 1996
- Hagemann *et al.*, *Met Trans B*, 2013
- Savolainen *et al.*, *ISIJ Int.*, 2009
- Krishnapisharody and Irons, *AISTech 2008*
- Xiao *et al.*, *Chin. J .Metal Sci. Tech.*, 1987
- Iguchi *et al.*, *ISIJ Int.*, 2000

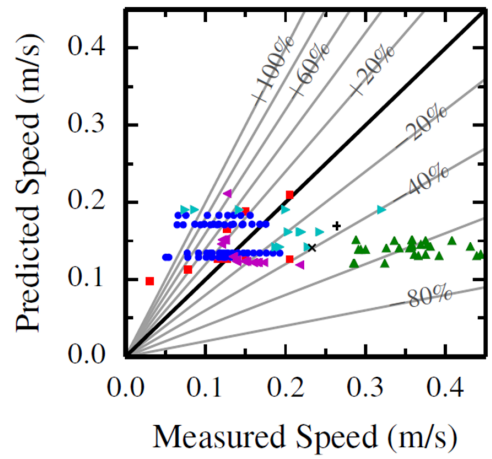
Previous Theoretical Work

Droplet Energy Criterion



$$V_{crit} = \sqrt[4]{48\Gamma_{u\ell}\frac{g(\rho_\ell - \rho_u)}{\rho_u^2}}$$

Asai, *Proc. 100th and 101st Nishiyama Mem. Lec.* ,1984



- Feldbauer, PhD Thesis, 1995
- Harman and Cramb, *Steelmaking Conf.*, 1996
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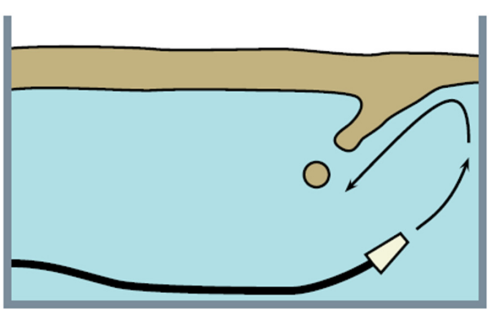
- Xiao *et al.*, *Chin. J .Metal Sci. Tech.*, 1987
- Iguchi *et al.*, *ISIJ Int.*, 2000

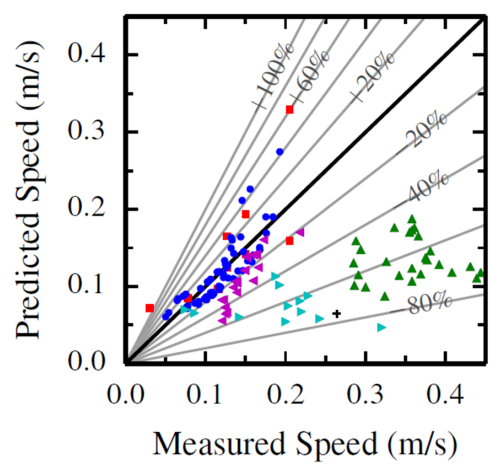
Previous Experimental Work

Hose Apparatus



$$V_{crit} = 3.065\frac{\Gamma_{u\ell}^{1.037}}{g^{0.012}}\frac{(\rho_\ell - \rho_u)^{0.239}}{\rho_u^{0.227}}\frac{\mu_u^{0.321}}{\mu_\ell^{1.370}}$$

Harman and Cramb, *79th Steelmaking Conf. Proc.*, 1996



- Feldbauer, PhD Thesis, 1995
- Harman and Cramb, *Steelmaking Conf.*, 1996
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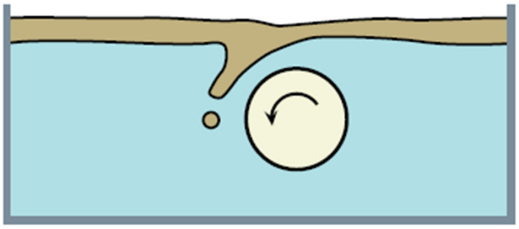
- Iguchi *et al.*, *ISIJ Int.*, 2000

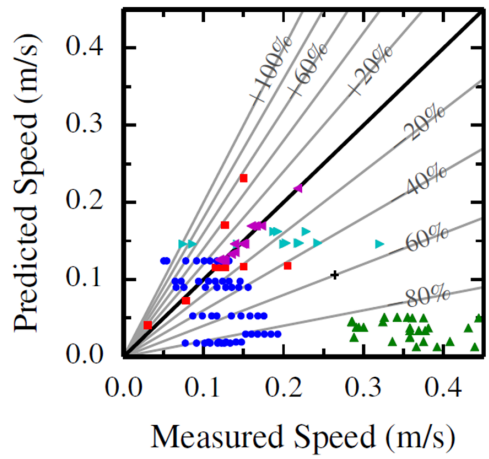
Previous Experimental Work

Rotating Cylinder Apparatus



$$V_{\text{crit}} = \frac{\Gamma_{\text{u}\ell}}{\mu_\ell}\left(2.8\times10^{-3} + 3\times10^{-6}\frac{\nu_{\text{u}}}{\nu_\ell}\right)$$

Hagemann *et al., Met Trans B,* 2013



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- Hagemann *et al., Met Trans B*, 2013
- Savolainen *et al., ISIJ Int.,* 2009
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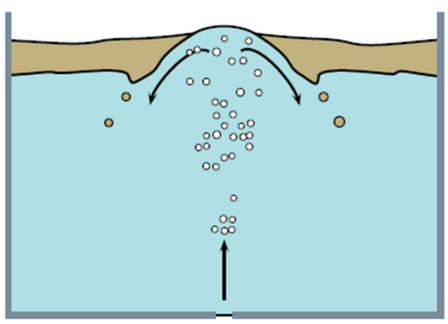
- Xiao *et al., Chin. J .Metal Sci. Tech*., 1987
- Iguchi *et al., ISIJ Int.*, 2000

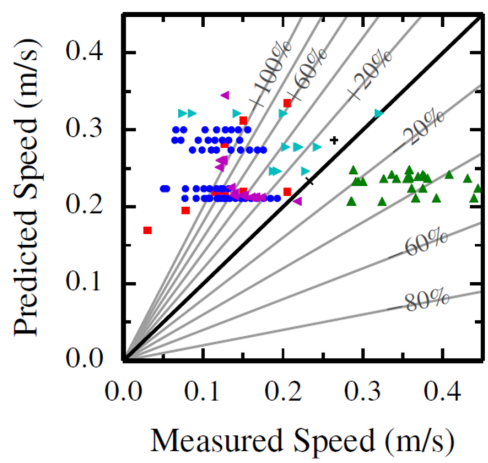
Previous Experimental Work

Ladle-like Apparatus



$$V_{\text{crit}} = \sqrt[4]{151.3\Gamma_{\text{u}\ell}\frac{g\left(\rho_\ell - \rho_{\text{u}}\right)}{\rho_\ell^2}}$$

Xiao *et al., Chin. J .Metal Sci. Tech*., 1987



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- Hagemann *et al., Met Trans B*, 2013
- Savolainen *et al., ISIJ Int.,* 2009
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- Xiao *et al., Chin. J .Metal Sci. Tech*., 1987
- Iguchi *et al., ISIJ Int.*, 2000

Comparison of Proposed Criteria

Fluid	Mass Density	Dynamic Shear Viscosity	Kinematic Shear Viscosity	Interfacial Tension	Capillary Wavelength	Characteristic Velocity	Characteristic Time
	Typical Properties				*Derived Quantities*		
	ρ	μ	ν	Γ	λ_c	V_c	t_c
	(kg/m^3)	(mPa·s)	(mm^2/s)	(mN/m)	(mm)	(m/s)	(s)
Oil	960	50	52.1	30	56.4	0.132	0.427
Water	997	0.9	1.00				
Slag	2500	300	120	1100	30.7	0.256	0.120
Steel	7200	5	0.694				

$$\lambda_c = 2\pi\sqrt{\frac{\Gamma_{u\ell}}{g\left(\rho_u - \rho_\ell\right)}} \qquad V_c = \sqrt[4]{\frac{g\Gamma_{u\ell}}{\rho_u}} \qquad t_c = \frac{\lambda_c}{V_c}$$

Comparison of Proposed Criteria

Critical Velocity (m/s)

System	Shear Instability	Droplet Energy	Hose	Rotating Cylinder	Ladle-like
Oil-Water	0.12	0.15	0.096	0.10	0.20
Slag-Steel	0.49	0.79	0.56	0.73	0.63

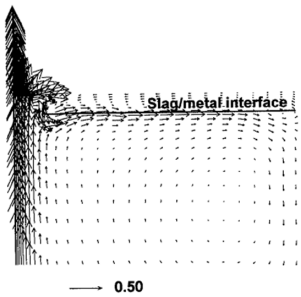
Lack of agreement among existing criteria motivates the need for more fundamental models

- Typical properties of oil, water, slag, and steel were used to compare criteria
- See previous slide for values of density, viscosity, and surface tension

Previous Numerical Work

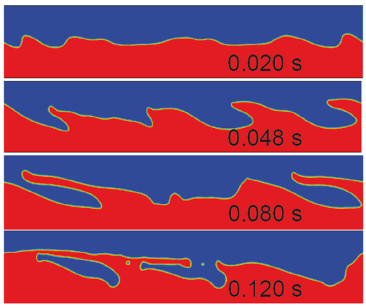
2D VOF

k-ε Turbulence Model



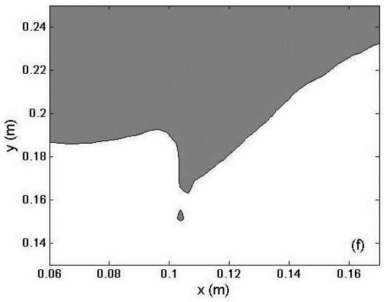
Jonsson and Jönsson, *ISIJ Int.*, 1996

DNS



Hibbeler *et al.*, *Proc. 7th ECCC*, 2011

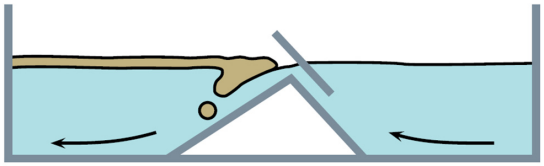
Jet eddy viscosity



Krishnapisharody and Irons, *EPD Congress*, 2008

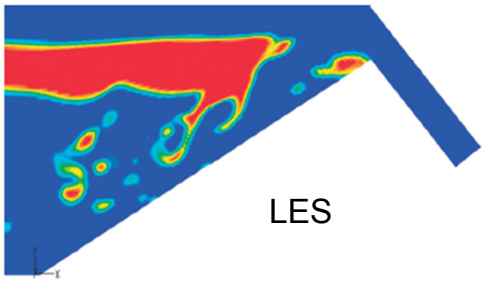
Previous Numerical Work

Ramp Apparatus



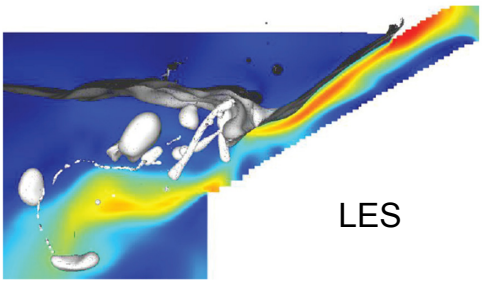
Savolainen *et al.*, *ISIJ Int.*, 2009

3D VOF



LES

Sulasalmi *et al.*, *ISIJ Int.*, 2009



LES

Senguttuvan and Irons, *AISTech 2013*

Current Model Description

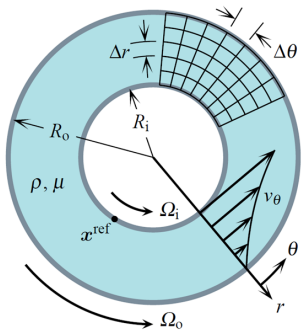
A 3D, transient, multiphase, turbulent numerical model has been developed using FLUENT to predict entrainment

Key Features Include:

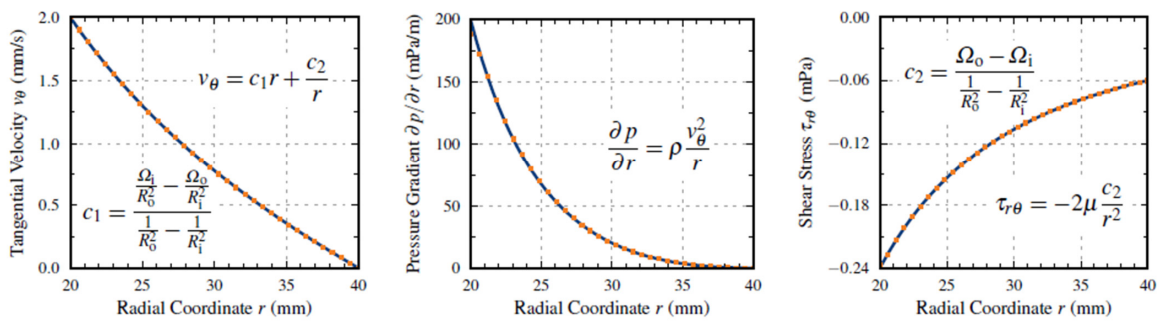
- **Explicit** time marching
- **Volume-of-fluid** method with **geometric-reconstruction** scheme
- **SST k-ω turbulence model** with low Reynolds number correction and turbulence damping at the interface
- Mesh with about **100,000 cells** with a cell length of about **2 mm**

Model Verification with Analytical Solutions

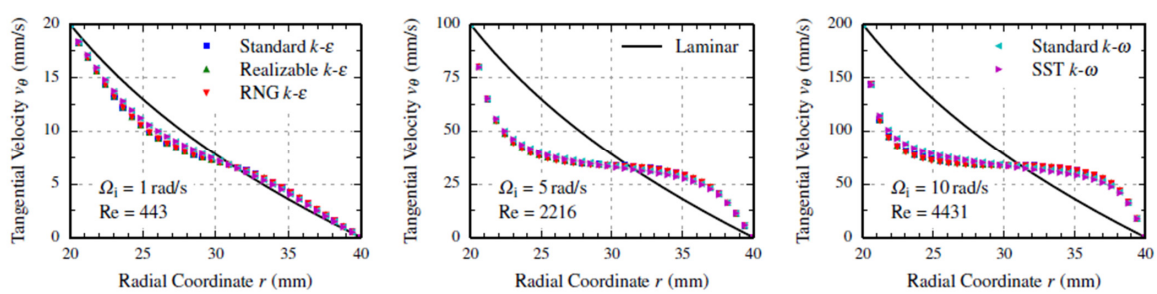
Laminar Tangential Annular Drag Flow



- Test problem proved the model could correctly relate velocities to pressures and shear stresses
- Analytical solution to laminar flow was matched

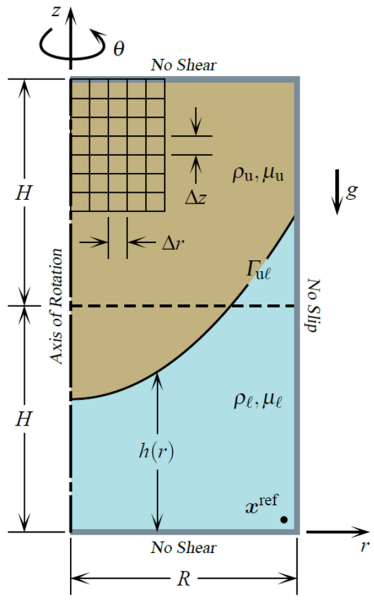


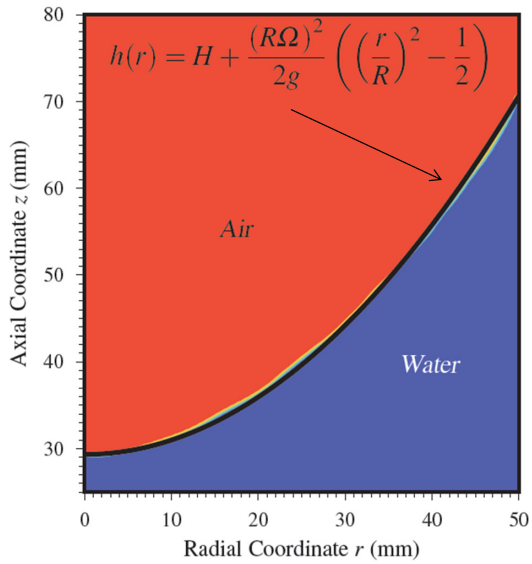
Turbulent Tangential Annular Drag Flow



- Turbulent conditions also were explored
- As velocity increases boundary layer shrinks
- 5 RANS turbulence models are in close agreement

Multiphase Axially-Rotating Cylinder



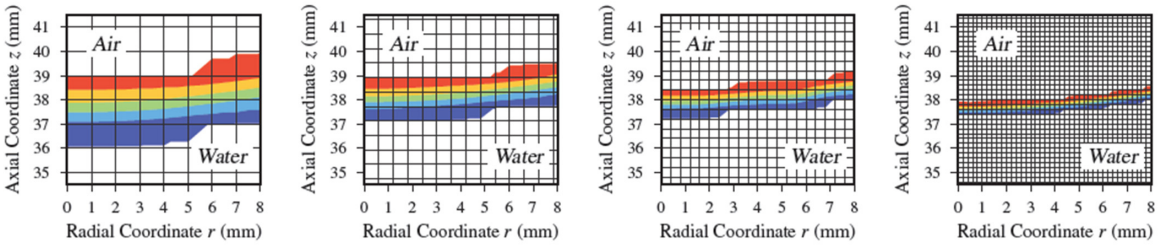


This test problem proved the model correctly simulates an interface

Multiphase Axially-Rotating Cylinder

Mesh Refinement Study

- Geo-reconstruct scheme keeps interface 3 cells wide regardless of mesh size
  - Need about 10 cells to fully resolve a droplet



1.0 mm cells | 0.6 mm cells | 0.4 mm cells | 0.2 mm cells

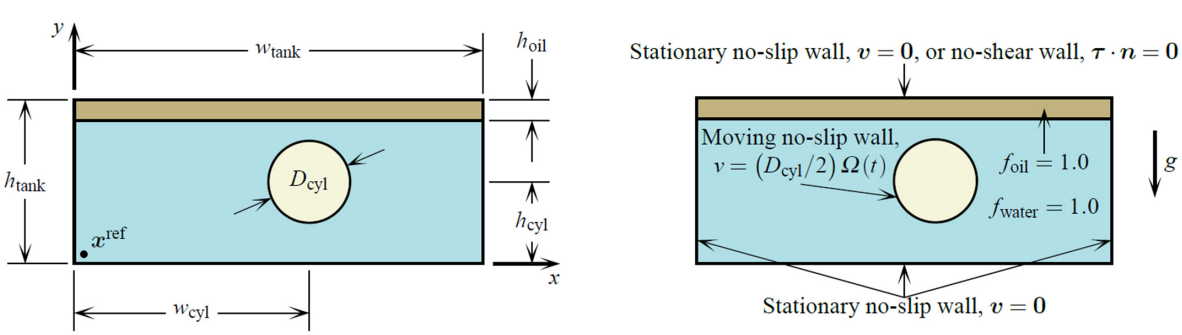
Phase contours of air from 0.01 to 0.99

Model Validation with Experimental Data

Rotating Cylinder Apparatus

Domain and Boundary Conditions

Experimental data used from **rotating cylinder apparatus**

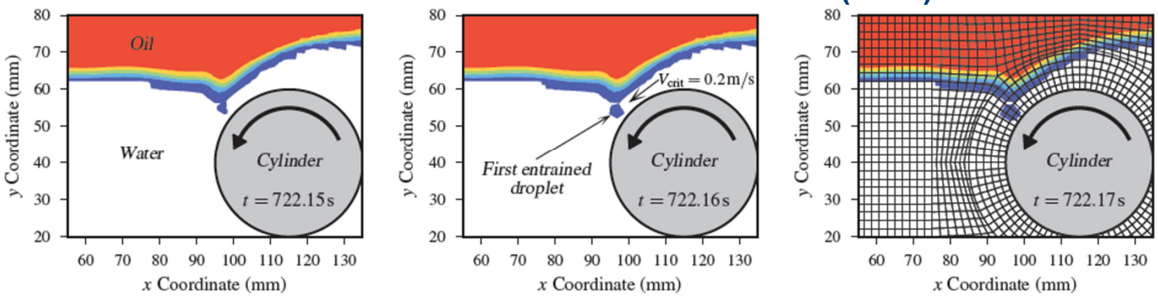


Hagemann *et al.*, *Met Trans B*, 2013

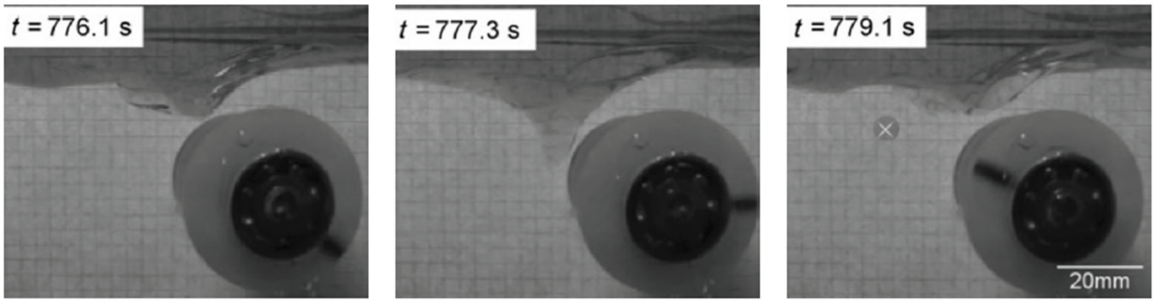
Rotating Cylinder Apparatus

Results (Side View)

Numerical Simulation Phase Contours (Oil 2)



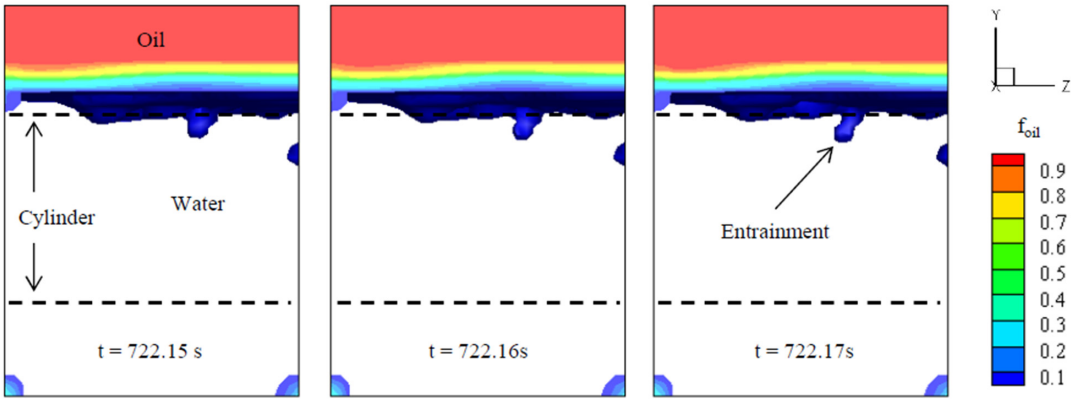
Photographs of Experiment



Rotating Cylinder Apparatus

Results (End View)

Numerical Simulation Oil Layer Iso-Surface (Oil 2)

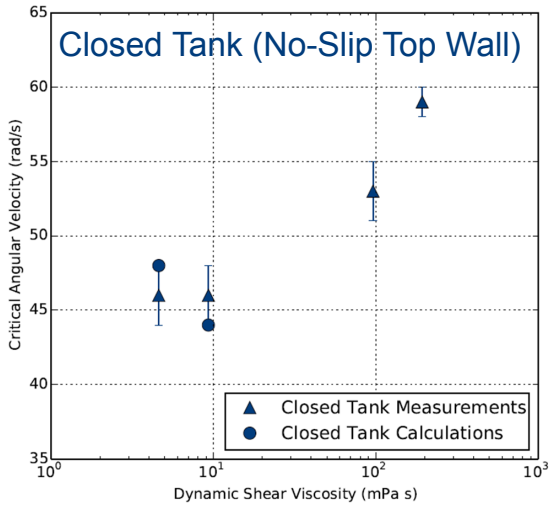


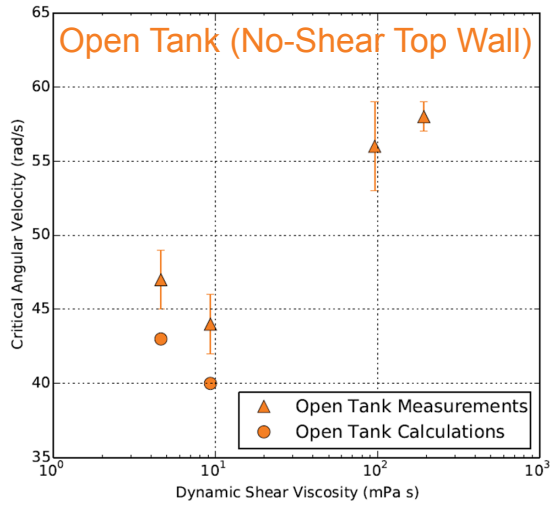
Droplets accumulating unrealistically in bottom corners

- With proper interpretation the model agreed well with the experiments
- Finger-like protrusions were seen in both simulations and experiments

Rotating Cylinder Apparatus

Critical Angular Velocities





- For the two less viscous oils the model agrees well with the data
  - Within **5% for closed tank** and within **10% for open tank**
- For the two more viscous oils the oil layer splits into two distinct sections and entrainment is not simulated

Conclusions

- A transient, 3D, multiphase, turbulent numerical model was developed using a relatively coarse mesh
- Model was verified with two test problems and validated with experimental data
- More work is needed to:
  - Accurately resolve and predict droplet size
  - Resolve the droplet accumulation in corners of tank
  - Correctly simulate more viscous oils
- **Model using these techniques will be used in the future to predict slag entrainment in continuous steel casting**

References

- Complete references and model description in

  K. E. Swartz, L. C. Hibbeler, B. P. Joyce, and B. G. Thomas, “Numerical Investigation of Slag Entrainment in Continuous Casting Molds.” *Proceedings of AISTech 2014*, pg. 1865-1879.

Acknowledgments

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

- Professor S. P. Vanka and Dr. Rui Liu for helpful discussions on the simulations