CCC Annual Report

UIUC, August 14, 2013

Numerical Simulation of the Hagemann Entrainment Experiments

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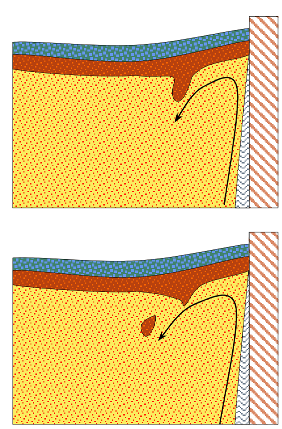
Background

- Slag entrainment is a major obstacle for making clean steel
- Entrainment can occur via at least 9 different mechanisms
  - Meniscus level fluctuations
  - Meniscus freezing / hooks
  - Argon bubble interactions
  - Slag crawling down the SEN
  - von Kármán vortex formation
  - Surface stationary wave instability
  - Shear-layer instability
  - **Upward flow impingement upon meniscus**
  - Meniscus balding
- See Hibbeler and Thomas, AISTech 2013 for review



Objectives

- Develop multiphase numerical model of slag entrainment
- Validate model with experiments of Hagemann *et al.*

Model Investigations on the Stability of the Steel-Slag Interface in Continuous-Casting Process

RENÉ HAGEMANN, RÜDIGER SCHWARZE, HANS P. HELLER, and PIOTR R. SCHELLER

Metallurgical and Materials Transactions B, Vol. 44 (2013), No. 1, p 80-90.

- Eventually:
  - Apply model to simulate real mold flow entrainment
  - Use model to predict entrainment criteria

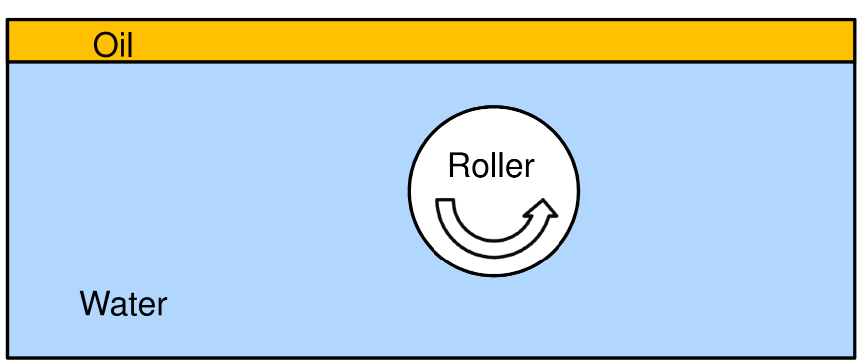
Hagemann Experiments

Experimental Apparatus

- Layer of oil placed on top of a tank of water
- Roller rotates at varying speeds

Tank Dimensions : 200 x 60 x 80 mm
(60 mm into page)

Gravity= 9.8067 m/s²

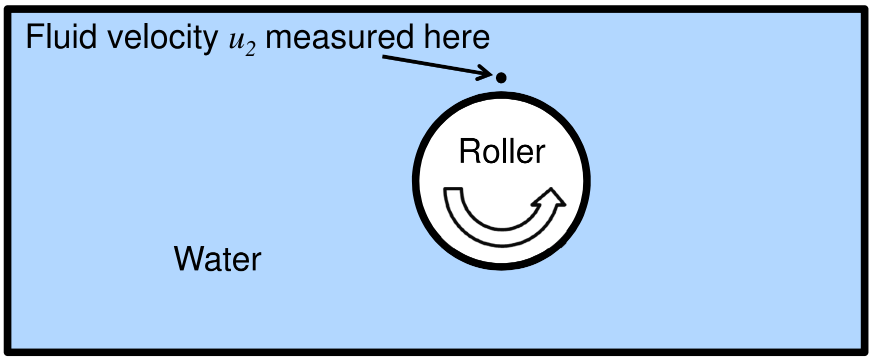


Drawn to scale

Hagemann Experiments

Single-Phase Experiments

- Hagemann removed the oil layer and replaced it with water
- Used particle-image velocimetry (PIV) to measure fluid velocity 2 mm from the roller
  - 8 different roller angular velocities
- He calculated the relationship between roller angular velocity and fluid velocity 2 mm from the roller (discussed later)
- **We are using the measurements (not the calibration) to validate our single-phase numerical model**



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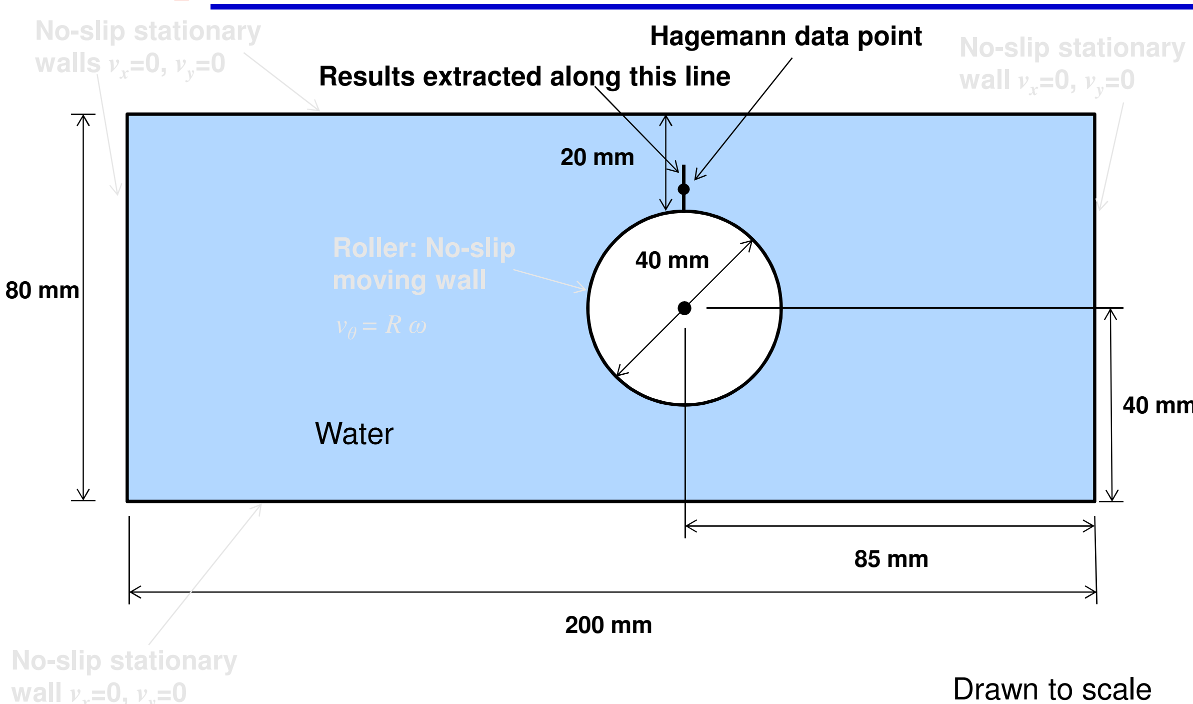
Validation with Single-Phase Experiments

Domain and Boundary Conditions



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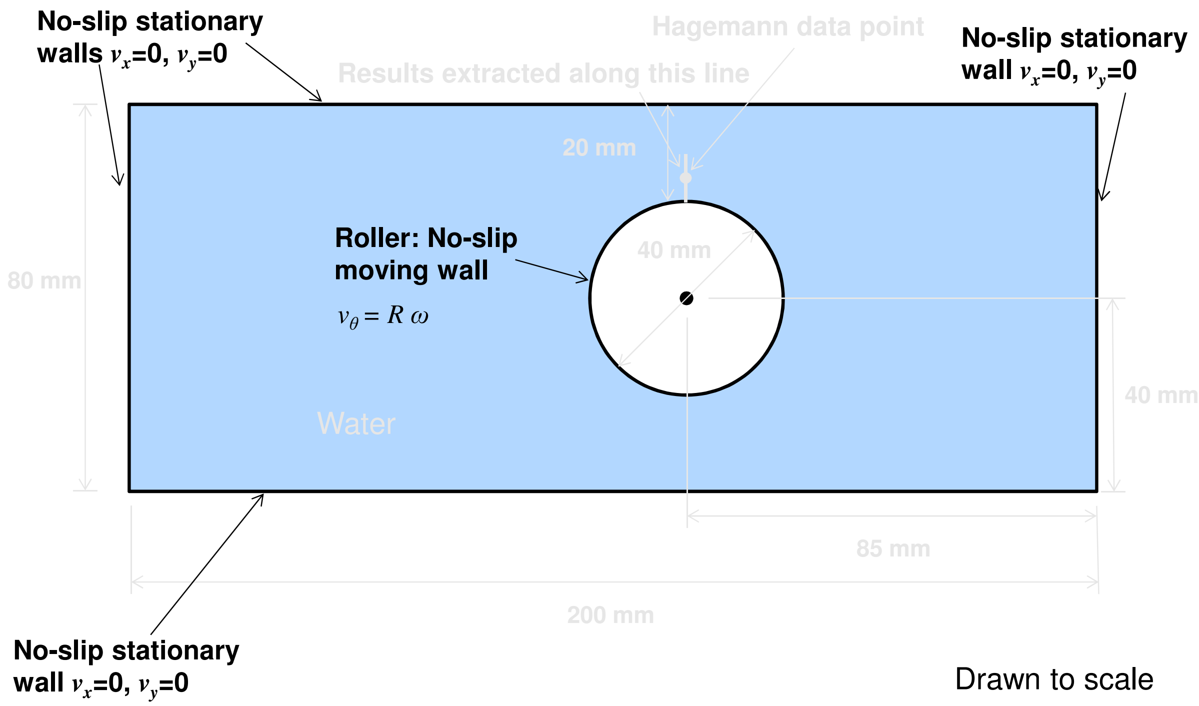
Validation with Single-Phase Experiments
Domain and Boundary Conditions



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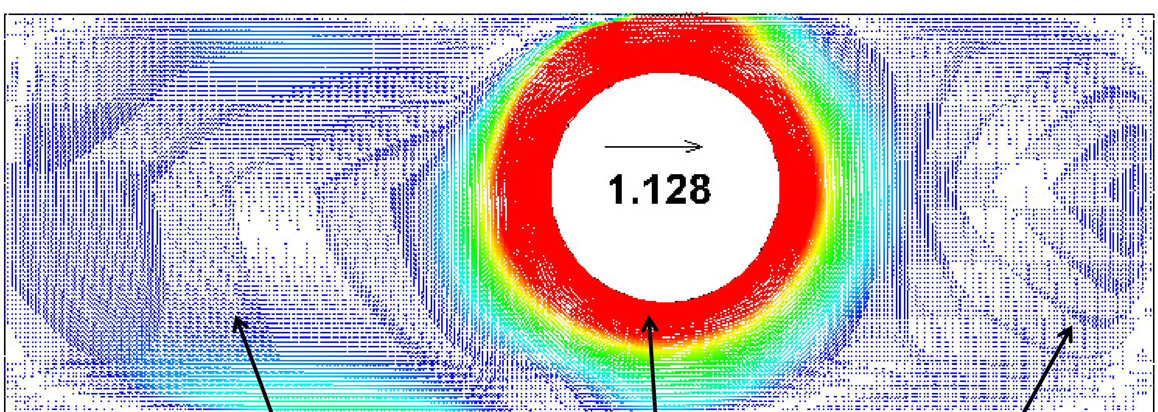
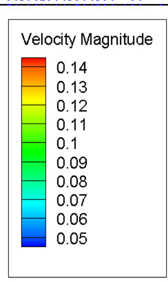
Validation with Single-Phase Experiments
Velocity Results





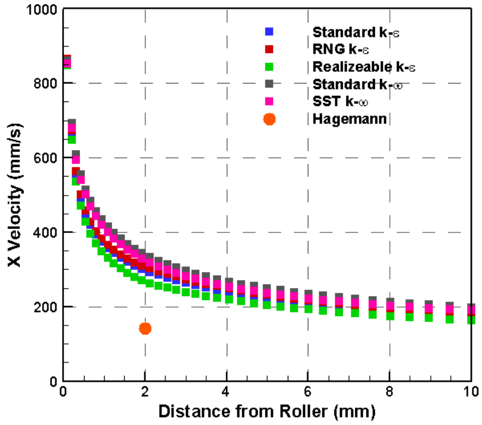
- Most fluid movement occurs near roller
- Some recirculation away from roller

Validation with Single-Phase Experiments

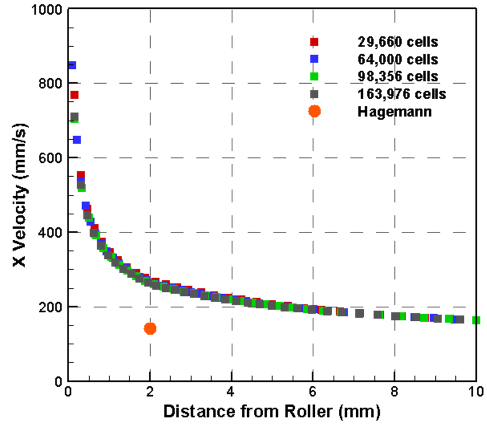
Turbulence Model & Mesh Refinement Study

ω = 56.4 rad/s

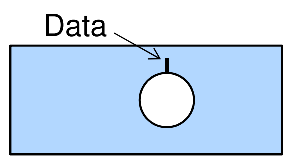
Turbulence Model Study



Mesh Refinement Study



Results are independent of turbulence model and mesh!



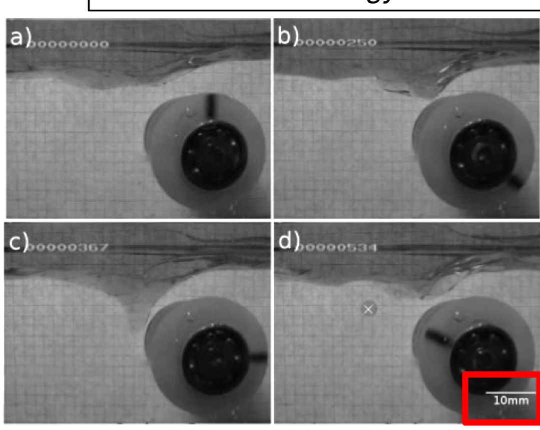
Hagemann Experiments

Oil Entrainment Experiments

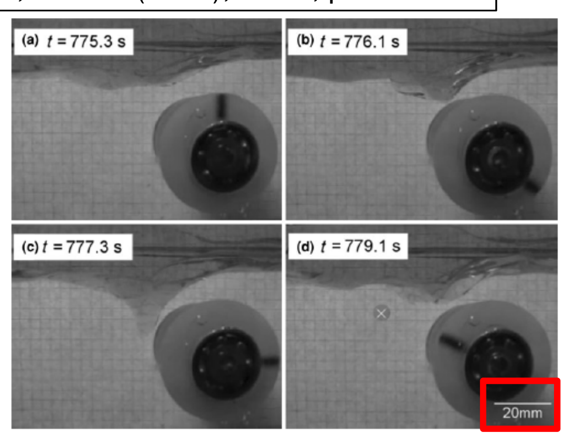
- Increase wheel speed at controlled acceleration until entrainment
- Record critical wheel angular velocity

MODEL INVESTIGATIONS ON SLAG ENTRAINMENT IN CONTINUOUS CASTING P.R. SCHELLER*, R. HAGEMANN*

Archives of Metallurgy and Materials, Vol. 57 (2012), No. 1, p 283-289.



2012 paper



2013 paper

Discrepancy with roller size

Validation with Oil Entrainment Experiments

Oil Entrainment Data

Hagemann *et al.* marked the boundary of stable and unstable interfaces by plotting capillary number at oil entrainment against the ratio of kinematic viscosities

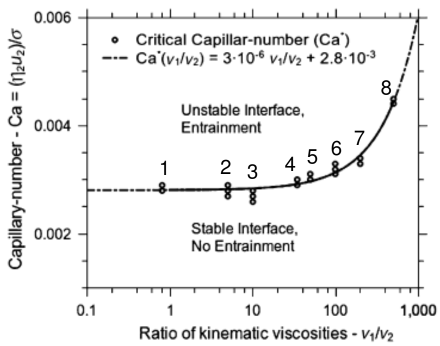


Figure 7 in Hagemann 2013

Data Point	Ratio of Kinematic Viscosities (--)	Capillary Number (--)	Critical Roller Angular Velocity (rad/s)
1	0.82	0.002859	55.4
2	5.10	0.002805	54.0
3	10.18	0.002702	51.4
4	34.70	0.002962	59.9
5	49.87	0.003067	62.6
6	99.49	0.003199	68.1
7	201.98	0.003358	76.6
8	503.14	0.004457	107.3

$$u_2(\omega) = 1.75 \cdot 10^{-3}[\mathrm{m}]\omega + 3.01 \cdot 10^{-2}[\mathrm{ms}^{-1}] \qquad [1]$$

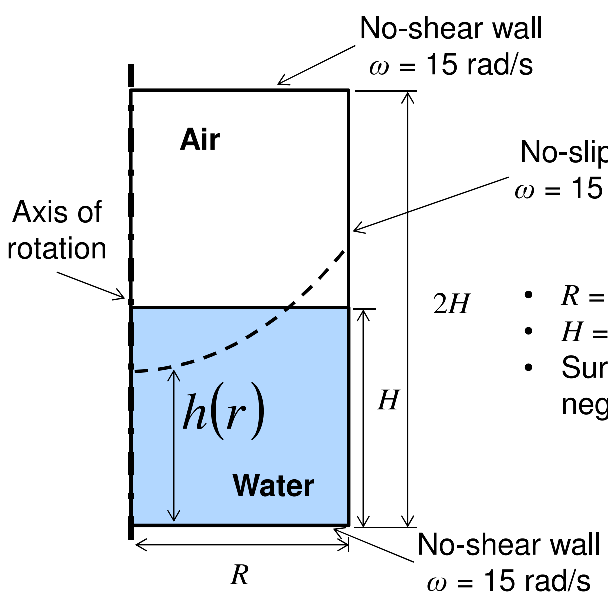
$$\frac{u_2 \eta_2}{\sigma} = \mathrm{Ca} \qquad [8]$$

- Equations 1 & 8 from the paper were used to convert capillary number to roller angular velocity
- **We will further validate the numerical model with these data points**

Validation with Oil Entrainment Experiments

Multiphase Test Problem

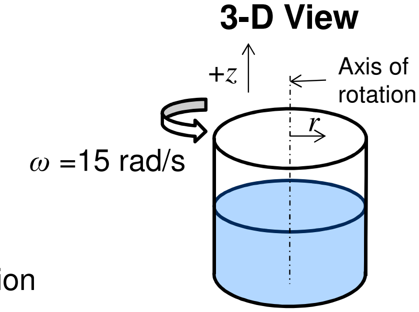
- Verify numerical model versus analytical solution
- Water and air in a closed cylinder, rotating at angular velocity ω
- Interface shape becomes parabolic



- R = 50 mm
- H = 50 mm
- Surface tension neglected

Gravity = 9.8067 m/s²

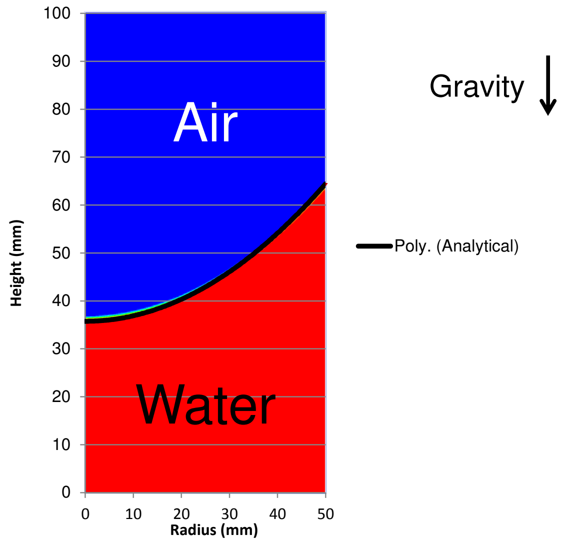
3-D View

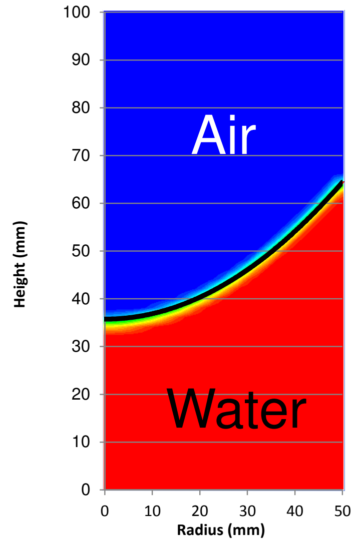


Analytical Solution

$$h(r) = \frac{\omega^2 r^2}{2g} + \left(H - \frac{\omega^2 R^2}{4g}\right)$$

Multiphase Test Problem
Transient Simulations: Results at Steady State

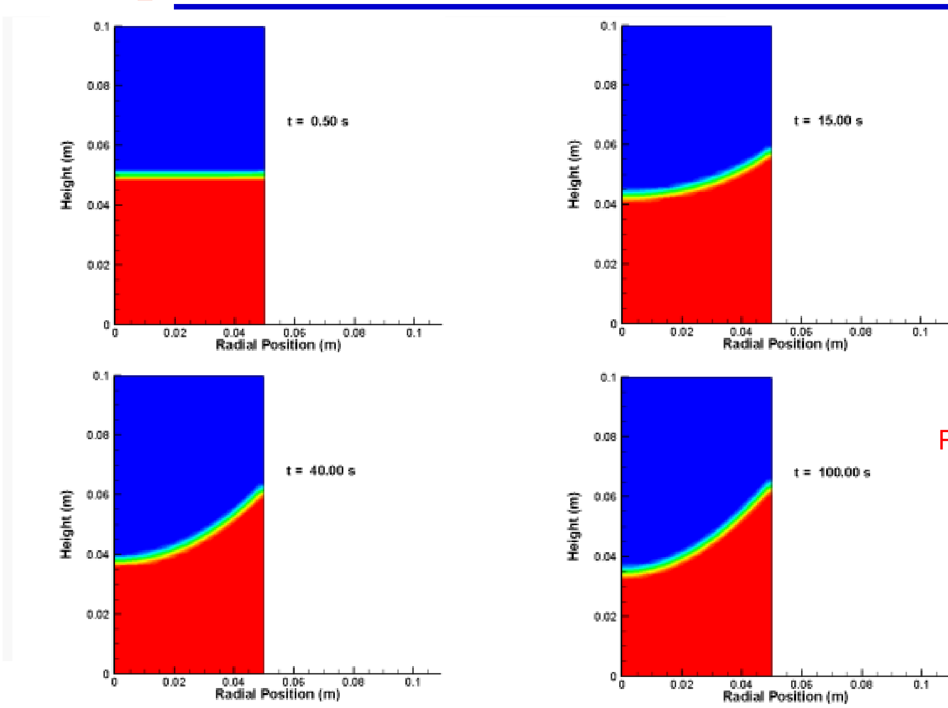




- Results at 75 s
- Cell length ~0.4 mm
- 31250 total cells
- Water volume increased by 5.09×10^{-5} %

- Results at 100 s
- Cell length ~2 mm
- 1250 total cells
- Water volume increased by 2.55×10^{-5} %

Multiphase Test Problem
Animation



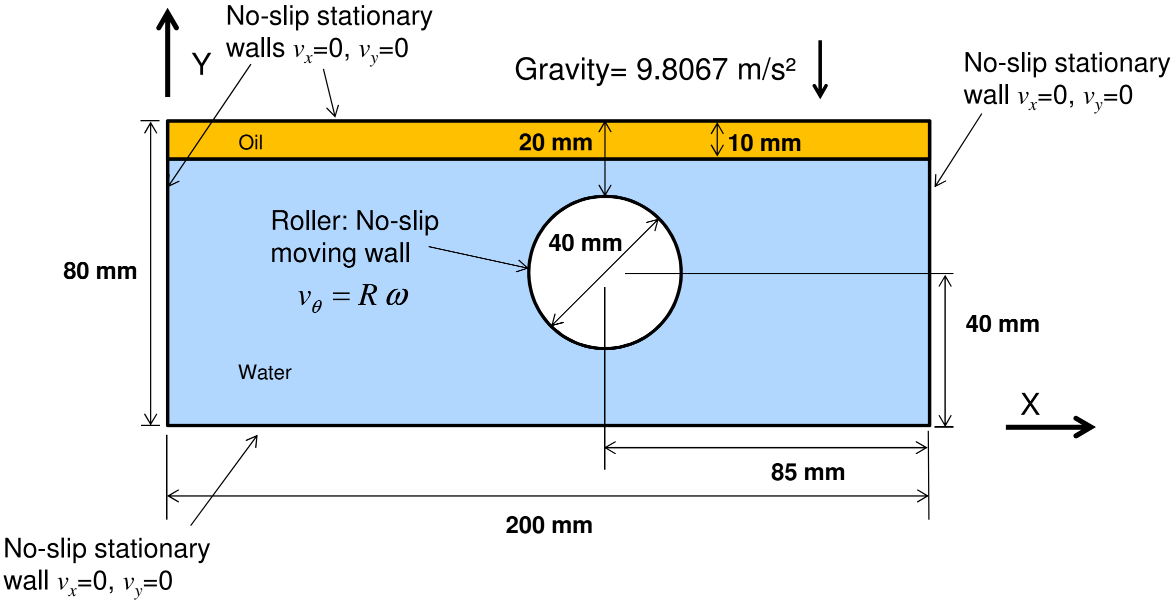
Gravity

Red = Water

Blue= Air

Validation with Oil Entrainment Experiments

Ak 10 Oil Entrainment Simulation



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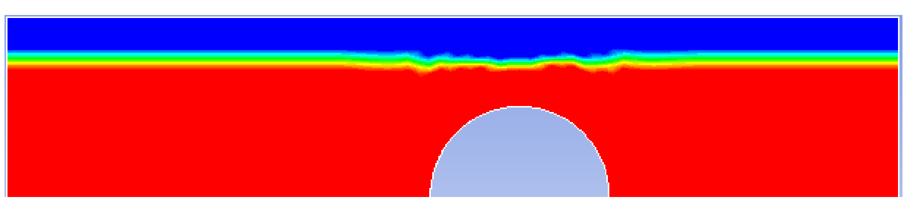
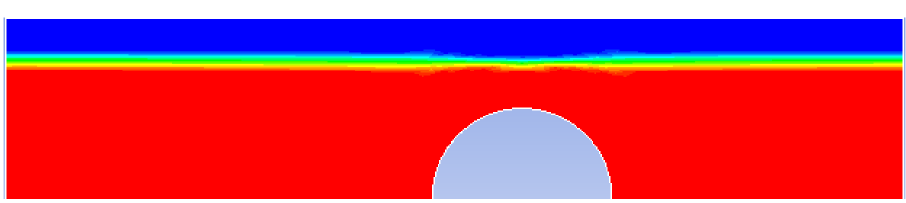
Validation with Oil Entrainment Experiments

Ak 10 Oil Entrainment Simulation (Coarse)

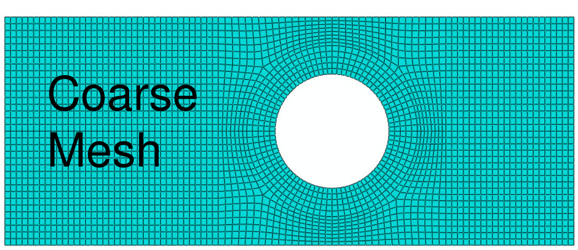
We included 1 second of settling time to let the interface to reach its natural position



t = 0 s



t = 1.0 s

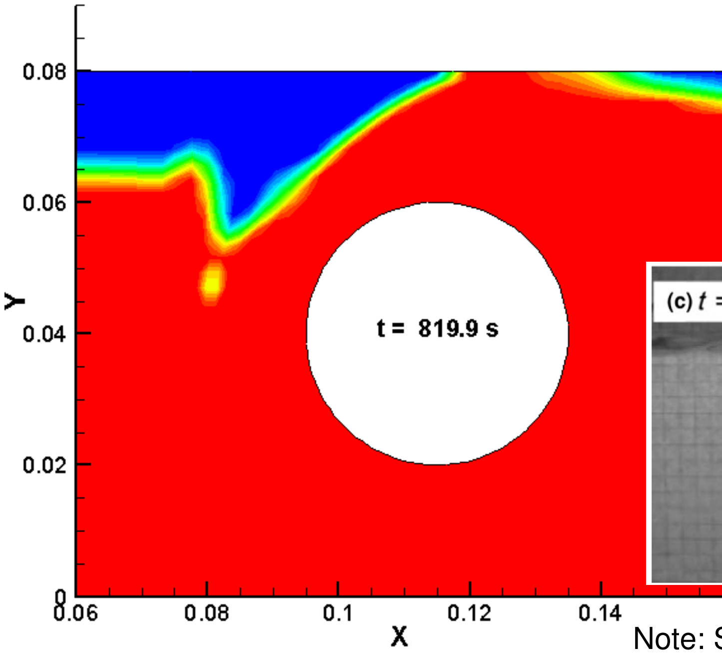


Roller speed (rad/s)

$$
\begin{cases}
\omega = 0 & t < 1 \\
\omega = 18 & 1 \le t < 201 \\
\omega = 18 + 0.05\,(t - 201) & t \ge 201
\end{cases}
$$

Validation with Oil Entrainment Experiments

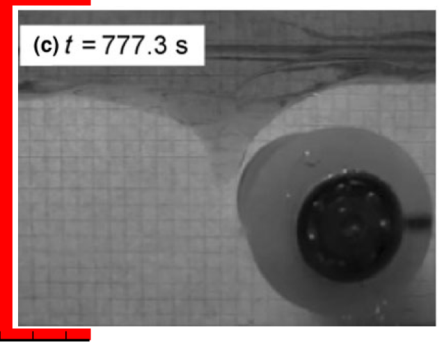
Ak 10 Oil Entrainment Simulation (Coarse)



Red = Water

Blue= Oil

Gravity ↓

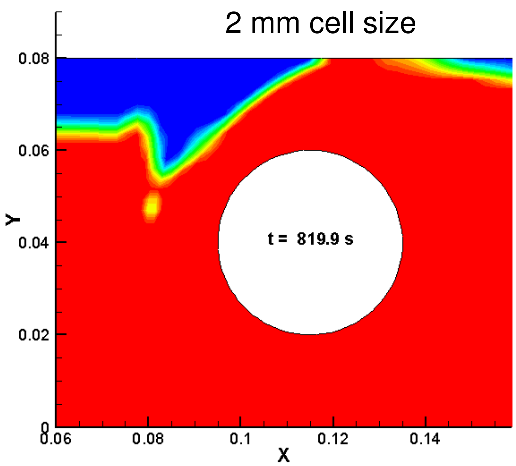


Note: Simulation snapshot and photograph use different oils

Validation with Oil Entrainment Experiments

Ak 10 Oil Entrainment Simulation (Coarse)

2 mm cell size



- **Surface tension neglected**
- Entrainment first occurred at 819.9 s
- Critical ω= 48.95 rad/s (0.98 m/s roller)
- Hagemann reports entrainment at 46 rad/s

Contours of Volume Fraction

Red = Water

Blue= Oil

Gravity ↓

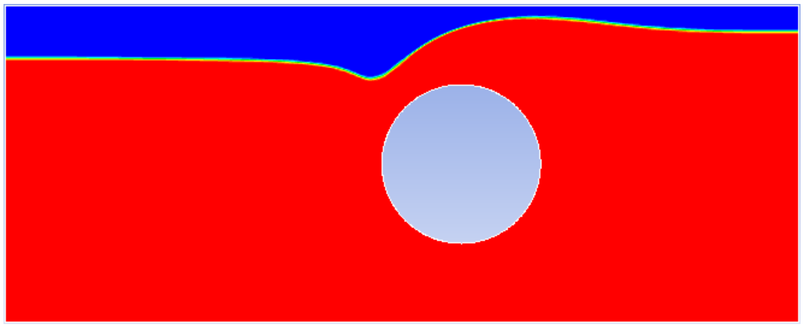
Roller speed (rad/s)

$$\begin{cases} \omega = 0 & t < 1 \\ \omega = 18 & 1 \le t < 201 \\ \omega = 18 + 0.05\,(t - 201) & t \ge 201 \end{cases}$$

Volume (m³)	Water	Oil (Ak 10)
Initial	0.01282516	0.001919403
Current	0.01282516	0.001919403

Validation with Oil Entrainment Experiments

Finer Mesh: Entrainment Simulation



Contours of Volume Fraction

Red = Water

Blue= Oil

Gravity ↓

Max y^+ ~ 2.5

- Simulation has run for 407.9 s
- Current ω = 28.3 rad/s
- Still running simulation

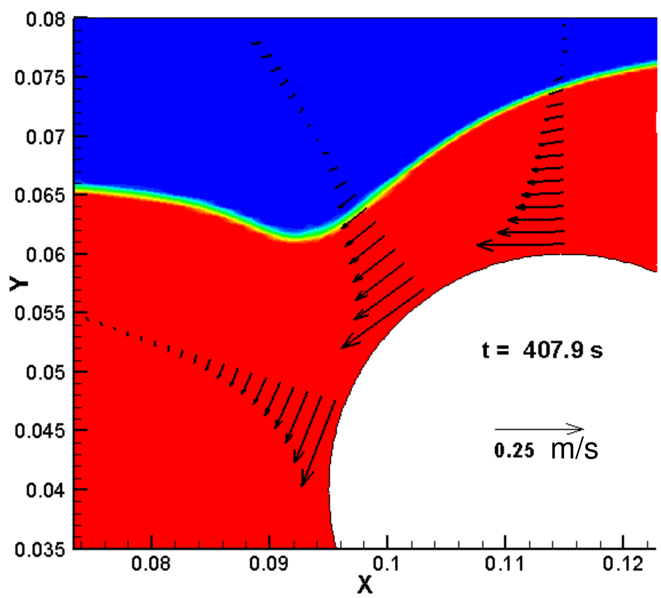
Volume (m³)	Water	Oil (Ak 10)
Initial	0.01274075	0.002002671
Current	0.01274075	0.002002669

Roller speed (rad/s)

$$\begin{cases} \omega = 0 & t < 1 \\ \omega = 18 & 1 \le t < 201 \\ \omega = 18 + 0.05\,(t - 201) & t \ge 201 \end{cases}$$

Validation with Oil Entrainment Experiments

Ak 10 Oil Entrainment Simulation Animation



Red = Water

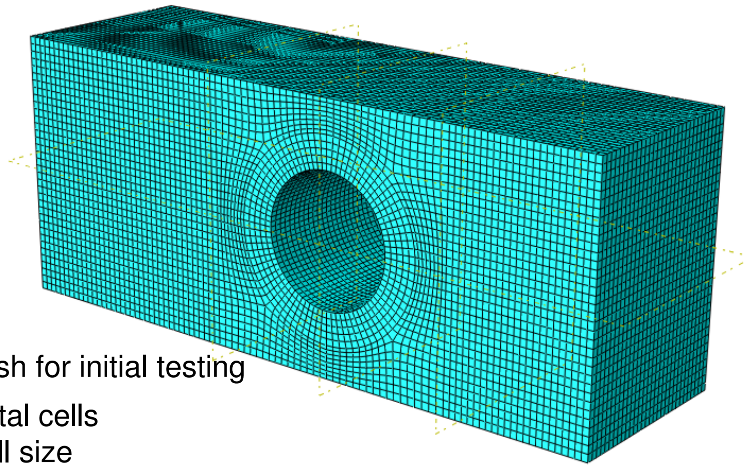
Blue= Oil

Gravity ↓

Validation with Oil Entrainment Experiments

Future Work

- 3D model with surface tension (includes droplet entrainment)
- CC mold simulations with slag and powder layers
- 3 phase simulations (air on top instead of solid wall)



- 3D Coarse mesh for initial testing
  - 102,360 total cells
  - ~ 2 mm cell size

Conclusions

- Transient multiphase (VOF) numerical model of entrainment of has been developed
- Model has been validated with several different test problems, including entrainment experiments by Hagemann
- Discrepancies with reporting of data and experimental set-up make validation effort difficult
- 2D model neglecting surface tension comes close to a Hagemann experiment
- 3D may with surface tension will be needed to accurately simulate entrainment

Acknowledgments

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

- Rui Liu

Appendices

- Single-phase experiments
  - Hagemann's data
  - Test problem: rotating cylinders
  - Modeling and mesh details
- Multi-phase test problem: rotating cylinder
  - Modeling details
  - Method and mesh refinement study
- Oil entrainment experiments
  - Modeling and mesh details
  - Simulation with small roller

Supports Slide 5

Hagemann Experiments

Single-Phase Experiments

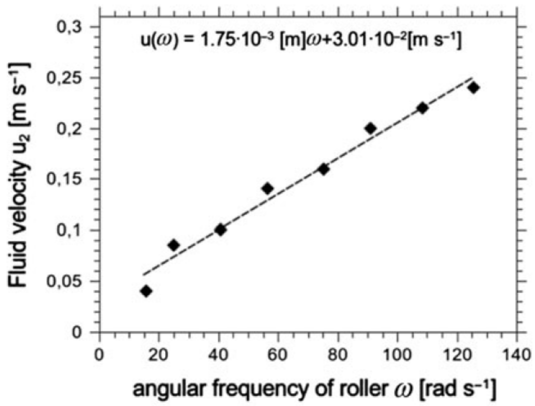


Figure 4b in Hagemann 2013

Roller Angular Velocity (rad/s)	Fluid Velocity (mm/s)
15.3	40.1
24.7	85.6
40.6	100.5
56.4	141.4
75.0	160.2
90.8	200.3
108.3	219.9
125.5	240.3

Hagemann calibrated the velocity of the fluid 2 mm off of the roller with the angular velocity of the roller. These data points are used as validation of the numerical model.

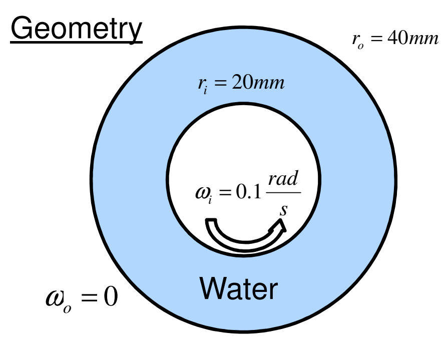
Supports Slides 5 – 9

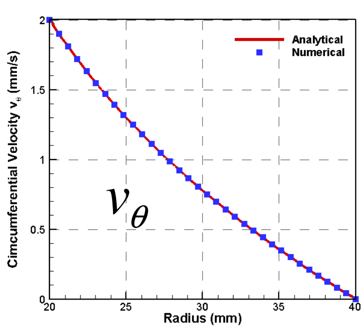
Validation with Single-Phase Experiments

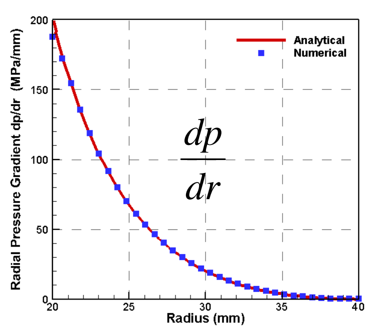
Rotating Cylinder Test Problem

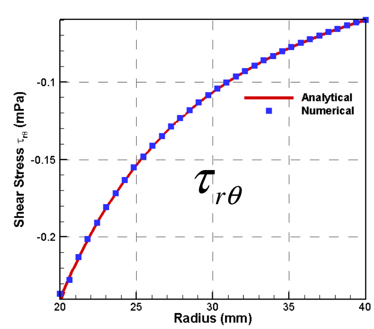
- Verify numerical model with analytical solution similar to single-phase experiment
- Tangential annular drag flow between concentric cylinders
- 2-D, laminar

Model Matches Analytical Solution









Supports Slides
5 – 9

Rotating Cylinder Test Problem

Analytical Solution

Assume steady, axisymmetric, 2D, no body forces

Velocity Profile	Pressure Gradient	Shear Stress
$v_r = 0$ $v_\theta = C_1\, r + \dfrac{C_2}{r}$ $v_z = 0$	$p = p(r)$ $\dfrac{dp}{dr} = \rho \dfrac{v_\theta^2}{r}$	$\tau_{r\theta} = \tau_{\theta r} = -2\mu \dfrac{C_2}{r^2}$ Other τ_{ij}=0

$$C_1 = \frac{\dfrac{\omega_i}{r_o^2} - \dfrac{\omega_o}{r_i^2}}{\dfrac{1}{r_o^2} - \dfrac{1}{r_i^2}} \qquad C_2 = -\frac{\omega_i - \omega_o}{\dfrac{1}{r_o^2} - \dfrac{1}{r_i^2}}$$

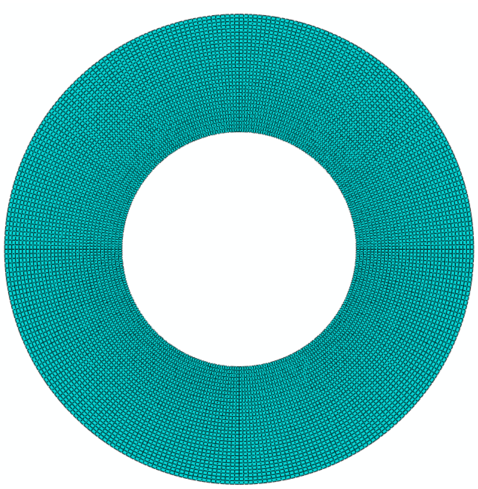
$$\mathrm{Re} = \frac{\rho V_i L}{\mu} \qquad V_i = \omega_i\, r_i \qquad L = r_o - r_i$$

$$\mathrm{Re} = \frac{997 \dfrac{kg}{m^3} \times 0.002 \dfrac{m}{s} \times 0.02m}{0.0009 Pa \cdot s} = 44$$

Supports Slides
5 – 9

Rotating Cylinder Test Problem

Mesh & Modeling Details



- 10,329 total cells
- 34 cells in the radial direction
- Cell size ~0.6 mm

	Relaxation Factor	Discretization
Gradient	--	Least Squares Cell Based
Pressure	0.3	PRESTO!
Density	0.5	--
Body Forces	0.5	--
Momentum	0.5	Second Order Upwind

Material	Density (kg/m³)	Dynamic Viscosity (kg/m·s)
Water	997	0.0009

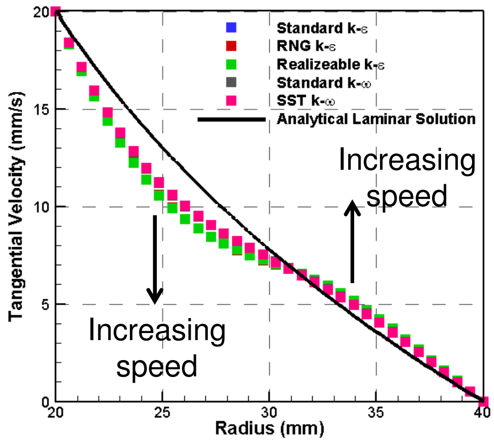
- 2-D, incompressible, steady-state
- Viscous laminar
- Gravity neglected
- Pressure-Velocity Coupling: PISO
  - -Skewness correction: 2
  - -Neighbor correction: 1
- Skewness-Neighbor Coupling enabled

Supports Slides
5 – 9

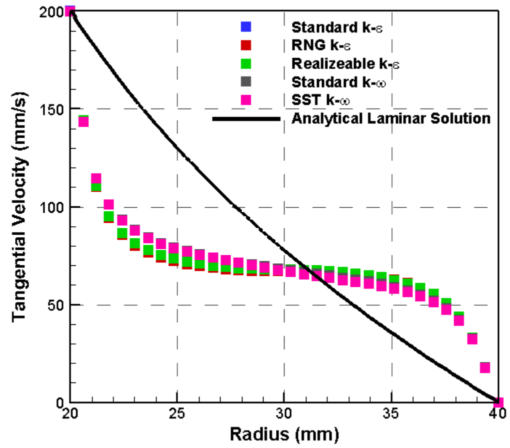
Rotating Cylinder Test Problem

Effect of Turbulence

ω_i = 1 rad/s



ω_i = 10 rad/s



- 5 turbulence models were tested with ω_i = 1 rad/s and ω_i = 10 rad/s
- k-ε models used with enhanced wall functions
- Turbulence causes boundary layers to form at both edges

Supports Slides
5 – 9

Validation with Single-Phase Experiments

Modeling Details

- Numerical model of Hagemann's experiment that relates the angular velocity of a plastic roller in a water tank to the free stream velocity of the water 2 mm off of the roller.

- 2-D, incompressible, steady-state
- Gravity neglected
- Different turbulence models tested
  - Realizable k-ε selected
- Enhanced Wall Treatment
  - Pressure gradient effects and curvature correction enabled

Supports Slides
5 – 9

Validation with Single-Phase Experiments
Modeling Details

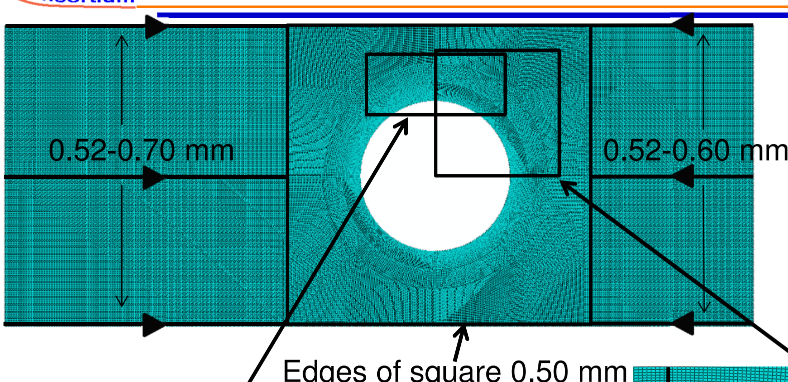
	Relaxation Factor	Discretization
Gradient	--	Least Squares Cell Based
Pressure	0.3	PRESTO!
Density	0.9	--
Body Forces	0.7	--
Momentum	0.75	Second Order Upwind
Turbulent Kinetic Energy	0.8	Second Order Upwind
Turbulent Dissipation Rate	0.8	Second Order Upwind
Turbulent Viscosity	1	--

Material	Density (kg/m^3)	Dynamic Viscosity ($kg/m \cdot s$)
Water	997	0.0009

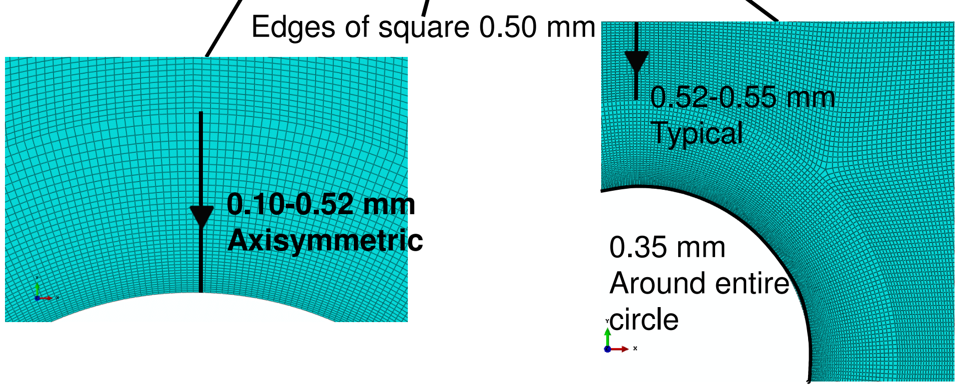
- Pressure-Velocity Coupling: PISO
  - -Skewness correction: 2
  - -Neighbor correction: 1
- Skewness-Neighbor Coupling enabled

Supports Slides
5 – 9

Validation with Single-Phase Experiments
Mesh: Biasing for Efficiency



- 64,000 total cells
- Biasing used to refine mesh in high velocity gradient areas
- Dimensions indicate cell size

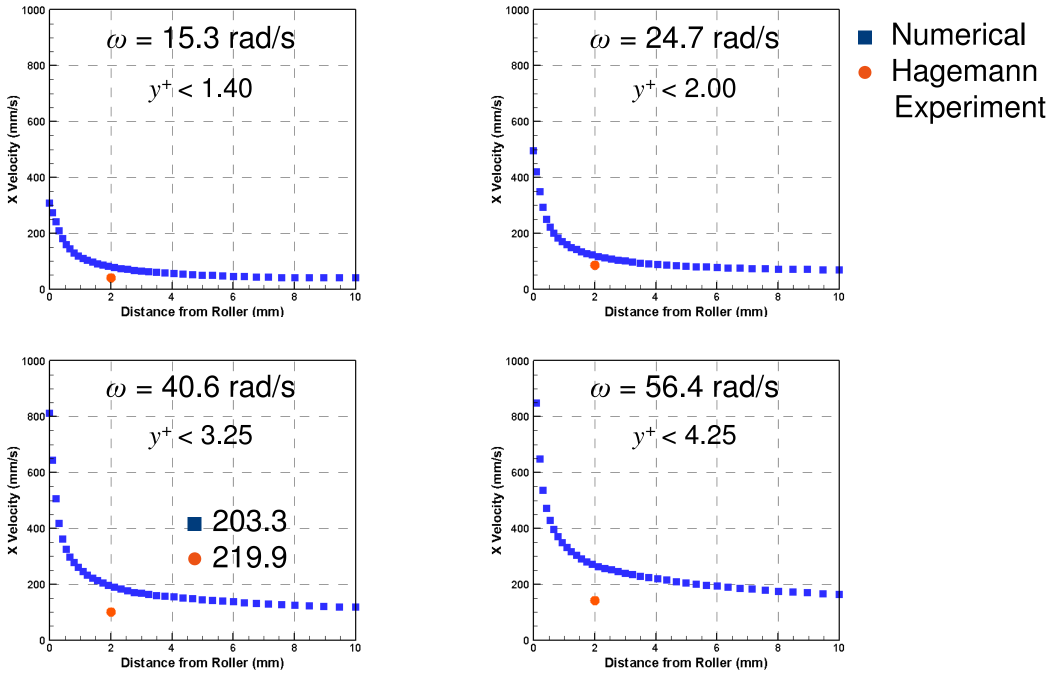


Supports Slides 5 – 9

Continuous Casting Consortium

Validation with Single-Phase Experiments

Simulated Velocity Profiles



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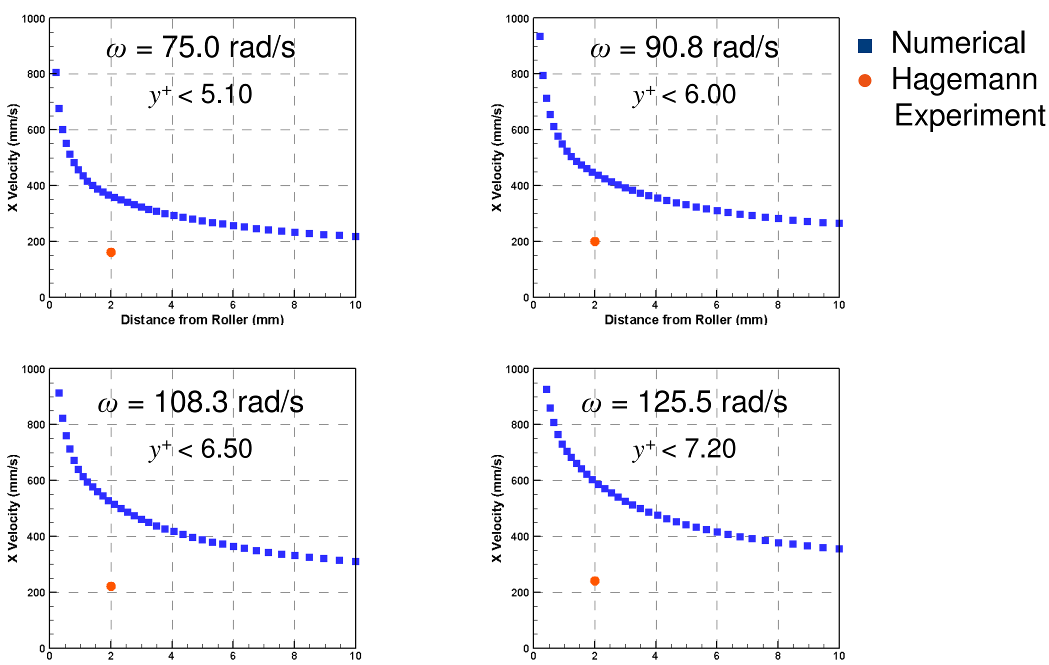
Continuous Casting Consortium

Validation with Single-Phase Experiments

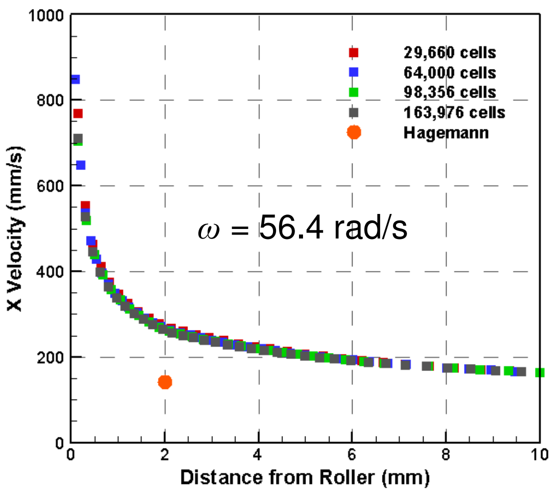
Simulated Velocity Profiles



Supports Slide 9

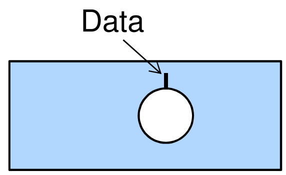
Validation with Single-Phase Experiments
Mesh Refinement Study

In order to test the effect of the mesh we tested 4 meshes of varying cell size



Number of Cells	Approx. Cell Size 2 mm from Roller	Max y^+
29,660	0.26 mm	6.00
64,000	0.21 mm	4.25
98,356*	0.12 mm	3.25
163,976**	0.07 mm	2.75

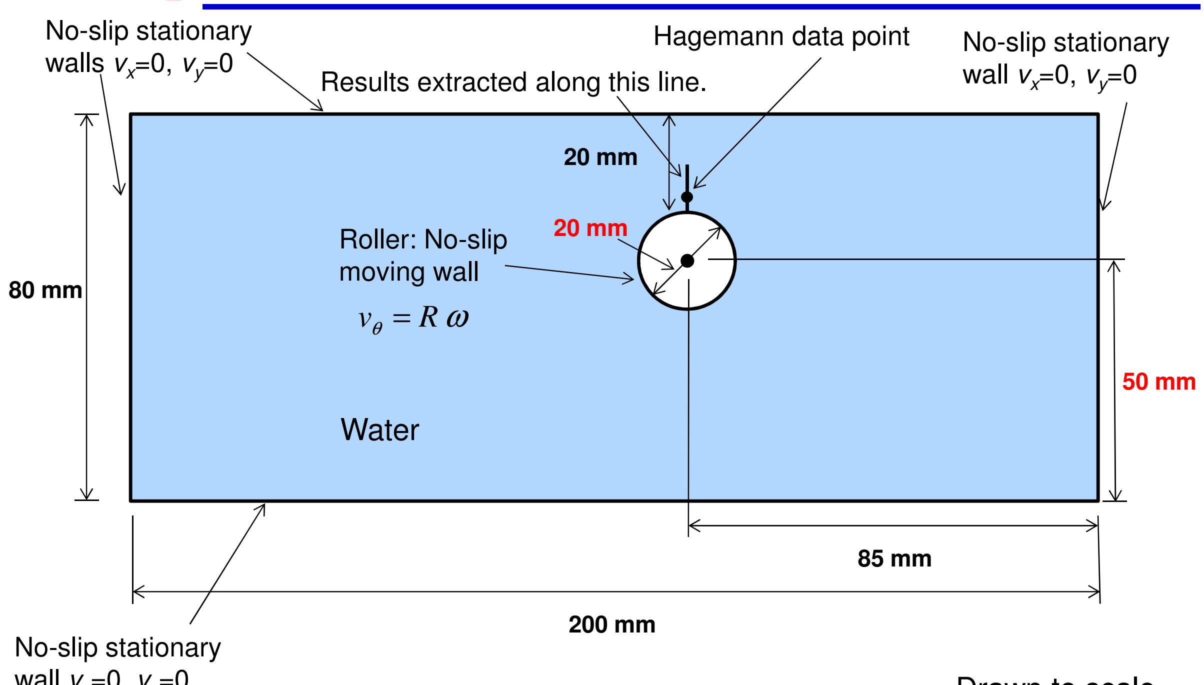
*Every other data point shown
**Every third data point shown



Results are mesh independent!

Supports Slides 5 – 10

Validation with Single-Phase Experiments
20 mm Roller Domain and Boundary Conditions



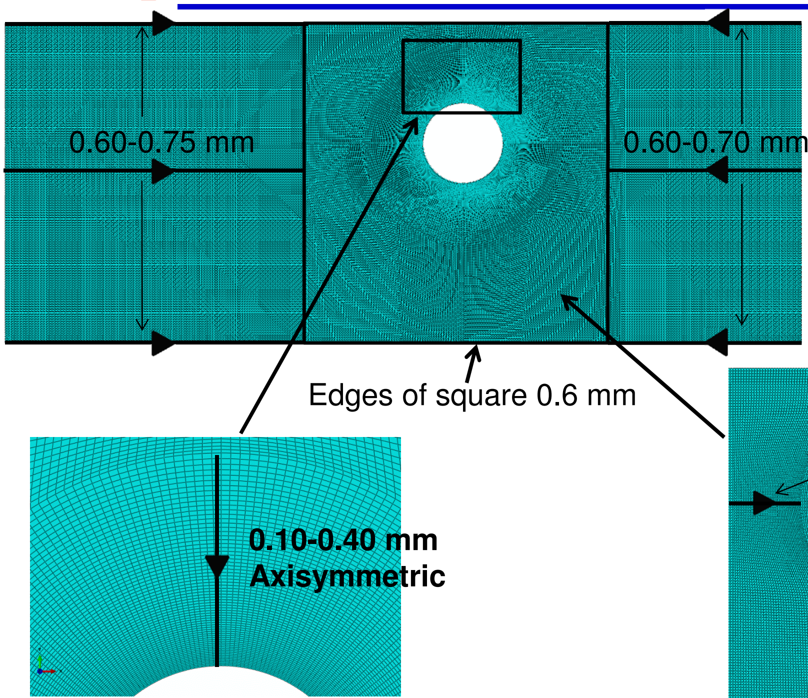
Drawn to scale

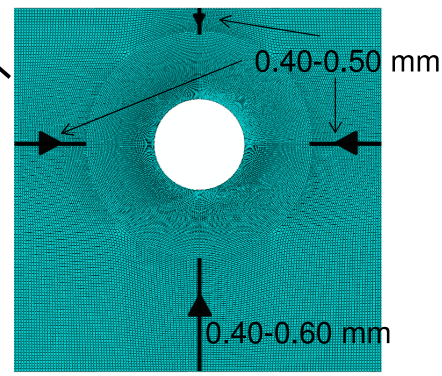
Hypothesis: Hagemann used a smaller roller

Supports Slides
5 – 10

Validation with Single-Phase Experiments

20 mm Roller Mesh



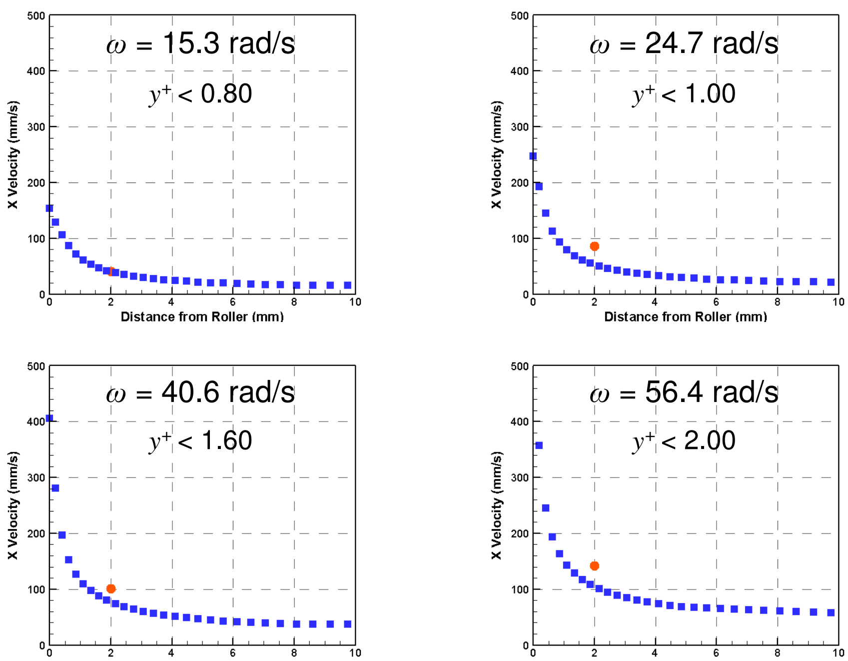


- 54,616 Total cells
- Biasing used to refine mesh in high velocity gradient areas
- Dimensions indicate cell size

Supports Slides
5 – 10

Validation with Single-Phase Experiments

20 mm Roller Velocity Profiles



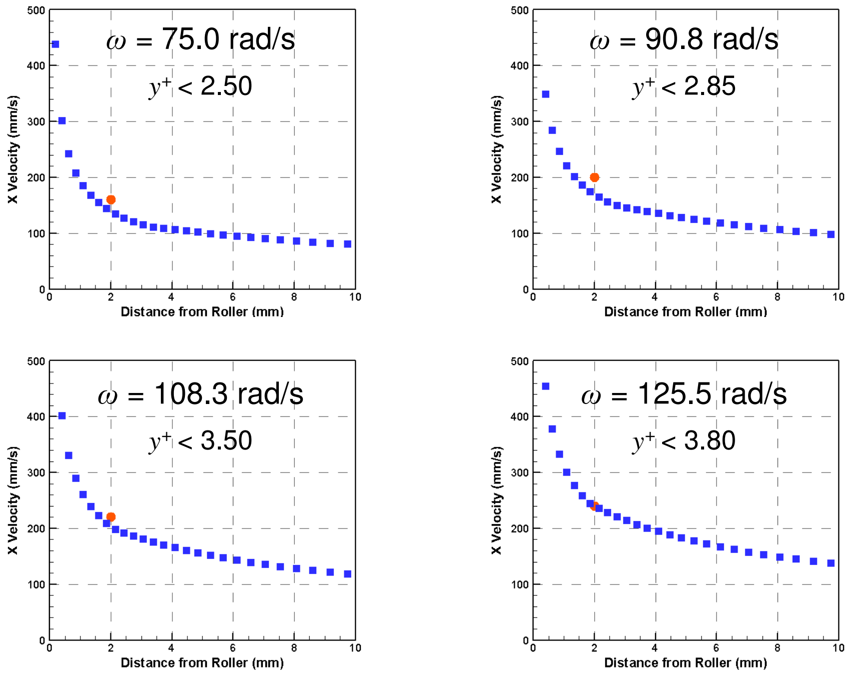
- Numerical
- Hagemann Experiment

*Numerical data points shown at every other cell

Supports Slides 5 – 10

Validation with Single-Phase Experiments

20 mm Roller Velocity Profiles



Numerical
Hagemann Experiment

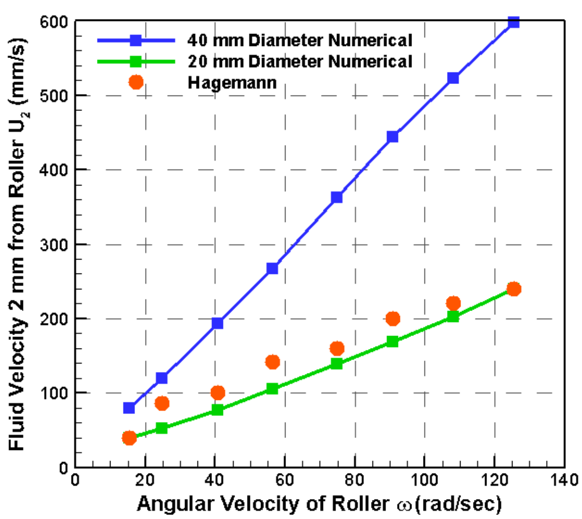
*Numerical data points shown at every other cell

Supports Slides 5 – 10

Validation with Single-Phase Experiments

Roller Diameter Comparison

Using the same modeling approach, we were able to better match the data points with a roller diameter of 20 mm (instead of 40 mm as stated by Hagemann).



Trend Lines

Hagemann

$$u_2(\omega) = 1.75[mm]\,\omega + 30.1\left[\frac{mm}{s}\right]$$

40 mm Diameter

$$u_2(\omega) = 4.78[mm]\,\omega + 2.50\left[\frac{mm}{s}\right]$$

R^2=0.9995

20 mm Diameter

$$u_2(\omega) = 1.82[mm]\,\omega + 6.34\left[\frac{mm}{s}\right]$$

R^2=0.9971

Supports Slides 5 – 10

Validation with Single-Phase Experiments

Roller Diameter Comparison

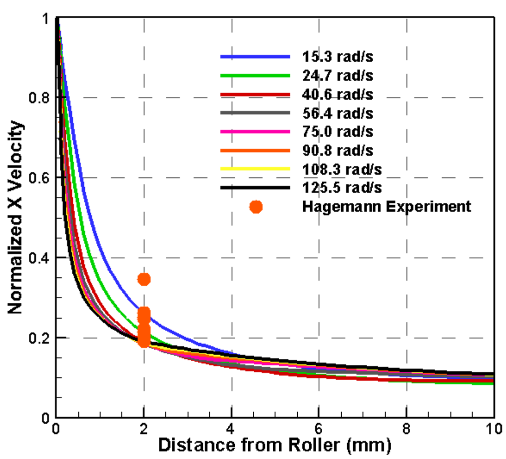
Roller Angular Velocity ω (rad/sec)	Hagemann u_2 (mm/s)	40 mm Diameter u_2 (mm/s)	40 mm Diameter Error	20 mm Diameter u_2 (mm/s)	20 mm Diameter Error
15.3	40.1	79.2	97.6 %	39.9	0.4 %
24.7	85.6	119.7	39.8 %	52.8	38.3 %
40.6	100.5	192.9	91.9 %	76.9	23.5 %
56.4	141.4	267.4	89.1 %	104.8	25.9 %
75.0	160.2	362.6	126.3 %	139.3	13.1 %
90.8	200.3	443.6	121.5 %	169.2	15.5 %
108.3	219.9	522.9	137.8 %	203.0	7.7 %
125.5	240.3	597.4	148.6 %	239.8	0.2 %

Supports Slides 5 – 10

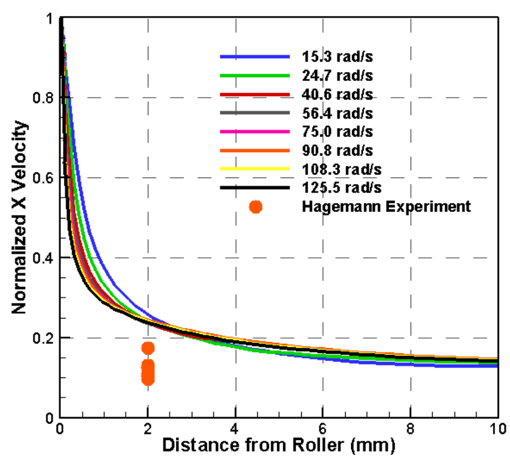
Validation with Single-Phase Experiments

Normalized Results

20 mm Diameter



40 mm Diameter



- Each data set normalized with respect to tangential velocity at surface of roller

$$v^* = \frac{v}{\omega R}$$

- Faster roller speeds lead to smaller boundary layers
- This results in steeper velocity gradients near the roller
- Hagemann may have measured inside the boundary layer

Supports Slides 12 – 14

Multiphase Test Problem

Modeling Details

We first attempted to find the analytical solution of interface shape using a steady simulation. The following modeling details were used.

- 2-D, Axisymmetric swirl, incompressible, steady
- Gravity enabled in $-z$ direction
- Multiphase Volume of Fluid model
  - Implicit VOF and Implicit Body Force
- Standard k-ϵ turbulence model with standard model constants
- Enhanced Wall Treatment
  - Pressure gradient effects enabled

Phase	Material	Density (kg/m^3)	Viscosity (kg/m·s)	Surface Tension (N/m)
1	Water	998.2	0.001003	0
2	Air	1.225	1.789×10^{-5}	

Supports Slides 12 – 14

Multiphase Test Problem

Modeling Details

	Relaxation Factor	Discretization Method
Gradient	--	Green-Gauss Node Based
Pressure	0.3	PRESTO!
Density	1	--
Body Forces	1	--
Momentum	0.7	Second Order Upwind
Swirl Velocity	0.9	Second Order Upwind
Volume Fraction	*0.1	**
Turbulent KE	0.8	Second Order Upwind
Turbulent Dissipation	0.8	Second Order Upwind
Turbulent Viscosity	1	--

- Pressure-Velocity Coupling: PISO
  - Skewness Correction = 1
  - Neighbor Correction = 1
- Skewness-Neighbor Coupling enabled

*This was the starting value and was lowered later when specified.
**We were testing different volume fraction discretization methods. Each method will be shown.

Supports Slides 12 – 14

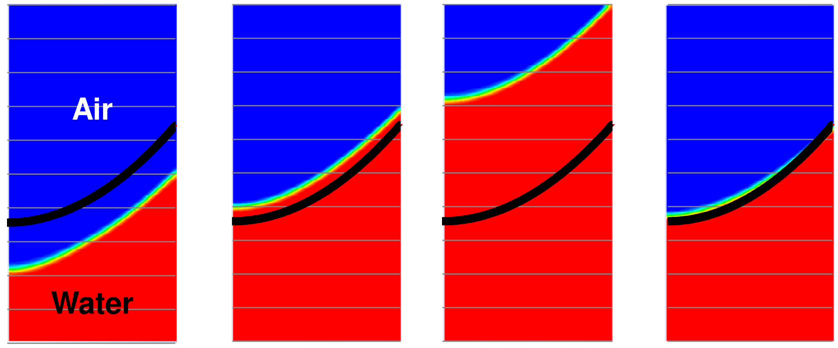
Multiphase Test Problem

Failed Steady Simulations

Analytical Solution

Gravity ↓

Mesh: 5000 Cells



	Modified HRIC		Compressive	
Volume Fraction Relaxation Factor	0.1	0.001	0.1	0.001
Approx. Residual Convergence	$1x10^{-2}$	$1x10^{-2}$	$1x10^{-2}$	$1x10^{-2}$
Water Volume Change	-25.9%	+10.8%	+73.6%	+2.7%
Oil Volume Change	+25.9%	-10.8%	-73.6%	-2.7%

Supports Slides 12 – 14

Multiphase Test Problem

Transient Cases Modeling Details

Steady simulations failed to match the analytical solution or conserve mass.
Transient simulations gave much better results.

- 2-D, Axisymmetric swirl, incompressible, transient
- Gravity enabled in $-z$ direction
- Multiphase Volume of Fluid model
  - Explicit VOF and Explicit Body Force
  - Courant Number = 0.25
- Standard k-ϵ turbulence model with standard model constants
- Enhanced Wall Treatment
  - Pressure gradient effects enabled

Phase	Material	Density (kg/m^3)	Viscosity (kg/m·s)	Surface Tension (N/m)
1	Water	998.2	0.001003	0
2	Air	1.225	1.789×10^{-5}	

Supports Slides
12 – 14

Continuous Casting Consortium

Multiphase Test Problem

Transient Test Problem Modeling Details

	Relaxation Factor	Discretization Method
Gradient	--	Green-Gauss Node Based
Pressure	1	PRESTO!
Momentum	1	Second Order Upwind
Swirl Velocity	1	Second Order Upwind
Volume Fraction	Explicit	Geo-Reconstruct
Turbulent KE	1	Second Order Upwind
Turbulent Dissipation	1	Second Order Upwind

- PISO Pressure-Velocity Coupling
  - -Neighbor Correction = 1
- First Order Implicit Transient Formulation
  - -Non-Iterative Time Advancement enabled

Time step started at 5 x 10^{-5} seconds. It could be increased as high as 2 x 10^{-3} seconds as the simulation went on and got closer to the steady-state solution. **It was kept low enough that the Courant number stayed below 0.5 at all times.**

Supports Slides
12 – 14

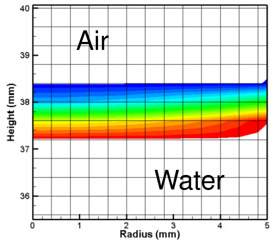
Continuous Casting Consortium

Multiphase Test Problem

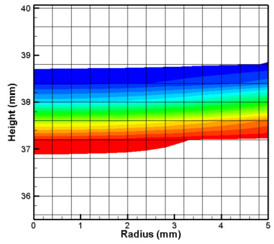
VOF Discretization Method Study

4 mm

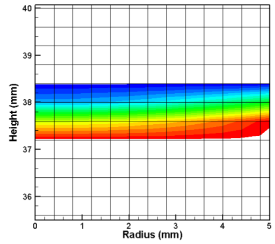
- 4 VOF discretization methods were tested
- Geo-Reconstruct gave the sharpest interface
  - Selected for our multiphase simulations



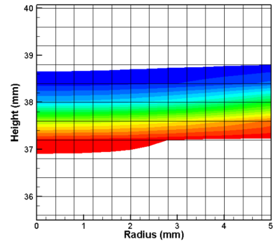
Geo-Reconstruct



Modified HRIC



CICSAM



Compressive

Gravity ↓

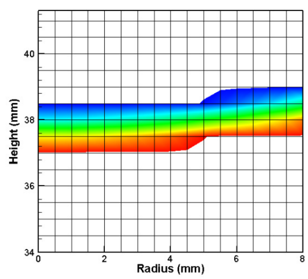
Phase contours from 0.01 to 0.99 VOF are displayed. All cases were simulated under identical conditions besides the VOF discretization on a mesh with cell size ~0.4 mm (31250 cells). The above results are from 2.00 seconds with swirl velocity patched into entire domain.

Supports Slides
12 – 14

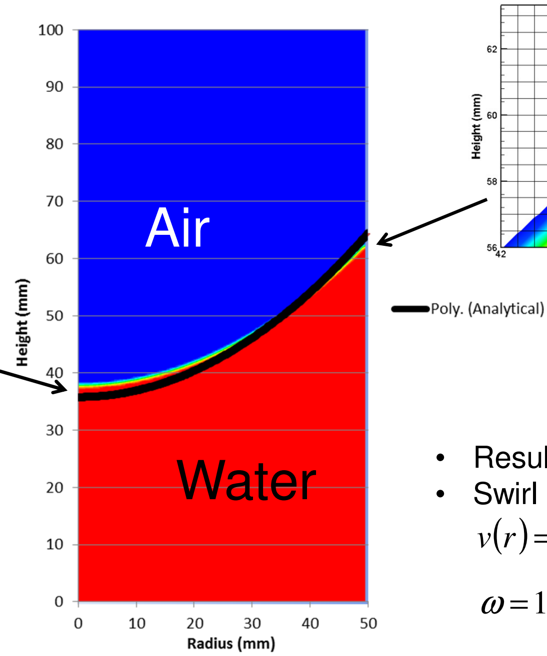
Multiphase Test Problem

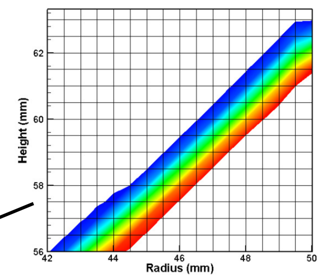
Typical Results of Mesh Study

- 20000 total cells
- Cell size ~0.5 mm



~1.5 mm interface





- Results at 2.00 seconds
- Swirl velocity patched in

$$v(r) = \omega r$$

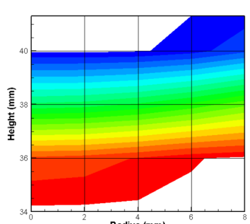
$$\omega = 15 \frac{rad}{s}$$

Supports Slides
12 – 14

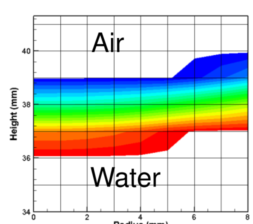
Multiphase Test Problem

Geo-Reconstruct Mesh Refinement Study

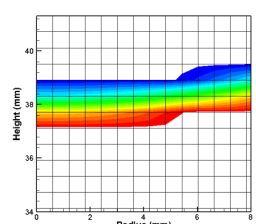
Geo-Reconstruct gave interface 3 cells wide *regardless of mesh size*



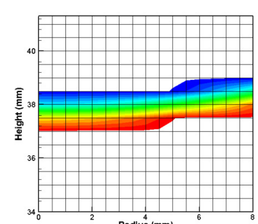
Cell size ~2 mm



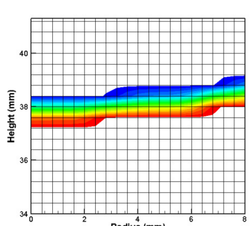
~1 mm



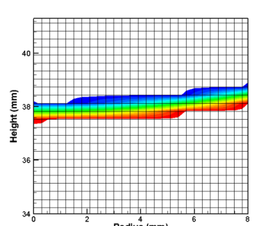
~0.6 mm



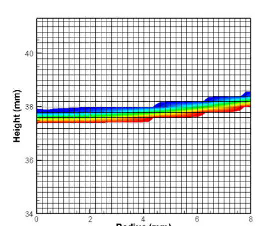
~0.5 mm



~0.4 mm



~0.3 mm



~0.2 mm

Gravity ↓

Mesh lines displayed on plots

Phase contours from 0.01 to 0.99 VOF are displayed. All cases were simulated under identical conditions besides mesh cell lengths. Cell lengths are given below each picture. Each picture is of the interface at 2.00 seconds with swirl velocity initialized.

Supports Slides 15 – 20

Continuous Casting Consortium

Validation with Oil Entrainment Experiments

Modeling Details

Phase	Material	Density (kg/m³)	Viscosity (kg/m·s)	Surface Tension (N/m)	
1	Water	997	0.0009	**0**	Coarse Mesh
2	**Oil (Ak 50)**	960	0.0480		

Phase	Material	Density (kg/m³)	Viscosity (kg/m-s)	Surface Tension (N/m)	
1	Water	997	0.0009	0.040	Fine Mesh
2	**Oil (Ak 10)**	930	0.0093		

Supports Slides 15 – 20

Continuous Casting Consortium

Validation with Oil Entrainment Experiments

Modeling Details

- 2-D, planar, incompressible, transient
- Gravity enabled in $-y$ direction
- Multiphase Volume of Fluid model
  - Explicit VOF and Body Force
  - Courant number = 0.25
- Standard k-ϵ turbulence model with standard model constants
  - Pressure gradient effects and curvature correction enabled

Applies to both Ak10 and Ak 50 oil simulations

Supports Slides 15 – 20

Continuous Casting Consortium

Validation with Oil Entrainment Experiments

Modeling Details

	Relaxation Factor	Discretization Method
Gradient	--	Green-Gauss Node Based
Pressure	1	PRESTO!
Momentum	1	Second Order Upwind
Volume Fraction	Explicit	Geo-Reconstruct
Turbulent KE	1	Second Order Upwind
Turbulent Dissipation	1	Second Order Upwind

- Pressure-Velocity Coupling: PISO
  - -Neighbor Correction = 1
- First Order Implicit Transient Formulation
  - -Non-Iterative Time Advancement enabled

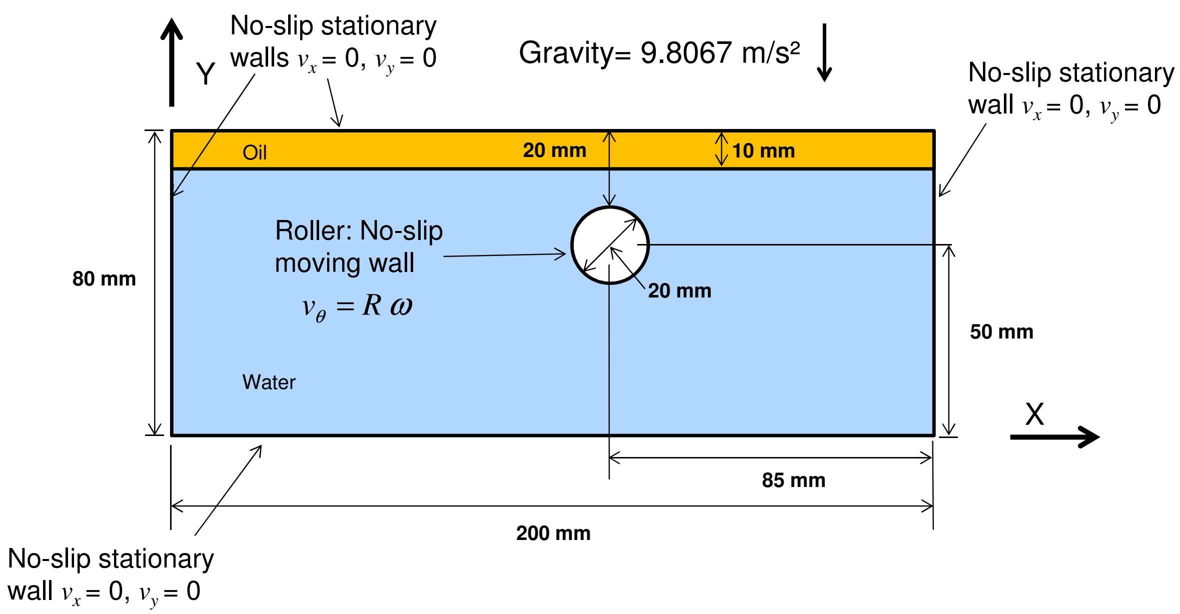
Applies to both Ak10 and Ak 50 oil simulations

Supports Slides 15 – 20

Continuous Casting Consortium

Validation with Oil Entrainment Experiments

Domain and Boundary Conditions

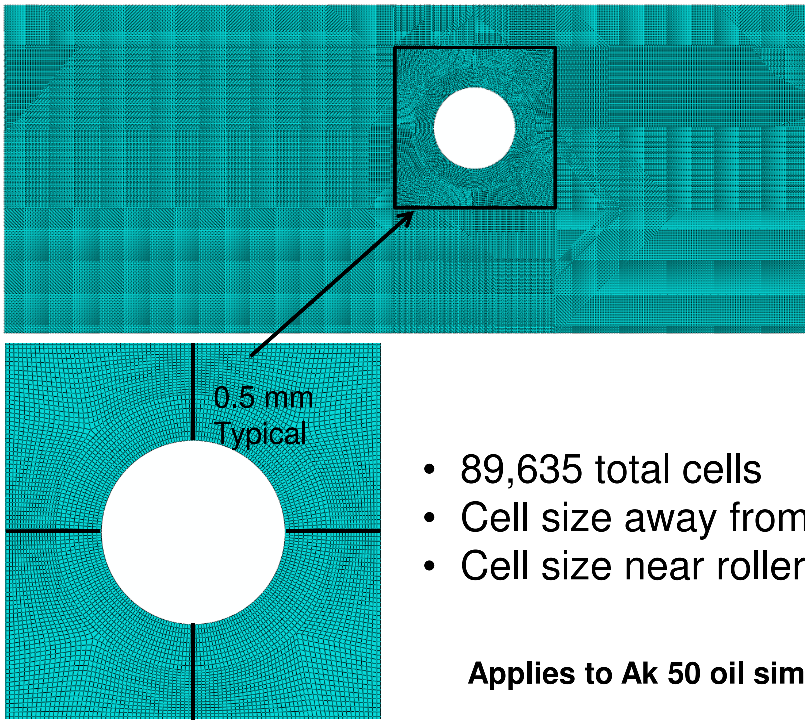


Applies to Ak 50 oil simulation

Drawn to scale

Validation with Oil Entrainment Experiments

Finer Mesh (with 20mm Roller)

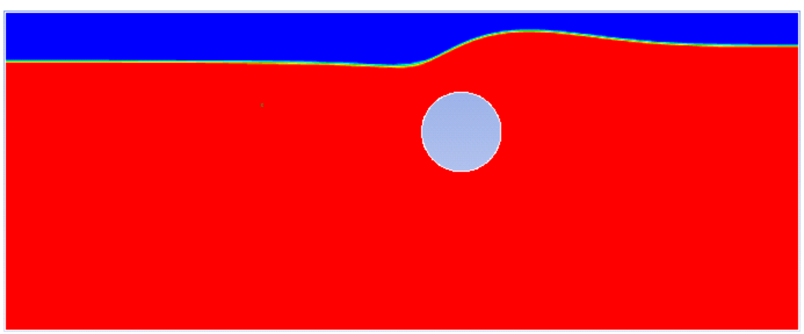


- 89,635 total cells
- Cell size away from roller 0.4 mm
- Cell size near roller 0.5 mm

Applies to Ak 50 oil simulation

Validation with Oil Entrainment Experiments

Ak 50 Oil Entrainment Simulation (20 mm Diameter)



Contours of Volume Fraction

Red = Water

Blue= Oil

Gravity ↓

Max y^+ ~ 15.0

- Simulation ran for 1522.9 s
- Final ω = 84.145 rad/s
- y^+ became too large as the roller sped up
- Entrainment did not occur when Hagemann reported
  - Hagemann's capillary number plot reports entrainment at 62.64 rad/s

Volume (m³)	Water	Oil (Ak 50)
Initial	0.01368584	0.002000000
Current	0.01368587	0.002000019

Roller speed (rad/s)

$$\omega = \begin{cases} 18 & t < 200 \\ 18 + 0.05\,(t - 200) & t \geq 200 \end{cases}$$