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Entrainment at the Mold Surface Due to High-Velocity Shear Flow

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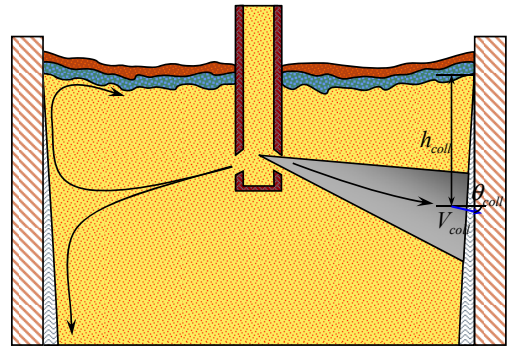
Wherever there is a slag layer, slag can become entrained

- A challenge to clean steel production is to avoid slag entrainment into the steel in all steps of the steelmaking and casting process
  - Blast furnaces
  - Ladles
  - Tundish
  - Mold
- This work focuses on the mold, and specifically the shear-related stability of the slag-metal interface

Mold Slag Entrainment Mechanism:
Meniscus Fluctuations

- Transient, high-frequency meniscus fluctuations can be responsible for slag entrainment



$$F = \rho_\ell Q V_{coll} \frac{(1-\sin\theta_{coll})}{4h_{coll}}$$ 3<F<5

Teshima *et al.*, *1988 Steelmaking Conf. Proc.*, **71**, pg. 111

$$V_{crit} = \sqrt{\frac{4}{\rho_u}\sqrt{3\Gamma_{u\ell} g(\rho_\ell - 3\rho_u)} - 2gA}$$

Yuyama *et al.*, *Tetsu-to-Hagane*, **72**:12 (1986), pg. S1018

$$A \approx 3 \cdot F \qquad V_{stream} = 0.0286 \cdot A$$

Kubota *et al.*, *1991 Steelmaking Conf. Proc.*, **74**, pg. 233

Mold Slag Entrainment Mechanism:
Argon Bubble Interactions

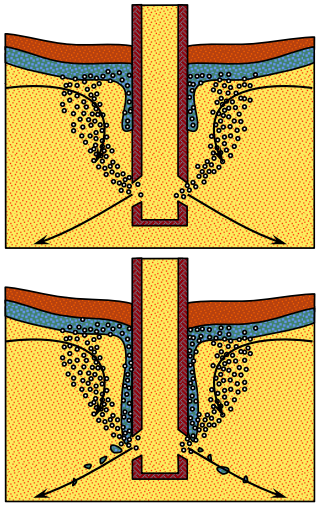
- Argon bubbles can form a foam with the slag, which crawls down the SEN and entrains with the jets

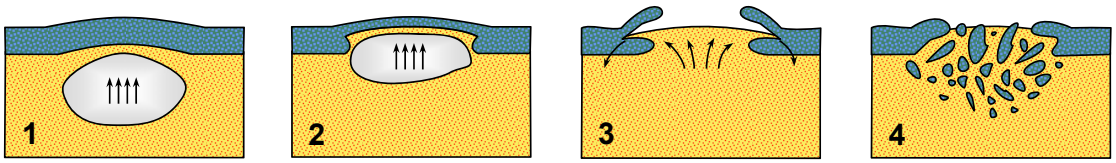
  Emling *et al.*, *1994 Steelmaking Conf. Proc.*, **77**, pg. 371

- Bubbles can also entrain slag when penetrating the slag layer

  Yamashita and Iguchi, *ISIJ Int.*, **41**:12 (2001), pg. 1529
  Watanabe and Iguchi, *ISIJ Int.*, **49**:2 (2009), pg. 182

- Argon flow rate must be carefully tuned with other parameters





Mold Slag Entrainment Mechanism:
Slag Crawling/Suction Down SEN

- Flow (asymmetric) past the SEN causes pressure drop in the wake, which can pull liquid slag down into the SEN ports
- Penetration depth of slag finger down the (circular) SEN given by:

$$h_p = 1.9\frac{C_{p,\max}\rho_u V_u^2 - C_{p,\min}\rho_\ell V_\ell^2}{g(\rho_\ell - \rho_u)} \qquad C_{p,\max} = 1.0 \qquad C_{p,\min} = -2.5$$

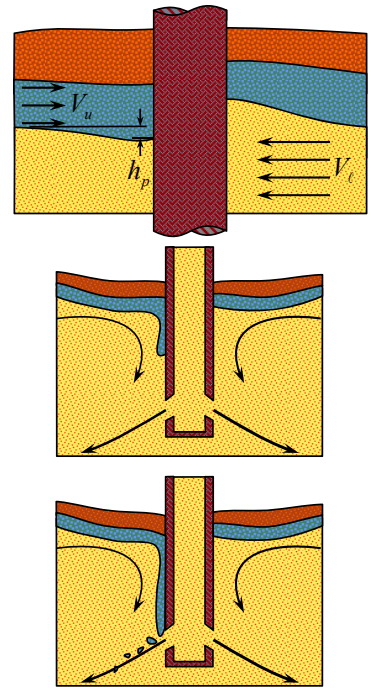
Yoshida *et al.*, *ISIJ Int.*, **45**:8 (2005), pg 1160

- Using an elliptical SEN reduces the penetration depth:

$$r = \frac{D_{major}}{D_{minor}} \qquad C_{p,\max} = 1.376 - 0.0652 \cdot r \qquad C_{p,\min} = 1.065\ln(r) - 1.978$$

Ueda *et al.*, *ISIJ Int.*, **44**:8 (2004), pg 1403

- Avoid entrainment with SEN immersion depth greater than slag penetration depth



Mold Slag Entrainment Mechanism:
von Kármán Vortexing

- Flow past the SEN creates vorticity in the plane of the meniscus (von Kármán vortex)
- The downward motion necessary to form a vortex is created where the opposing roll flow patterns meet
- Stronger asymmetric flow increases vortex formation frequency and size

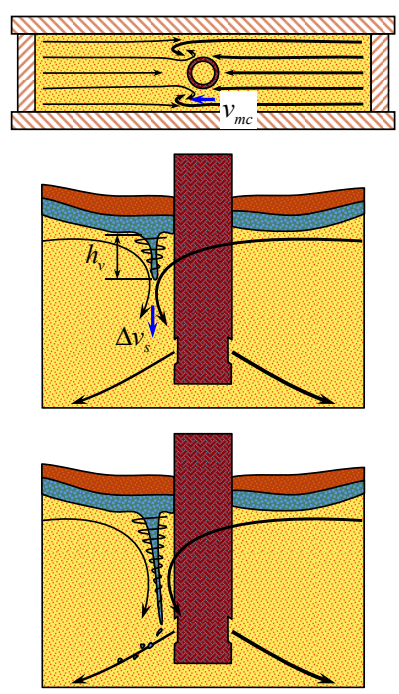
He, *ISIJ Int.*, **33**:2 (1993), pg. 343

- Vortex depth given by:

$$h_v = \frac{\rho_\ell}{(\rho_\ell - \rho_u)}\frac{v_{mc}^2}{g} + \alpha\left[\frac{\rho_u \Delta v_s^2}{g(\rho_\ell - \rho_u)}\right]^{0.55} \qquad \alpha = 0.0562\ \mathrm{m}^{0.45}$$

Kasai and Iguchi, *ISIJ Int.*, **47**:7 (2007), pg. 982

- Avoid entrainment with SEN immersion depth greater than vortex depth

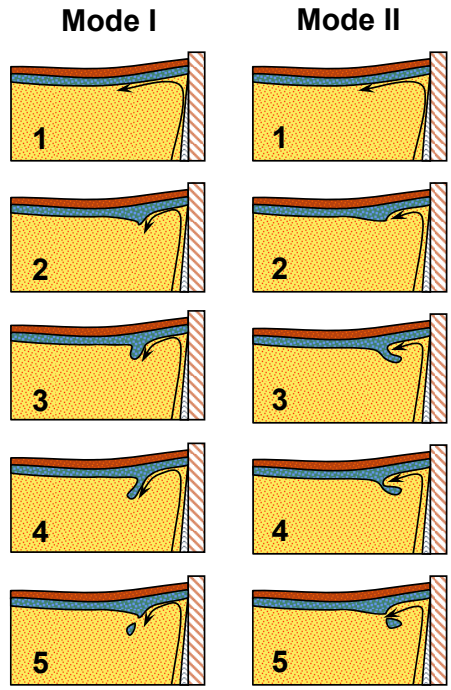


Mold Slag Entrainment Mechanism:
Narrow Face Spout Impinging Flow

- Part of the SEN jet rises to the meniscus after impinging upon the narrow faces
  - Can shear off some of the liquid slag layer in two ways
  - Varying results of velocity at which phenomena occurs
  - Many models available in the literature, e.g.:

$$V_{crit} = 3.065 \frac{\Gamma_{u\ell}^{0.292} g^{0.115}}{\delta^{0.365}} \frac{\Delta\rho^{0.215}}{\rho_u^{0.694}} \frac{\mu_u^{0.231}}{\mu_\ell^{0.043}}$$

Harman and Cramb, *1996 Steelmaking Conf. Proc.*, **79**, pg. 773



Mold Slag Entrainment Mechanism:
Standing Meniscus Wave Instability

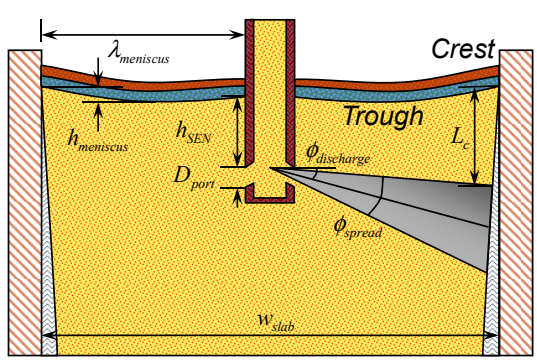
- Standing wave at meniscus goes unstable at too-high a height-to-length ratio
- Wavelength can be taken as distance from SEN to narrow face. Many models can predict the meniscus standing wave height
- Avoid entrainment by respecting Rottman's ratio to keep the standing wave stable (usually easy)

$$\left(\frac{h_{meniscus}}{\lambda_{meniscus}}\right)_{critical} = 0.21 + 0.14\left(\frac{\rho_u}{\rho_\ell}\right)^2$$

Rottman, *J. Fluid Mech.*, **124** (1982), pg. 283

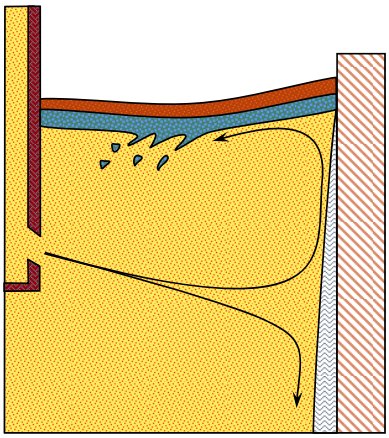
$$h_{meniscus} = 0.31 \frac{V_{port}^2}{g} \frac{D_{port}}{L_c} \frac{\rho_\ell + \rho_u}{\rho_\ell - \rho_u}$$

Theodorakakos and Bergeles, *Metall. Mat. Trans.*, **29B**:6 (1998), pg. 1321



Mold Slag Entrainment Mechanism:
Interfacial Shear

- The highest sub-meniscus velocity can cause a shear instability at slag-metal interface
  - Similar phenomenon in ladle "eyes"
  - Influenced by magnetic field
- No conclusive investigations yet performed, though many researchers indicate this is an entrainment mechanism
- Some water model experiments match Milne-Thomson's equation:

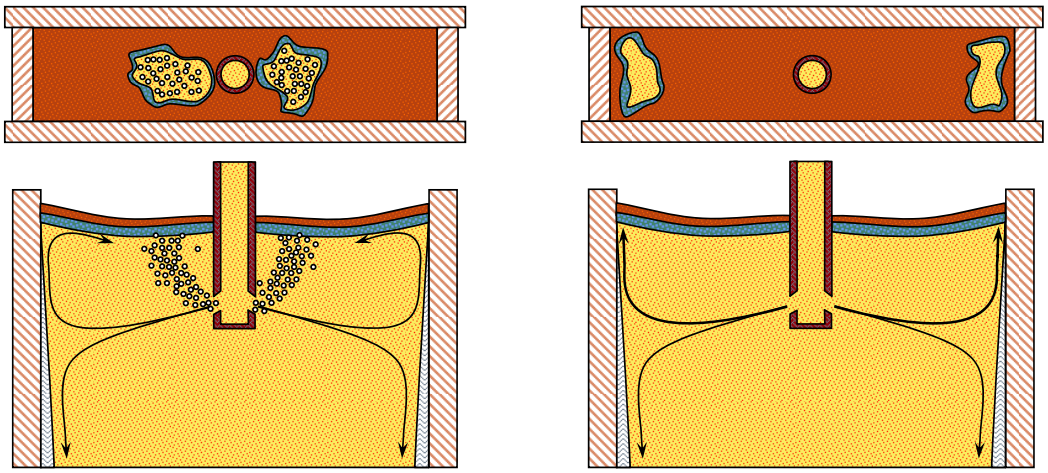


$$(\Delta V_{crit})^2 = (\rho_\ell - \rho_u) g \left(\frac{H_u}{\rho_u} + \frac{H_\ell}{\rho_\ell} \right)$$

Iguchi *et al.*, *ISIJ Int.*, **40**:7 (2000), pg. 685

Inclusion Formation Mechanism:
Meniscus Balding

- Excessive argon flow rates and narrow face spout velocity can expose the liquid steel to the powder layer and/or atmosphere



Safe Operating Window(s):
Argon Flow Rate and EMBr

Too Little		*Too Much*
Nozzle clogging Exposure to ambient air in SEN Vortex formation	**Argon Flow Rate** **f(EMBr, h_{SEN}, w_{slab}, V_c)**	Meniscus fluctuations Slag foaming Meniscus balding

Too Little		*Too Much*
No benefit	**EMBr** **f(Q_{Ar}, w_{slab}, V_c, h_{SEN})**	Revert to single roll flow Meniscus fluctuations Complex flow Meniscus freezing Hook formation

Safe Operating Window(s):
SEN Design and Operation

Too Little (Shallow)		*Too Much (Deep)*
Shear entrainment Meniscus fluctuations Slag crawling Vortex formation	**SEN Immersion Depth** **f(Q_{Ar}, EMBr, w_{slab}, V_c)**	Meniscus freezing Hook formation Shell remelting too low

Too Little (Deep)		*Too Much (Shallow)*
Hook formation No inclusion floatation	**SEN Port Angles** **f(V_c, h_{SEN}, superheat)**	Single roll flow pattern Meniscus balding Vortex formation

For more on SEN design, see Najjar, Thomas, and Hershey, *Metall. Mat. Trans.* **26B**:4 (1995), pg. 749

Safe Operating Window(s):
Slag Layer Properties

Too Little (Weak)	**Steel/Slag Interfacial Tension**	*Too Much (Strong)*
Shear entrainment Slag foaming		Unable to capture bubbles and inclusion particles

Too Little (Thin)	**Slag Layer Thickness**	*Too Much (Thick)*
Excessive heat loss Meniscus balding		Large slag rims Shear entrainment

Too Little (Light)	**Slag Layer Density**	*Too Much (Heavy)*
Slag foaming?		No stratification Large meniscus wave Shear entrainment Vortex formation

Too Little (Thin)	**Slag Viscosity**	*Too Much (Thick)*
Shear entrainment		Slag foaming

Slag Entrainment Model

- The goal of this work is to investigate shear-based slag entrainment mechanisms with numerical models
- Mass conservation: Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = S$$

- Momentum conservation: Navier-Stokes

$$\rho \frac{D\boldsymbol{v}}{Dt} = -\nabla p + \nabla \cdot (2\mu \mathbf{D}) + \rho \boldsymbol{b} \qquad \mathbf{D} = \tfrac{1}{2}\left[(\nabla \otimes \boldsymbol{v}) + (\nabla \otimes \boldsymbol{v})^T\right]$$

- Interfacial compatibility

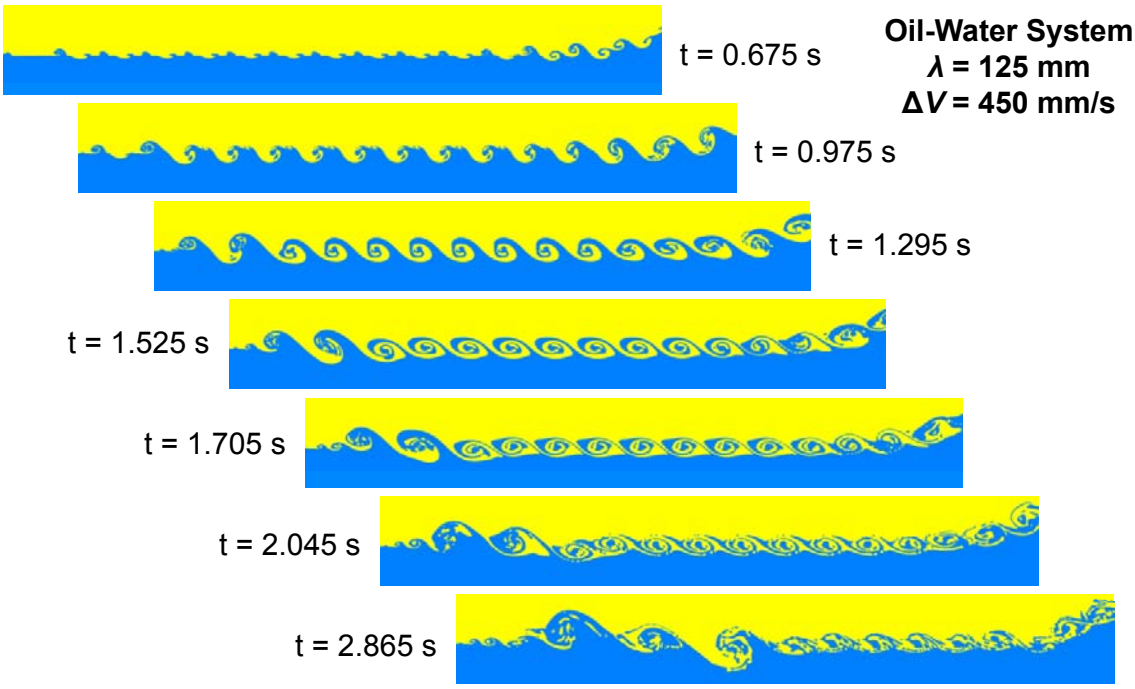
$$\boldsymbol{v}_A = \boldsymbol{v}_B$$

- Interfacial force balance: Generalized Young-Laplace

$$2\mu_A \mathbf{D}_A \cdot \boldsymbol{n} - 2\mu_B \mathbf{D}_B \cdot \boldsymbol{n} - (p_A - p_B)\boldsymbol{n} = 2\kappa_m \Gamma_{AB} \boldsymbol{n} + \nabla_{surf}(\Gamma_{AB})$$

- Use the commercial CFD program FLUENT 6.3
  - Advection discretization scheme: 3rd-order MUSCL
  - Pressure-velocity coupling: Pressure Implicit w/ Splitting of Operators
  - Multiphase model: Volume-of-Fluid (assume interface at VOF=0.5)
  - Interfacial tension model: Continuum Surface Force

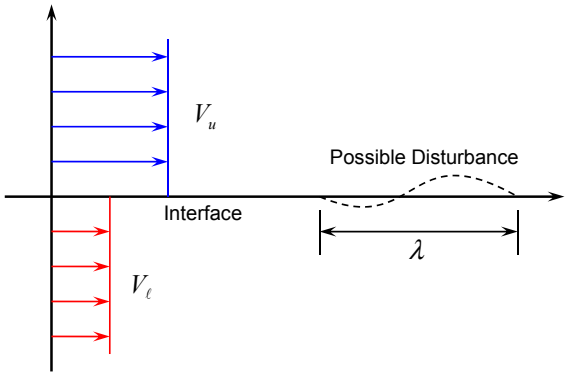
Example Results



Oil-Water System
λ = 125 mm
ΔV = 450 mm/s

Stability of a Stratified Shear Layer: Kelvin-Helmholtz Instability

- Interfacial stability of two parallel-flowing, inviscid, irrotational, incompressible, semi-infinite fluids
- Predicts the increase in velocity at the interface at which small waves grow without bound



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

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

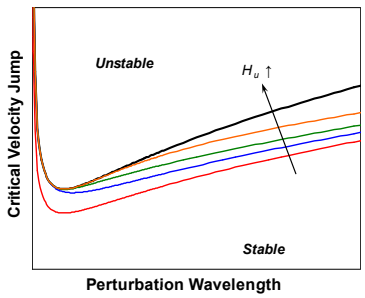
$$\lambda_{\min} = 2\pi\sqrt{\frac{\Gamma_{u\ell}}{g\left(\rho_\ell - \rho_u\right)}}$$

Effect of Properties on the Kelvin-Helmholtz Instability

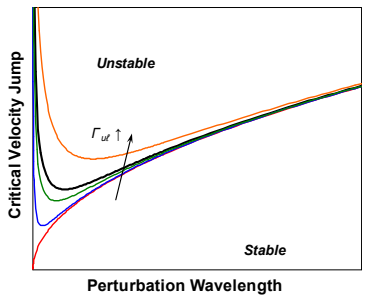
Extend to a finite channel:

Finite channel depth H_ℓ and H_u

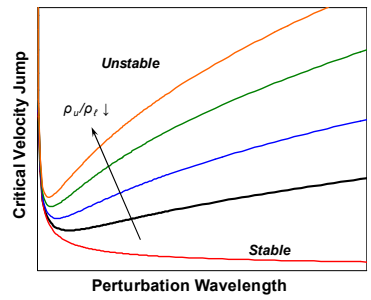
$$\Delta V_{crit} = \sqrt{\left[\frac{\tanh\left[(2\pi/\lambda)H_\ell\right]}{\rho_\ell} + \frac{\tanh\left[(2\pi/\lambda)H_u\right]}{\rho_u}\right]\left[\frac{\lambda}{2\pi}g(\rho_\ell - \rho_u) + \frac{2\pi}{\lambda}\Gamma_{u\ell}\right]}$$



Slag layer thickness: does not agree with experiments



Interfacial tension: agrees with experiments

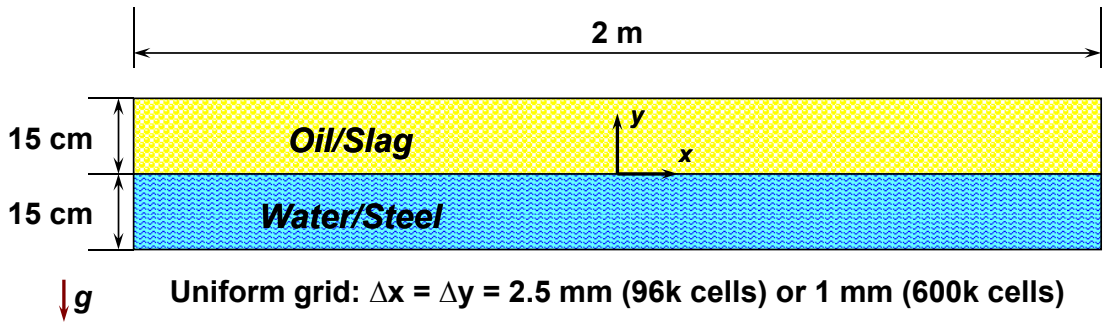


Density ratio: agrees with experiments

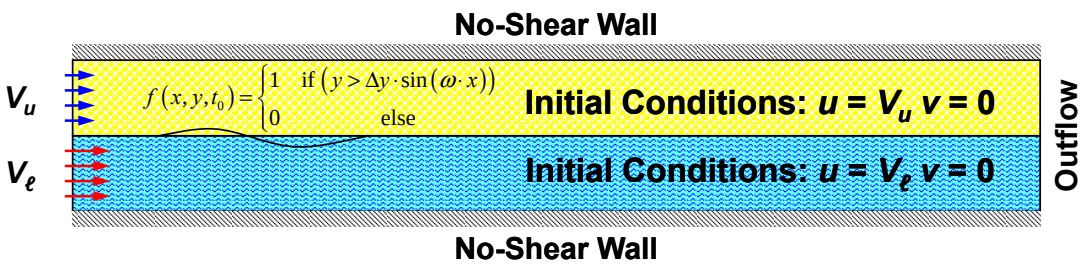
Model Validation:
Compare with Analytical Solution

- Test the capabilities of the FLUENT model to properly simulate Kelvin-Helmholtz instability
  - Nominal/theoretical problem
    - Constant density
    - Inviscid liquids
    - Step change in velocity and density at interface
  - Initially perturbed interface
    - Volume fraction field only
    - Sinusoid, varying frequency
    - Amplitude of one cell height
  - Brute-force search for the neutral stability curve

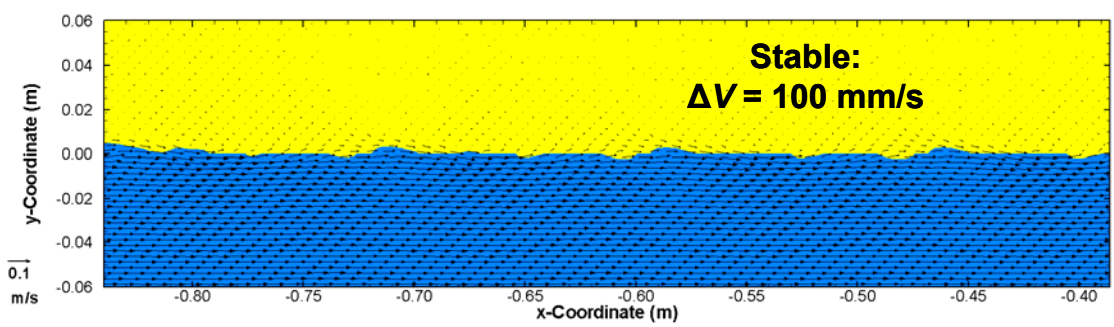
Model Validation:
Domain and Boundary Conditions



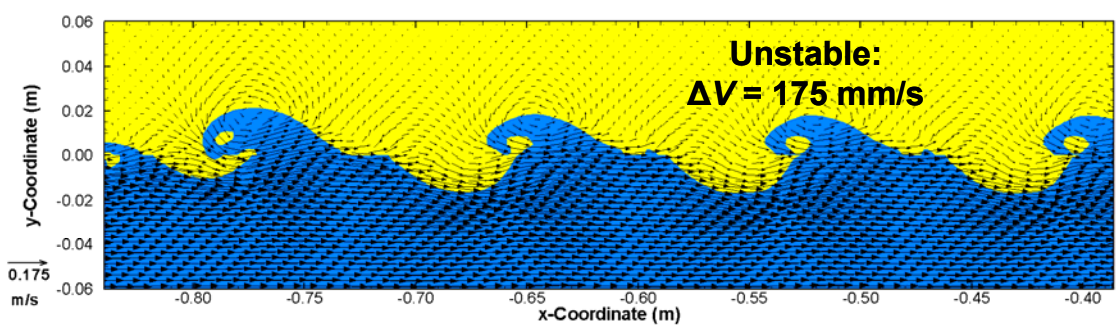
Uniform grid: $\Delta x = \Delta y = 2.5$ mm (96k cells) or 1 mm (600k cells)



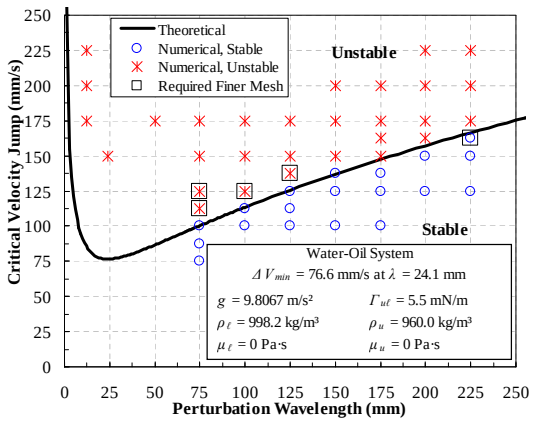
Model Validation:
Kelvin-Helmholtz Unstable Interface



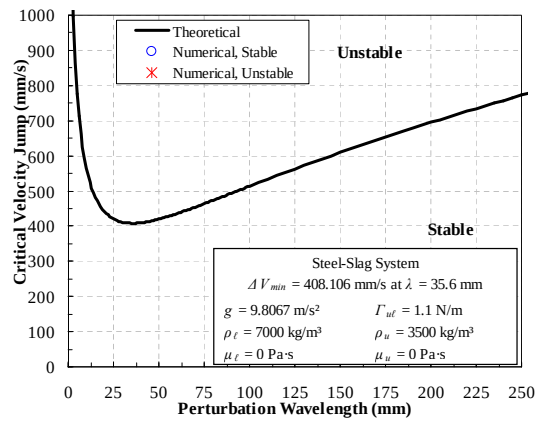
Oil-Water System, perturbation λ = 125 mm



Model Validation:
Kelvin-Helmholtz Stability Curves



Oil-Water System



Slag-Steel System

Conclusions

- SEN design and immersion depth, EMBr settings, argon flow rate, slag layer properties and thickness need to be carefully optimized for a given slab width and casting speed to avoid inclusions while keeping overall casting throughput high
- Many slag entrainment mechanisms are governed by the shear-stability of the slag-metal interface
- A new FLUENT model has been developed to investigate slag-metal interface behavior
  - Fine and/or adaptive mesh required for higher frequency perturbations
  - Correct prediction of Kelvin-Helmholtz instability shows model validation
  - More realistic simulations coming

Acknowledgements

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