ZCO-77: Dross Minimization in Galvanizing Bath

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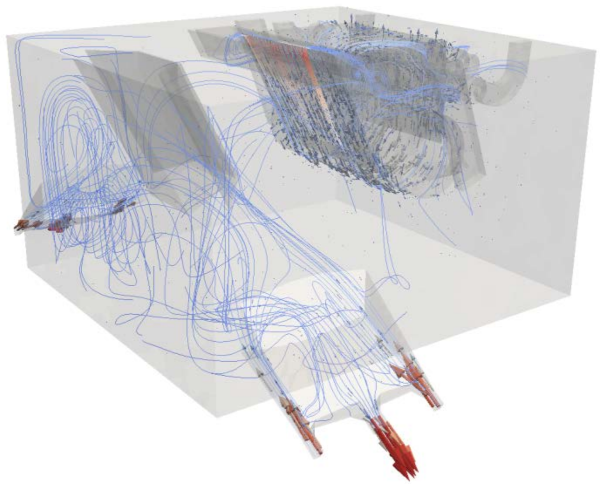
1. **Goal and Objectives**
2. **Wiping gas jet and local skimming generation model**
3. **Dross formation in ZM bath**

Goal and Objectives

1. Develop a better understanding of the nature of gas flow from the coating control rig that impinges on the bath surface, with respect to various process parameters, to guide efforts to minimize production of top skimmings.

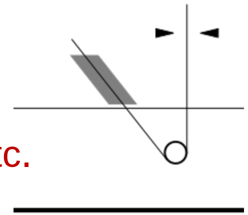
2. Determine how different ingot addition practices and pot and hardware geometries influence dross production from ZM coatings.



WIPING GAS JET MODEL

Unsteady 3D model to better understand the liquid zinc backflow from the air-knife unit

It is needed to have an efficient numerical model of the gas jet wiping process, predicting the value of interests.



Gas jet wiping is the main method for coating thickness control for CGL

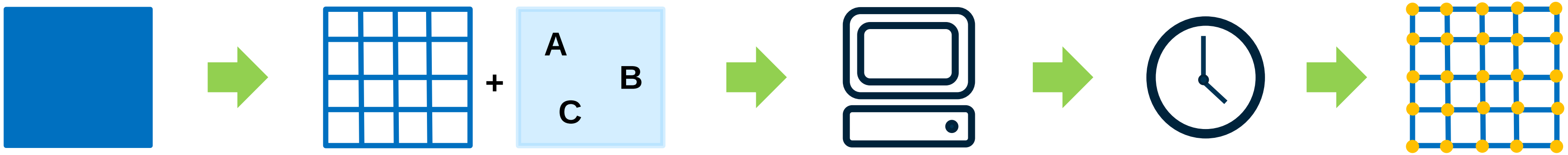
+++: Safe, efficient, economical ⟺ ---: sensitive z/d, splashing, skimming, etc.

Numerical model may be used to gain useful insights for complex phenomena.

1. Handy to answer what-if questions
2. A laboratory with physics “controlled”

A good model should predict the desired parameters accurately and efficiently

Key consideration: Accuracy vs. Efficiency



- 2mm of coating length needs 24 h on 24 CPU cores: Pfeiler et al. (2017)
- an infamous example: Turbulence model (DNS, LES, eddy-viscosity)

What interactions are there at the air knife / zinc bath?

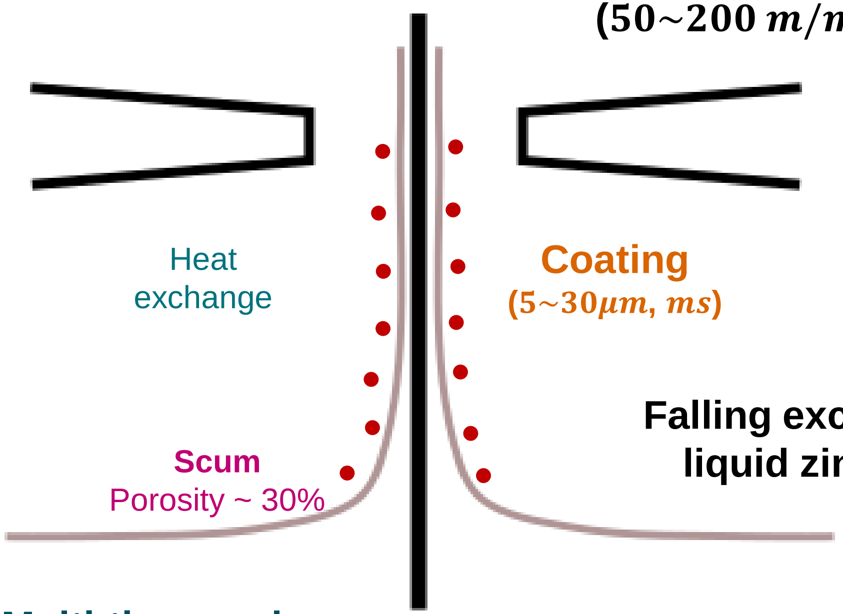
High velocity gas flow

Impinging gas jet from the air-knife

Moving steel strip at high speed ($50 \sim 200\ m/min$)

Sheet stability

Interaction gas-liquid-solid



Essential to predict the characteristics of the free surface of the falling liquid zinc below the nozzle

Formation of skimming

Oxides + Fe_2Al_5 + Zn

Porosity ~ 50%

$\uparrow \boldsymbol{Skim.} \propto \uparrow \boldsymbol{Speed} + \uparrow \boldsymbol{Pressure}$

Falling excess liquid zinc

Flow of zinc near surface

Bath

(m, s)

Multi-time-scales

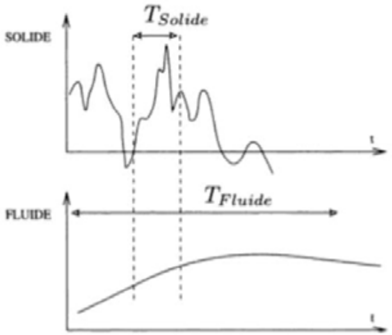
Multi-flow-regimes

Multi-length-scales

Multi-phases

Couplings in fluid-structure interaction largely depend on the relative characteristic time scale

Emmanuel de Langre (2002), Fluides et Solides



Small reduced velocity

$T_{solid} \ll T_{fluid}$ (small reduced velocity)

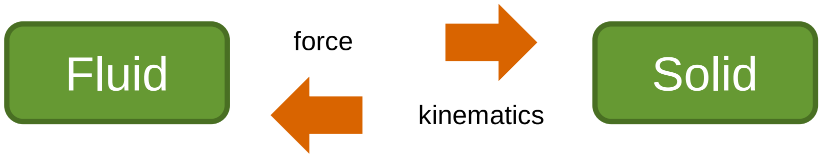
The fluid behaves like at rest with respect to the solid (rigid).

Effect of fluid can be well captured as added mass and added stiffness for the solid equation!

$T_{solid} \gg T_{fluid}$ (large reduced velocity)

The solid domain behaves like at rest with respect to the fluid.

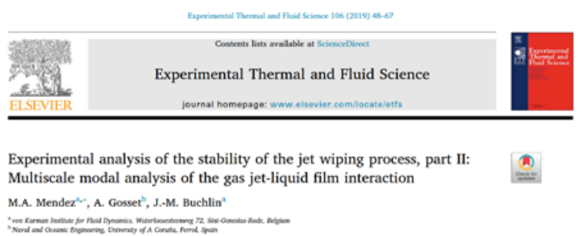
e.g. aeroelasticity



Even more interesting when the numerical scheme needs the exact location of the deforming boundary

$T_{solid} \approx T_{fluid}$ (medium reduced velocity) $\Leftarrow$ strongly coupled

Interaction studies from literature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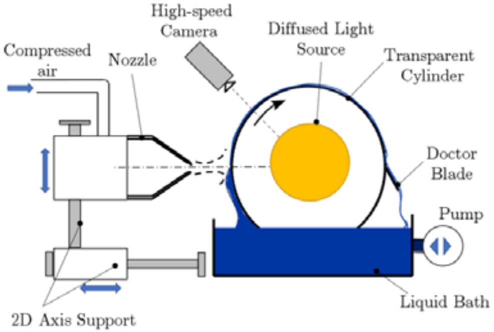
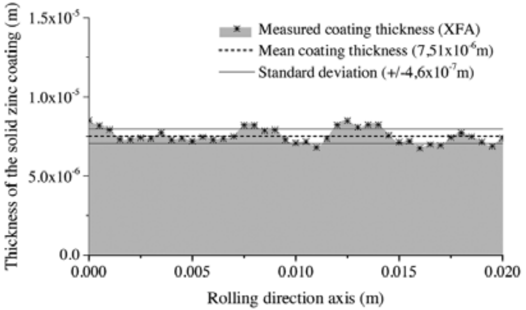
Experimental analysis of the stability of the jet wiping process, part II: Multiscale modal analysis of the gas jet-liquid film interaction

M.A. Mendez[a,*], A. Gosset[b], J.-M. Buchlin[a]

- McMaster university investigated the acoustic feedback in a gas jet impinging on a flat plate at high jet velocity.
- VKI studied the "undulation" at low speed flow & proposed that it is linked to jet geometrical confinement.
  - 2 possible responses ⇐ timescale of confinement perturbation
  - $\hat{Z} = \{12{,}16\}$; $\hat{A}$ from 2.5 – 6% h_0, λ_H from 2.5 – 10 h_0
- One-way coupling ⇒ final averaged coating thickness very well, even 0D model works nicely (Gosset et al. (2019))
- Waves ($1\ \mu m$) found after nozzle on coating (Pfeiler et al. (2017))
  - Solid wave < liquid wave ⇐ smoothen by surface tension



Gosset et al. (2019)



Pfeiler et al. (2017)

Interaction studies from literature

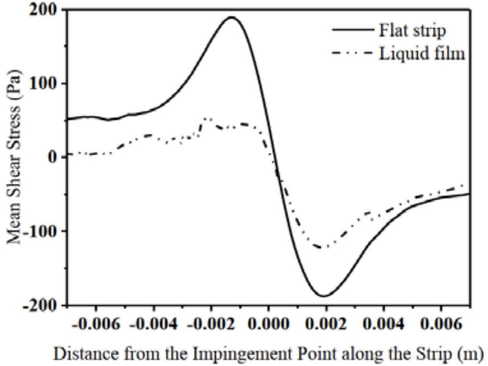
Pfeiler et al. (2015) Galvatech

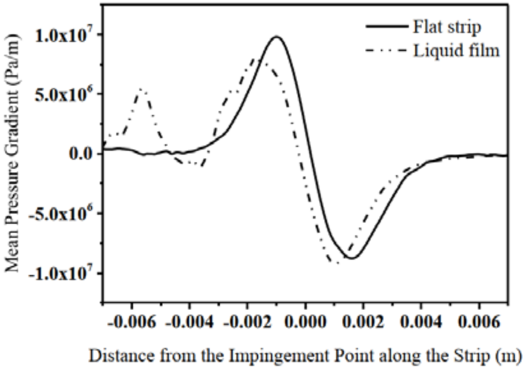
"Importance of the Zinc Film Modeling for Gas Jet Wiping Simulation"

- Coating thickness mainly due to ∇P
- Shown that gas responses are different when there is a liquid coating near the impingement zone ($\pm 6mm$)

Some thoughts:

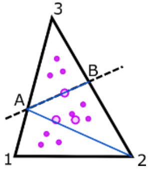
- How long are these results averaged over time ($0.01s$)?
- How are the deforming free surface handled in the numerical solver scheme?
- **Are the averaged free surface also changing significantly below the nozzle as the gas jet?**

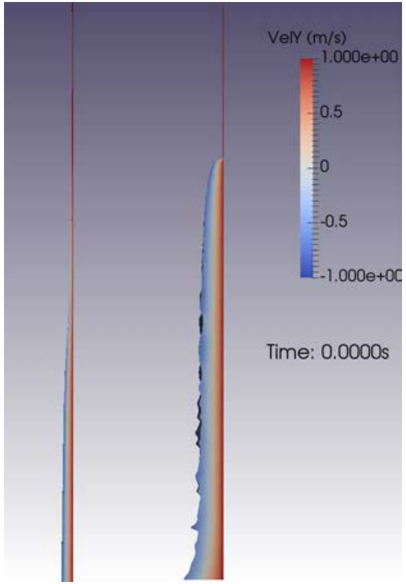




Gas jet wiping model overview

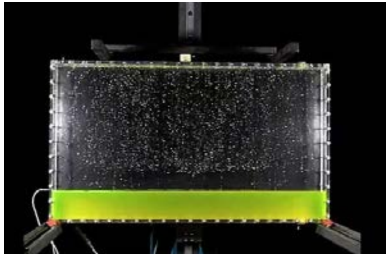
Compressible flow: SU2 / in-house FEM code
validated with measurements by Alibeigi (2013)



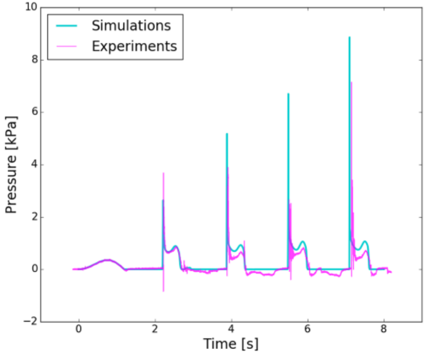


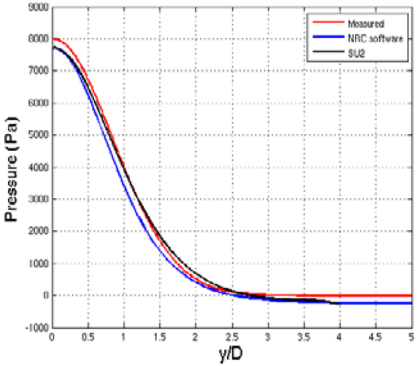
Liquid: in-house FEM code + level-set (free surface) + method of discontinuous pressure (ρ and P resolution)

validated with experiment by Souto-Iglesias et al. (2011)



$Re \approx 97{,}546;\ \theta_{max} = 4°;\ \mathrm{T} = 1.63s$





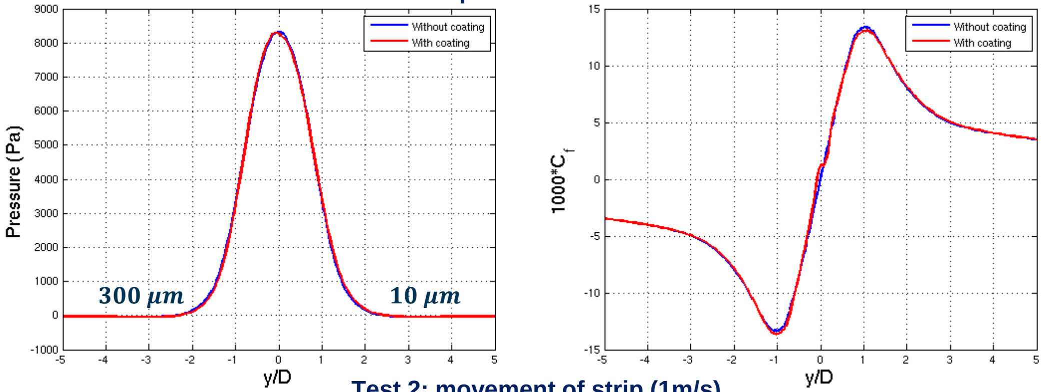
$Re = 11{,}000;\ Ma = 0.33;\ V = 113\ m/s;\ z/d = 6$

Wiping challenge: length scale (μm vs. m) ⇐ \$\$\$ ⇐ high aspect ratio element (300)

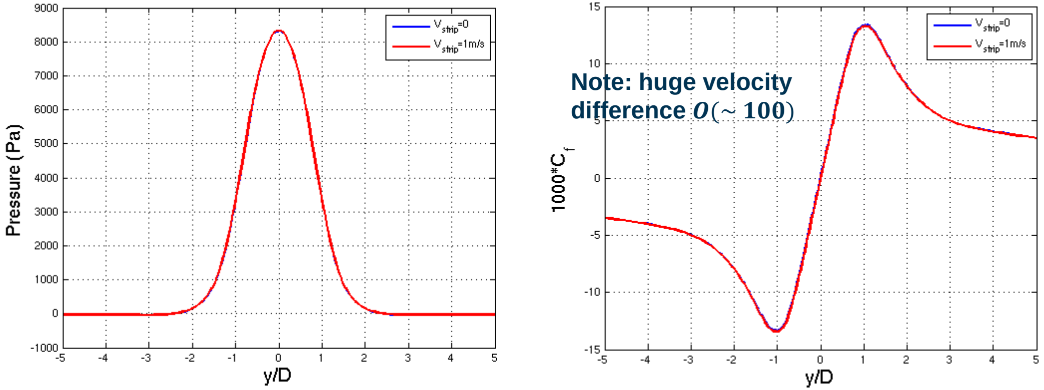
⇒ For a sheet-length of 60cm, about $3{,}600{,}000$ elements are saved!

Preliminary test of the effect of the liquid zinc coating exerted onto the gas jet flow

Test 1: presence of zinc film



Test 2: movement of strip (1m/s)



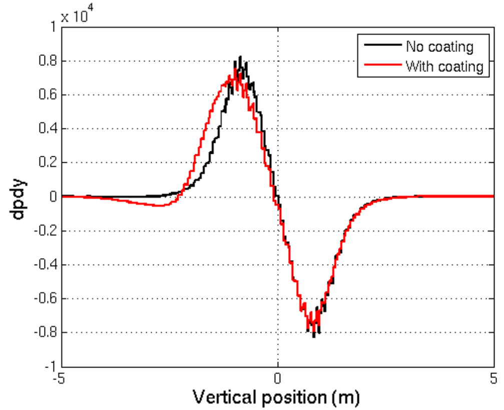
Interaction level dictates if weak coupling could be reasonable.

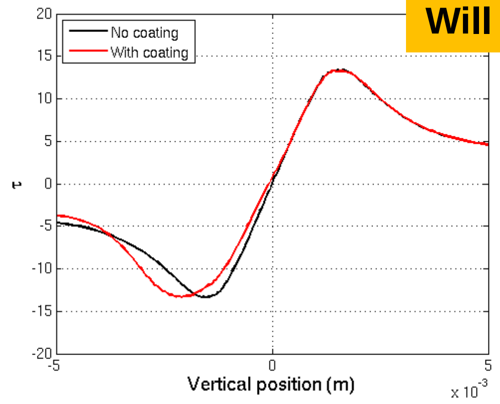
Benchmark: gas jet on flat static plate

Both cases exert very little feedbacks onto the gas flow field.

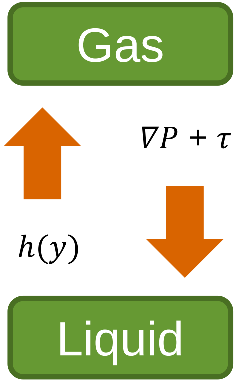
This suggests that the interaction is mainly unidirectional from the gas field to the liquid zinc.

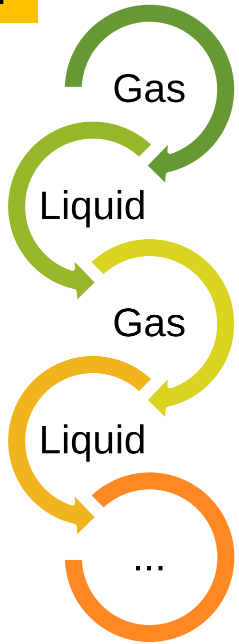
What will happen when one cycles through the coupling between the gas and the free surface?



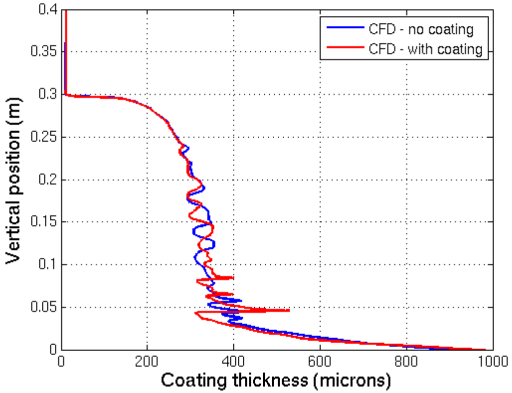


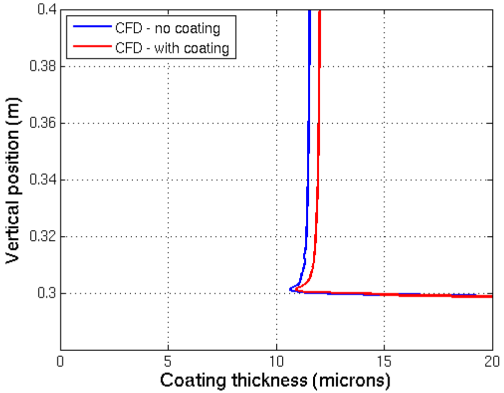
Will the solution further converge?





- ∇P and τ shift lower after 1 cycle
- But not much different for liquid profile





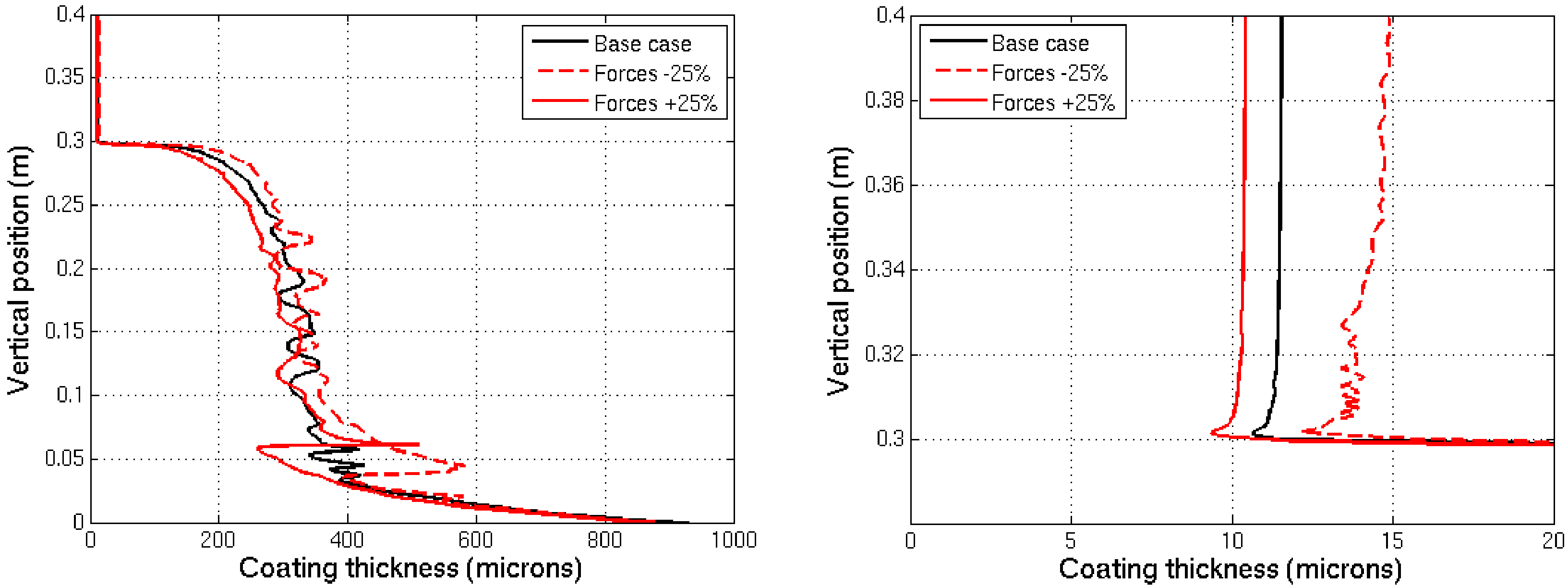
One-way coupling Seems adequate

Previously, the gas jet model is employed to conduct sensitivity studies and study the free surface profiles.

Case			Average coating thickness (μm)		Relative thickness to the Base (%)	
			⇓	⇑	⇓	⇑
Base			11.550		0.00	
Air-knife height (m)	0.2	0.4	11.419	11.153	-1.13	-3.44
Strip-to-knife distance	-20%	+20%	11.647	11.321	0.84	-1.98
Air-knife force	-25%	+25%	***14.828***	***10.422***	***28.38***	***-9.77***
Strip speed (m/s)	0.75	1.50	**9.003**	**17.719**	**-22.05**	**53.41**
Zinc viscosity	-25%	+25%	***8.982***	***12.588***	***-22.23***	***8.99***
Zinc density	-25%	+25%	**12.639**	**10.649**	**9.43**	**-7.80**

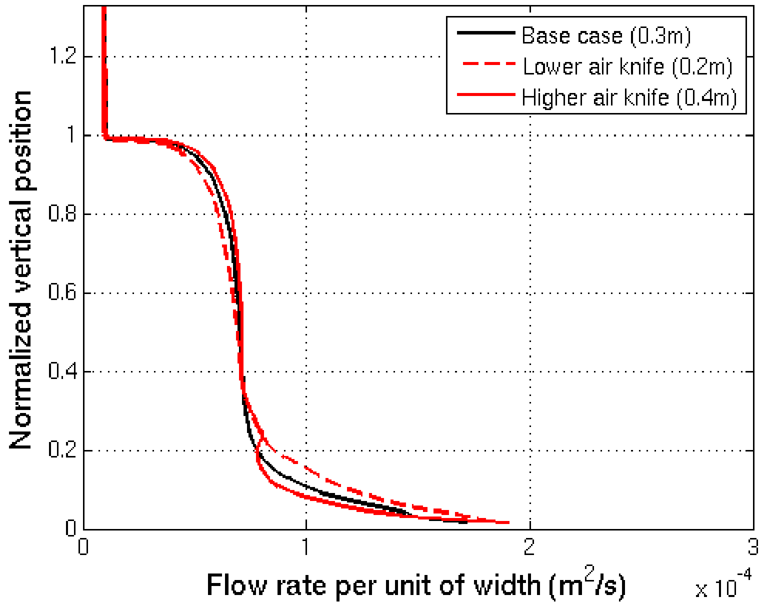
Linear response; ***Non-linear response***

Previously, below the air-knife, the profile is much more wavy, increasing the surface area for oxide formation.

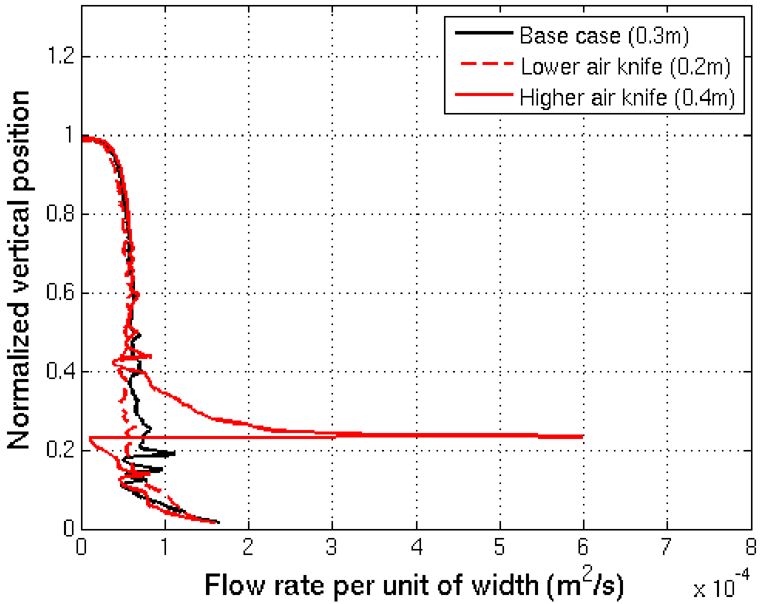


Non-linear response

Previously, lower air knife yields smoother downward flow profile ⇒ the reference case may not be optimal

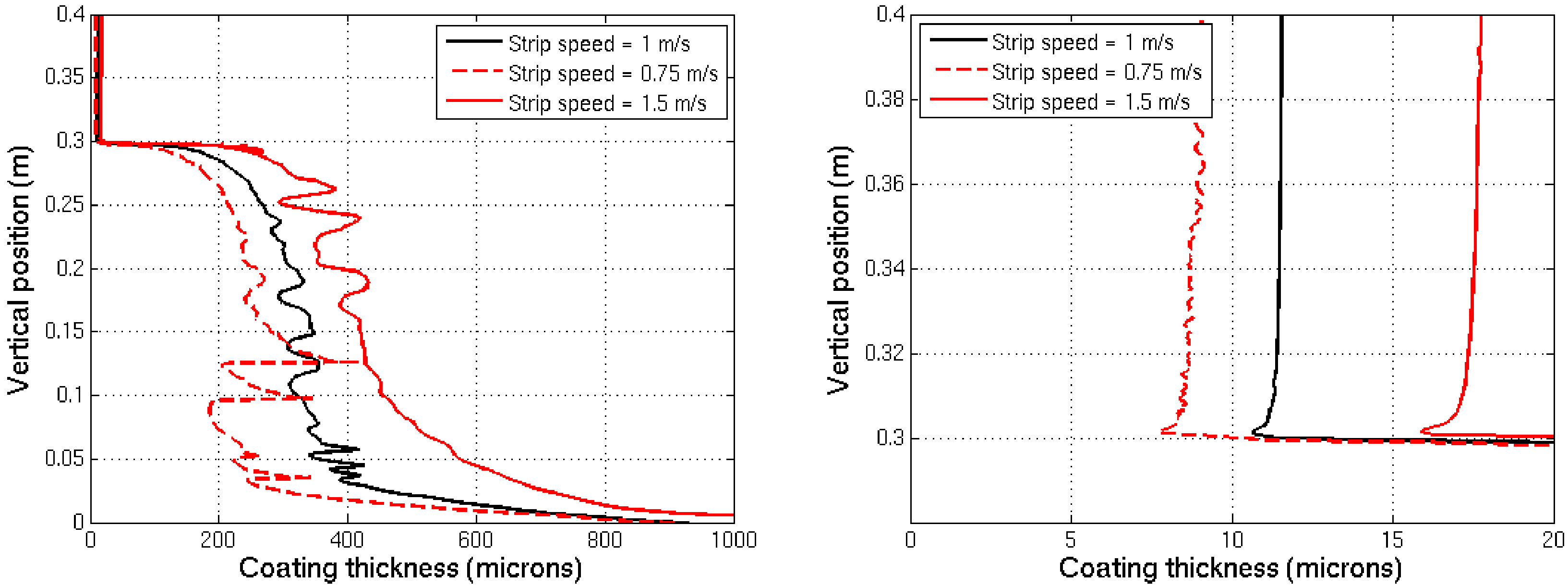


Upward flow



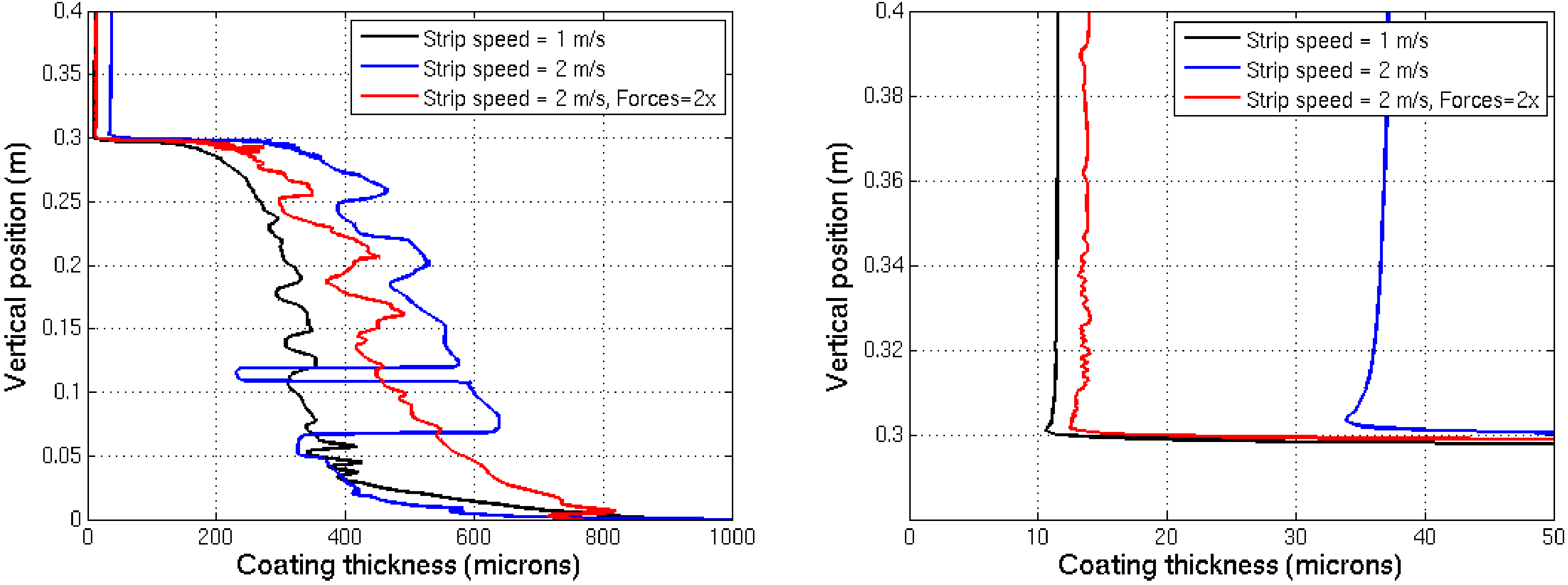
Downward flow

Previously, the strip speed is found to yield a linear response for coating thickness.



Linear response

New test shows that higher speed needs higher force to keep similar coating thickness, but differs in ratio.



Linear response

Summary

Gas-liquid interaction work reviewed from literature.

New numerical experiment supports that one-way coupling is adequate to capture the free surface profile under the nozzle, which is the key target feature to be predicted.

New test shows that at higher strip speed, one needs larger wiping force to keep the similar coating thickness, which agrees well with intuition.

The model can provide a viable mean to quantify parameters that are expected to be important for the skimming formation, but are difficult to obtain.

SKIMMING GENERATION MODEL

Predictive Model for Skimming generation

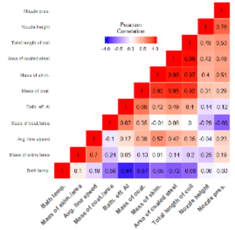
Outline of skimming generation study

Data from 13 CGL lines received,
24 complete records for GA, GI, ZM

Not trivial to collect data from line

CGL Data

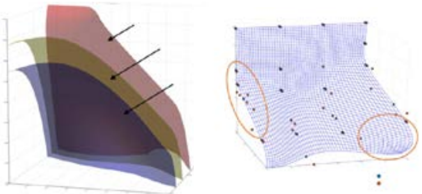
Feature Selection / Ranking
- Stepwise methods
- Linear regression
- Penalized linear regression (LARS)
- Ensemble methods (RF, GB)



Predictive Model ?

Evaluation

EDA / ML



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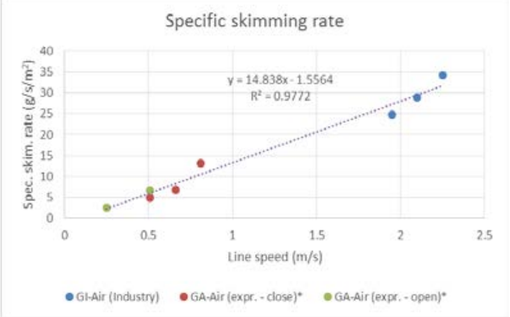
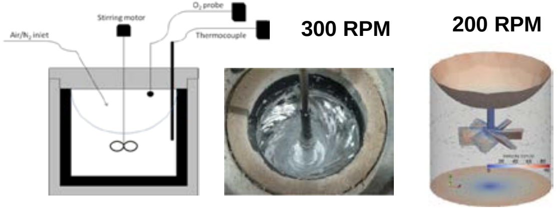
Fitting for specific 'GI' skimming rate for air



Model

Bench-scale experiment



Dross skimming generation model

From literature, only a few studies on top skimming generation are found:

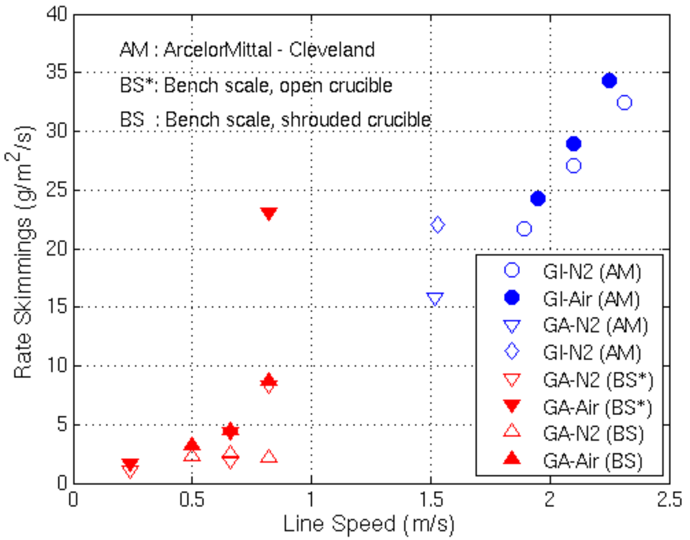
- Dubois (2004) / Goodwin and Dubois (2012)
- Thiounn et al. (2008)
- Strutzenberger and Pree (2017)

Skimming (scum): a "mushy" foam (Zn + oxides + Fe_2Al_5)

$\uparrow \boldsymbol{Skimming} \propto \uparrow \boldsymbol{Speed} + \uparrow \boldsymbol{Pressure}$

Possibly affected by the air-knife, product spec, and galvanizing bath (design, composition), line operations; conflicted findings on certain parameters (e.g. width)

Prohibitively costly to rigorously study all these possible factors



Ajersch et al. (2011)

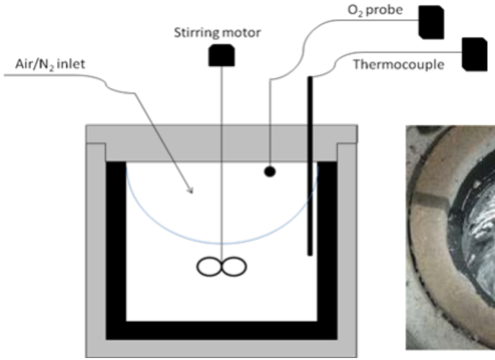
Bench scale experiment could support a generic skimming formation model!

Overview of bench scale experiment

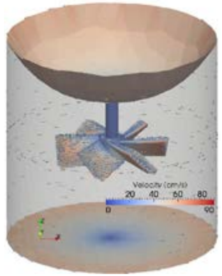
Koutsaris (2011): Scum is produced near the strip exit, high mixing + area exposed for oxidation.

Stirring experiment: mimic skimming formation at the strip exit region

Steel impeller agitates liquid zinc alloy in a crucible at various speed, impinged with gas (air / N_2)



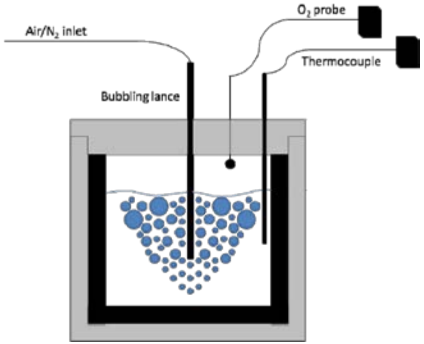
300 RPM



200 RPM

Bubbling experiment: simulate the mass transfer between the return Zn and the gas jet

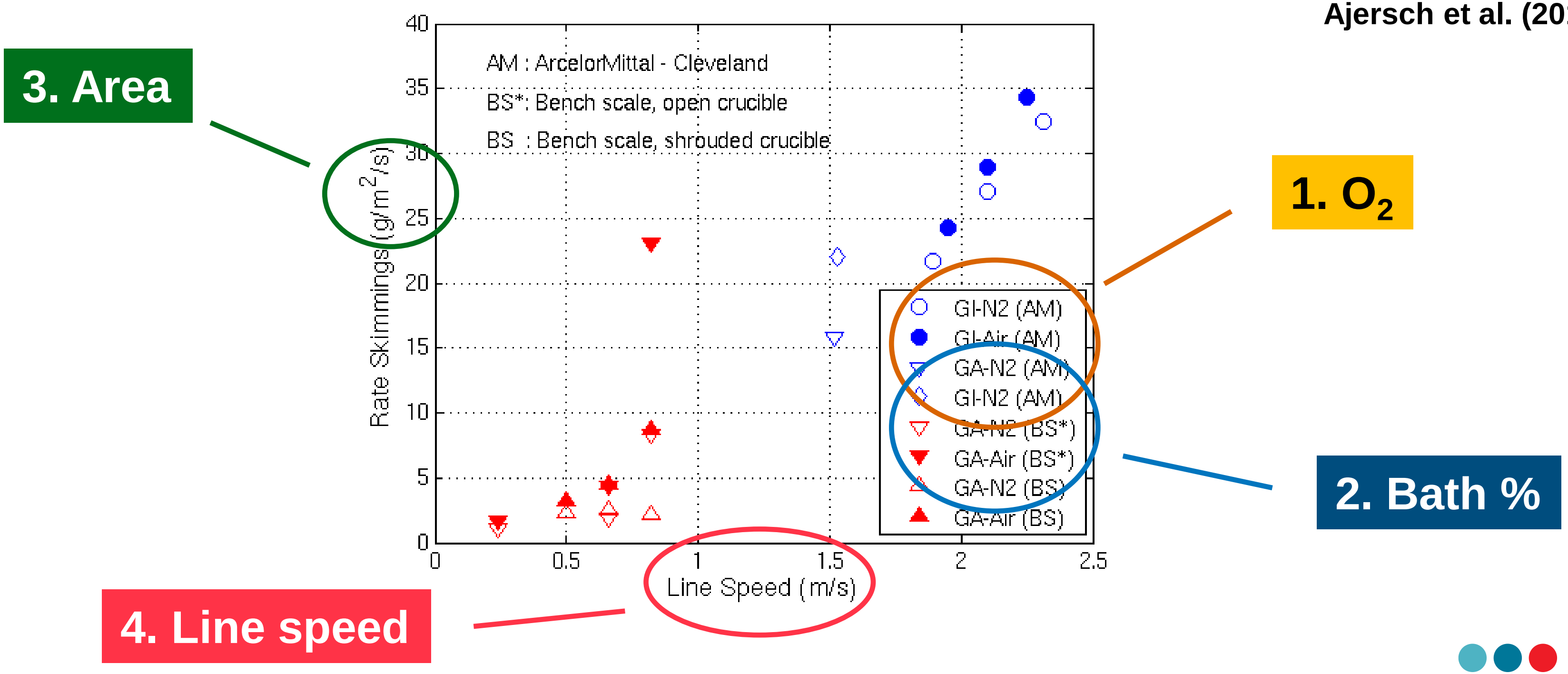
Bubbling gas (air / N_2) into liquid zinc alloy for 20 min.



Key factors from the bench scale experiment

Effect of gas jet not explicitly considered, but the adjusted skimming rate comparable to industrial data.

Ajersch et al. (2011)



1. O_2 concentration: “reaction-kinetics” formula

Skimming considered as complex Zn oxides

Reaction:

$$Zn + O_2 \longrightarrow skimming$$

Rate:

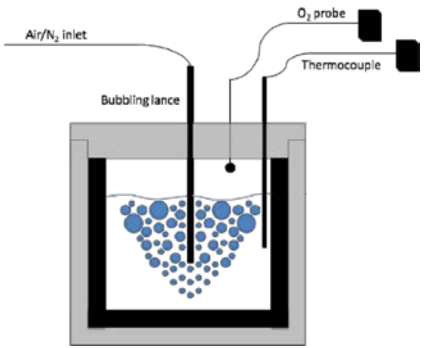
$$r = k[Zn]^0[O_2]^X$$

- Abundant in Zn at that back flow area, so assume zero-order reaction.
- Reaction constant k may consider temperature using Arrhenius equation.
- The reaction order of O_2 estimated from the Bubbling experiment.

1. O_2 concentration: O_2 reaction order

Gas (air or N_2) is bubbled into a device for 20 minutes. Skimming is then measured.

Experiment	T 10s (℃)	T 20min (℃)	O_2 20min (mol%)	Skim. (g/s)
N_2	451.67	461.17	8.81	0.242
N_2	**456.00**	**460.50**	**9.49**	***0.140***
Air	452.17	460.67	20.19	0.637
Air	456.00	460.50	19.94	0.686



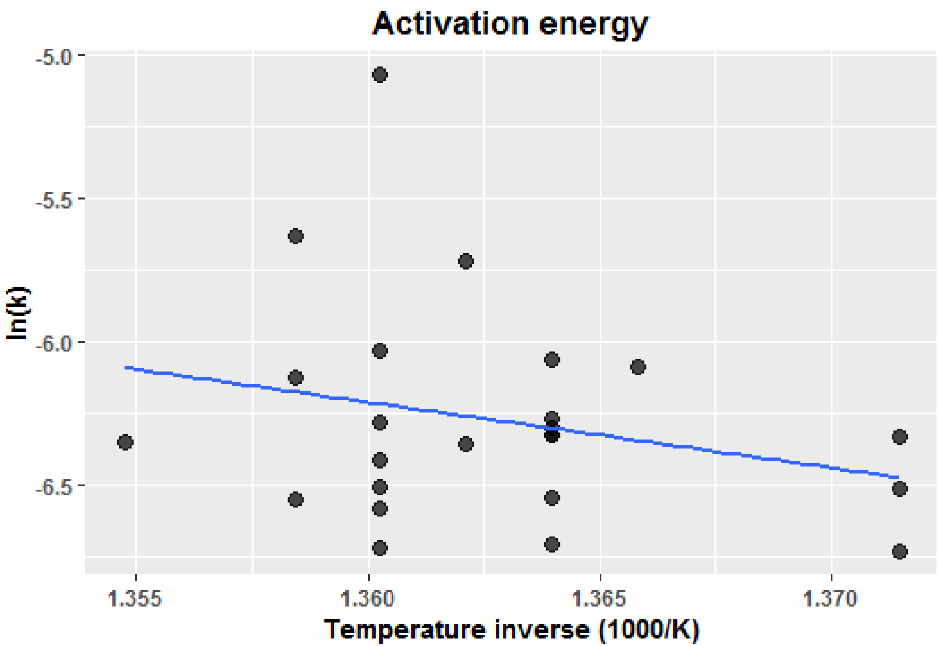
Koutsaris (2011)

$$r = k[Zn]^0[O_2]^X$$

$$X \approx 2$$

$$k \approx 1.5\, e^{-3}\, \frac{1}{mol/L \cdot s}$$

1. O_2 concentration: temperature dependency



$$r = k[Zn]^0[O_2]^2$$

$$k = Ae^{-\frac{E_a}{RT}}; \quad R = 8.314\,\frac{J}{mol \cdot K}$$

$$A = 0.12\,e^9\,\frac{1}{mol/L \cdot s} \qquad E_a = 189.9\,\frac{kJ}{mol}$$

Not very nice fit: $r^2 = 0.065$

Possible cause:

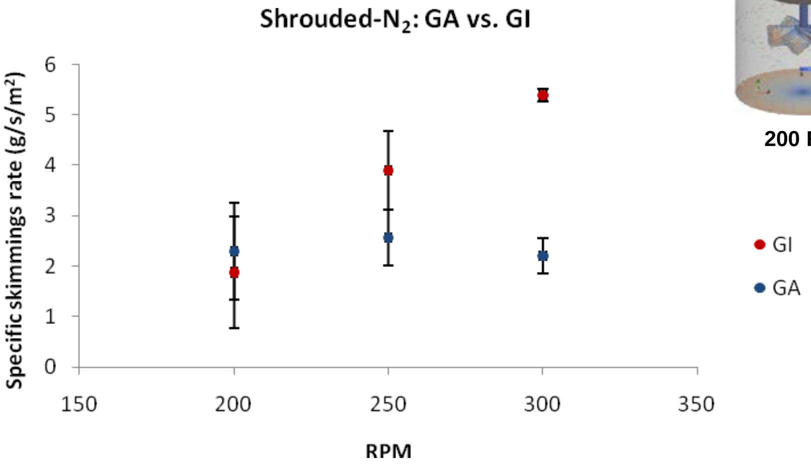
1. Measurement noise
2. Narrow temperature range
3. Temperature not constant during test

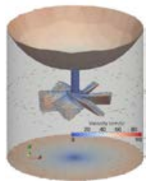
Better keep temperature constant for now

2. Bath composition %

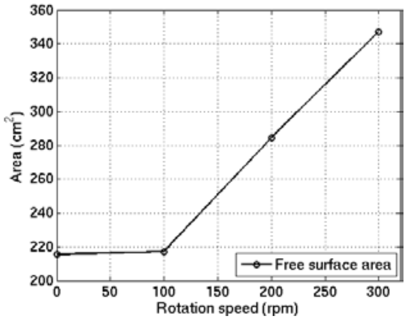
Reports that GI skimming > GA; Fe_2Al_5 acts like a catalyst, ↓ E_a

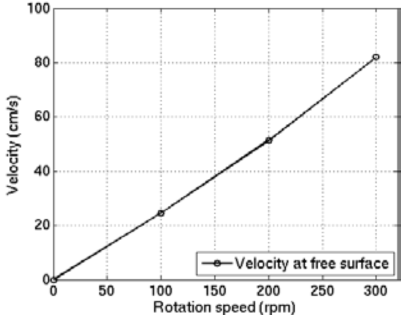
Koutsaris (2011): Stirring experiment
Top dross + oxides help to stabilize the skimming





200 RPM





Modeling such effect is not trivial:

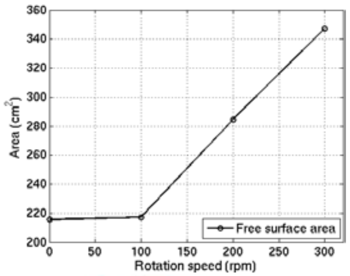
1. High uncertainties
2. Narrow RPM (line speed) range ⇒ ↑ Sensitivity
3. Large variance but sample size is small
   open air: $GA_{@300RPM}$ $(23.1\ g/s/m^2)$ > GI $(< \sim 18\ g/s/m^2)$

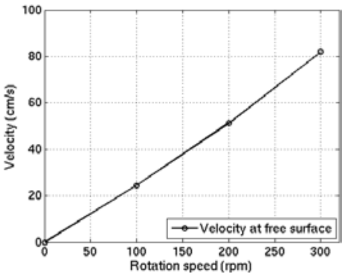
Assume: GI = 1.5 GA

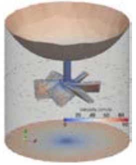
Based only on the industrial data in the report

Need more data to model this effect

3. + 4. Reactive area and Line speed



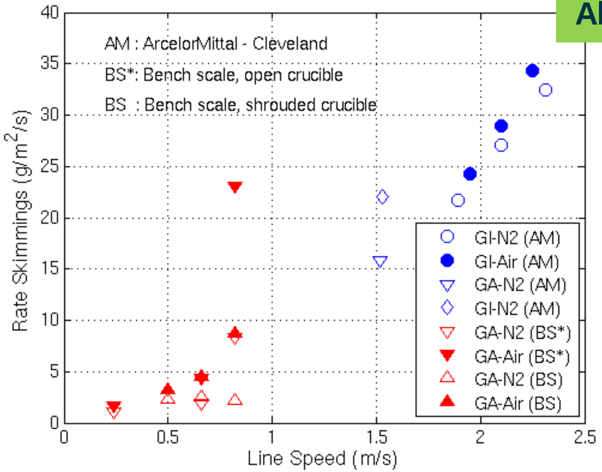


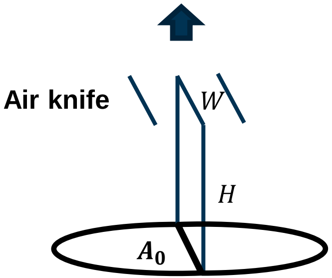


200 RPM

Note: the skimming unit here is different from Dubois (2004)

Almost linear (slightly quadratic)





$$A_0 = 2(H \times W) + \pi(0.5W)^2$$

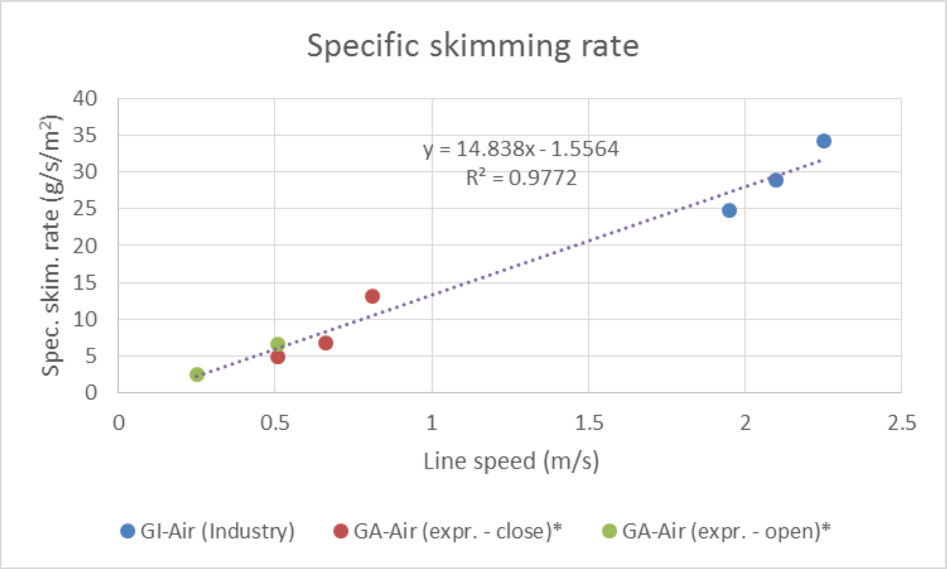
Dubois (2004)	Ajersch et al. (2011)
$\dfrac{skimming}{total\ coated\ area}$	$\dfrac{skimming}{time \times active\ area}$
$= \dfrac{skimming}{time \times width \times line.speed}$	$= \dfrac{skimming}{time \times width \times nozzle.height}$

In practice, $LS \propto H$ to avoid splashing, they differs only by a time constant

In comparison, the expression of Ajersch can be adapted to other condition more easily.

Specific skimming formation rate

Fitting for specific 'GI' skimming rate for air



Data from stirring experiment + industrial data (air)

Values of stirring experiment (GA) is increased 50%

$$\dot{s} = (14.84\, LS - 1.56)\frac{{O_l}^2}{21^2} f_B$$

Oxygen level O_l : $\{0 - 100\%\}$

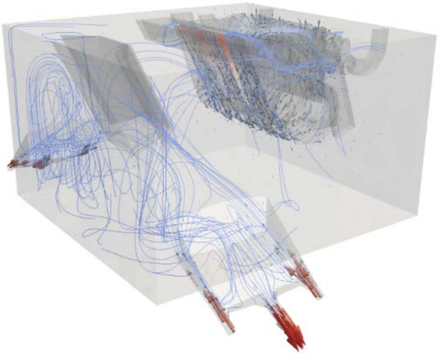
Factor Bath % GI: $f_B = 1$ and GA: $f_B = 0.67$

Expression is configuration independent

Future work for skimming model

Improvements

1. Validation data: experiment and industry
2. Effect of temperature
3. Effect of bath composition
4. Consideration of gas jet pressure



Each potentially important factor from the industrial settings could be made generic using a comparable bench scale experiment.

To be coupled with the gas jet wiping numerical model

Summary

Outline a systematic approach potentially viable to advance the fundamental understanding of skimming generation for CGL lines.

A simple phenomenological model, inspired from reaction kinetics, is elaborated in more details based on bench scale experiment results.

Next, the model will be coupled in numerical simulation to predict the skimming formation characteristics.

ZM BATH DROSS FORMATION

Effect of pot hardware configuration changes

Numerical model for galvanizing bath

Aim to analyze the overall dross formation pattern (typical 250 ton bath)

Governing equations

- Zinc (incompressible): Navier-Stokes (RANS) + energy equations
- [Fe], [Al] concentration: convection-diffusion equations

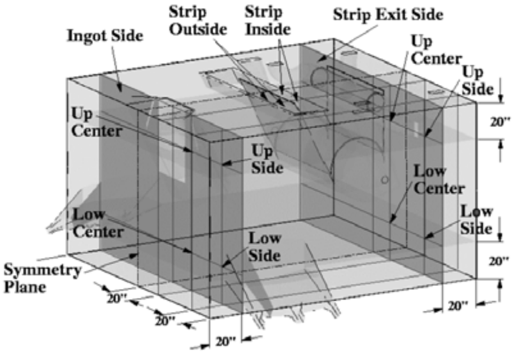
Boundary condition

- [Fe] dissolution from strip + [Al] uptake by strip and ingot melting
- Heat exchange: strip, inductor, side wall, ambient on the top
- Strip speed $1.75\ m/s$ with temperature $460℃$

Initial condition

T_{bath} = $460℃$, Saturated in [Fe]

Location	Name	X (in / mm)	Y (in / mm)	Z (in / mm)
Ingot Side	Up Center	-61 / -1549	-20 / -508	20 / 508
	Up Side	-61 / -1549	-20 / -508	55 / 1397
	Low Center	-61 / -1549	-76 / -1930	20 / 508
	Low Side	-61 / -1549	-76 / -1930	55 / 1397
Strip Exit Side	Up Center	61 / 1549	-20 / -508	20 / 508
	Up Side	61 / 1549	-20 / -508	55 / 1397
	Low Center	61 / 1549	-76 / -1930	20 / 508
	Low Side	61 / 1549	-76 / -1930	55 / 1397
Snout region	Inside center	2 / 50	-6 / -150	6 / 150
	Inside Extremity	2 / 50	-6 / -150	25 / 635
	Outside center	-3 / -75	-6 / -150	6 / 150
	Outside Extremity	-3 / -75	-6 / -150	25 / 635



Dross formation: based on Fe solubility limit
function of local solute concentration and temperature

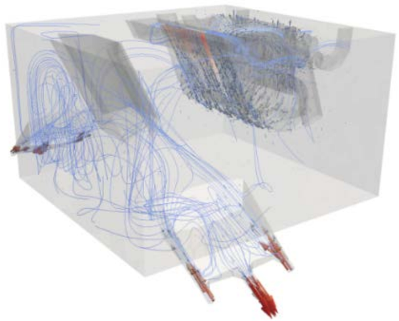
Pot hardware configuration studies

- Two hours period covering two 1 hour cycles
- Cycle: 20 minutes at high power (ingot melting),
  40 minutes at low power
- Ingots composition is 0.5% Al

Al: 1 – 3 wt%

Mg: 1 – 2 wt%

Dross: Fe_4Al_{13}



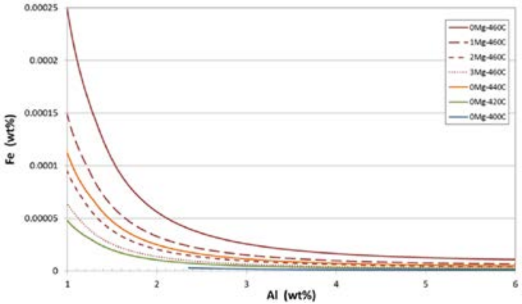
1. Case A: Base configuration
2. Case A.1: Al concentration in ingot 0%
3. Case A.2: Al concentration in ingot 1%
4. Case A.4: Bath with 0.1% Al and saturated with Fe
5. Case A.5: Bath with 0.2% Al and saturated with Fe
6. Case A.6: Strip entry temperature 420C
7. Case A.7: Strip deposition rate 100g/m^2
8. Case B.1: 100 ton bath
9. Case B.2: 500 ton bath
10. Case C: Side ingot charging
11. Case D.1: Gradual ingot charging at bath center
12. Case D.2: Gradual ingot charging at bath side
13. Case E: Front-back inductors
14. Case F.1: 30'' sink roll depth
15. Case F.2: Asymmetric hardware
16. Case G.1: Smaller snout size
17. Case G.2: Deeper snout

Dross formation model

Special thanks to Daniel Liu (Tech Metals Ltd.)

1. Zn-Al-Mg-Fe phase diagram (Al 1-3 wt%, Mg 1-2 wt%)

✓ An exponential-decay-like curve or look up table



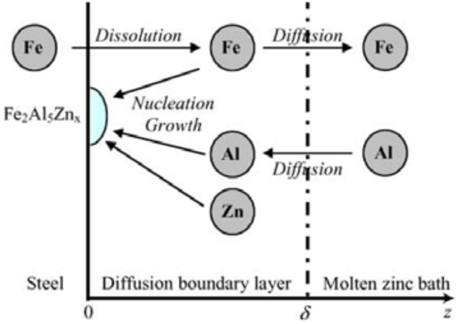
2. Averaged Fe dissolution + Al uptake rates

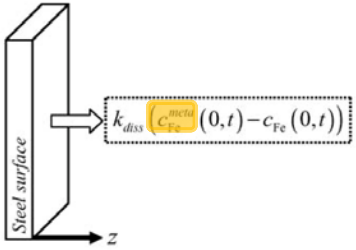
$$D_{\mathrm{Fe}}^{\mathrm{Zn(L)}} \frac{\partial^2 c_{\mathrm{Fe}}}{\partial z^2} = \frac{\partial c_{\mathrm{Fe}}}{\partial t}$$

$$D_{\mathrm{Al}}^{\mathrm{Zn(L)}} \frac{\partial^2 c_{\mathrm{Al}}}{\partial z^2} = \frac{\partial c_{\mathrm{Al}}}{\partial t}$$

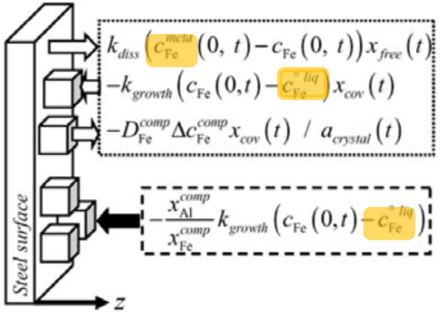
$$I = \frac{k_{nucl}}{\eta} \exp\left(-\frac{\Delta G^*}{k_B T}\right)$$

- Adapting the model of Giorgi et al. (2005) on interfacial reactions between solid Fe and liquid Zn-Al alloy

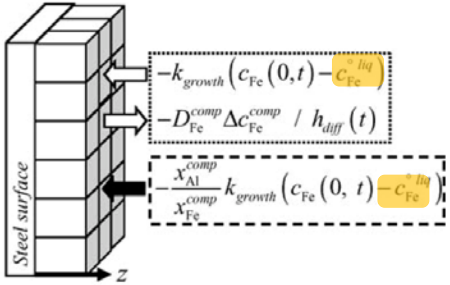




a) Dissolution of iron



b) Lateral growth of $Fe_2Al_5Zn_x$

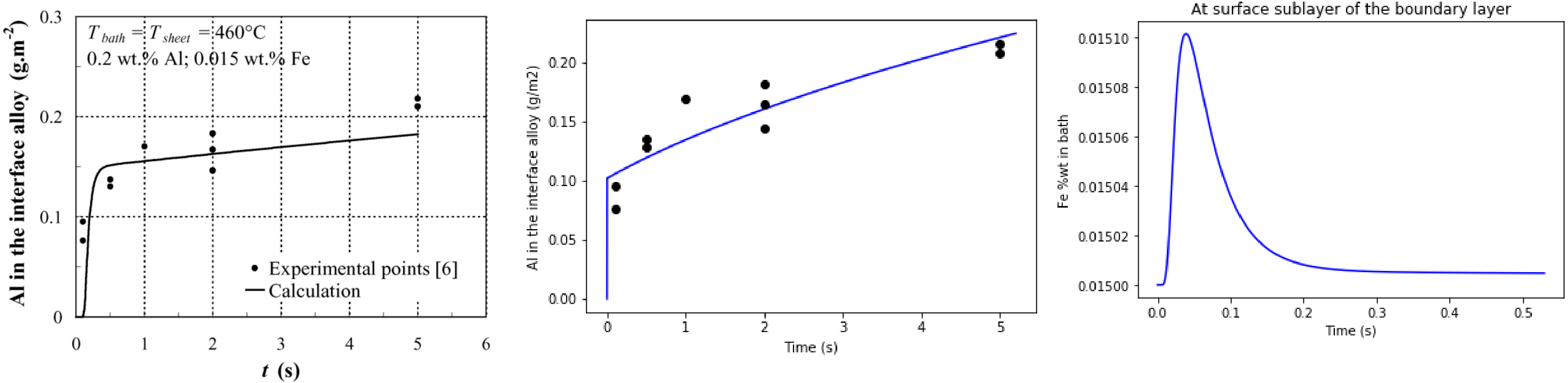


c) Uniform growth of $Fe_2Al_5Zn_x$

Giorgi et al. (2005)

Model of interfacial reaction

Solved with finite difference method; validate using coefficients (except C_{meta}) from Giorgi et al. (2005)



Overall, good agreement in Al content in interface alloy

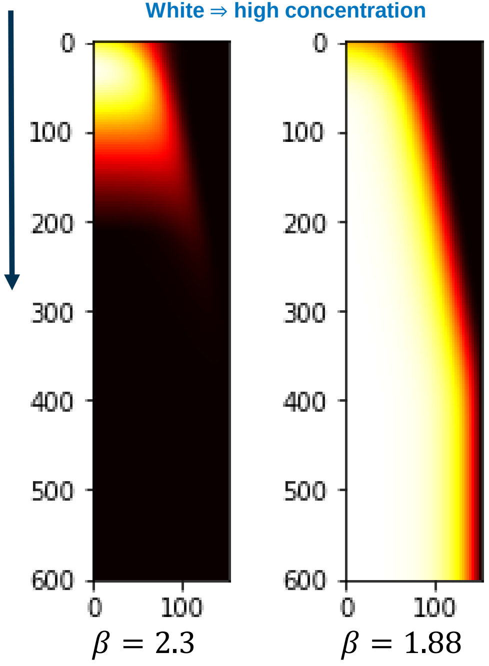
Main reaction takes place in about 0.2s

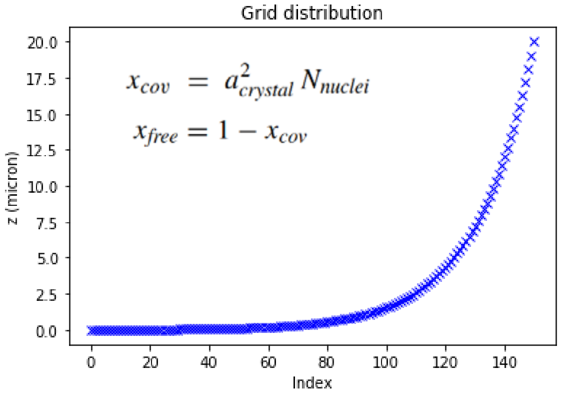
Experiment by Toussaint (1997)

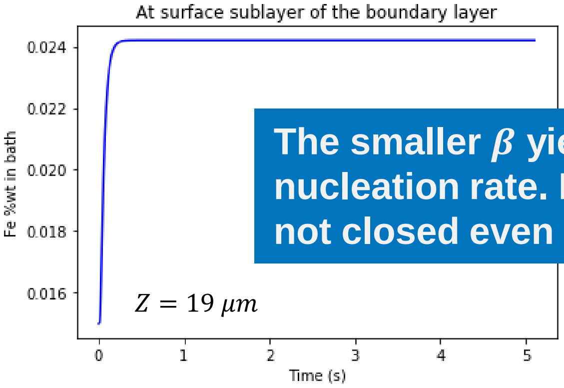
Model of interfacial reaction

Model very sensitive with the degree of supersaturation β

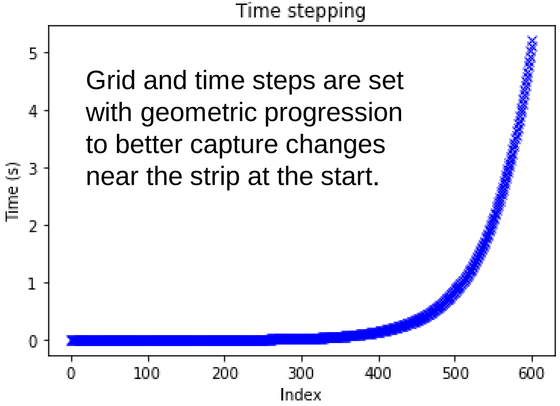
Area not proportional



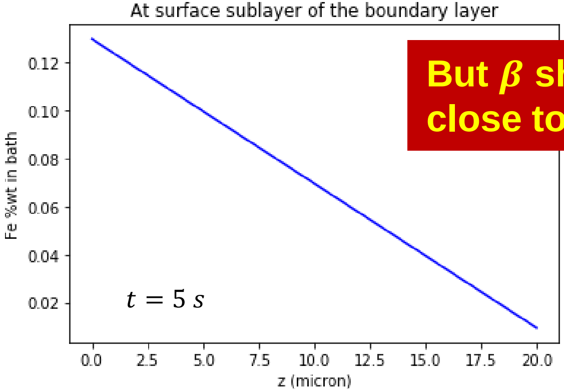




The smaller β yields slow nucleation rate. First layer not closed even after 5s



Grid and time steps are set with geometric progression to better capture changes near the strip at the start.



But β should be close to 1.88

Summary

Overview the approach to study the pot hardware configurations

Implemented the Fe solubility limit curve for the relevant operation window

Implementing the mathematical model of Giorgi et al. (2005) for the prediction of the rates of Fe dissolution and Al uptake

Acknowledgement

Zinc ...essential for life

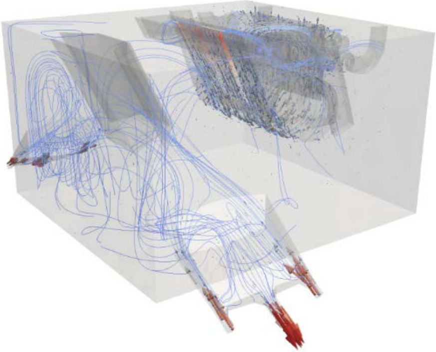
international zinc association

Sponsors of the Galvanized Autobody Partnership program

Canada

NRC·CNRC

Advanced Manufacturing Program of NRC



THANK YOU

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