ZCO-77: Dross Minimization in Galvanizing Bath

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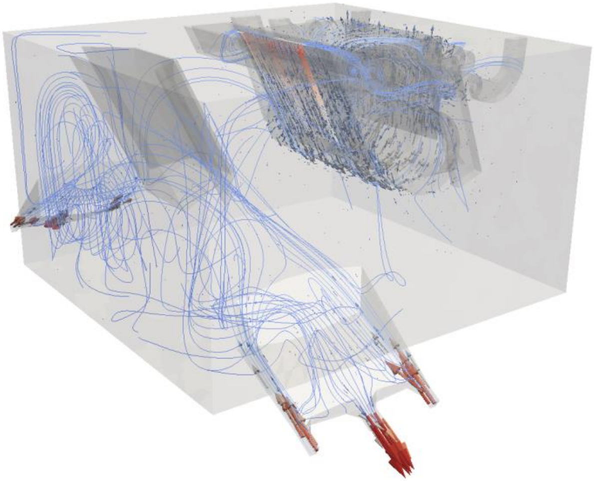
1. Goal and Objectives
2. Wiping gas jet model
3. Skimming generation phenomenological model
4. ZnAlMg dross formation model

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 ZnAlMg coatings.



WIPING GAS JET MODEL

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

The gas jet wiping process is the primarily method for zinc coating thickness control for CGL

For high quality coating:

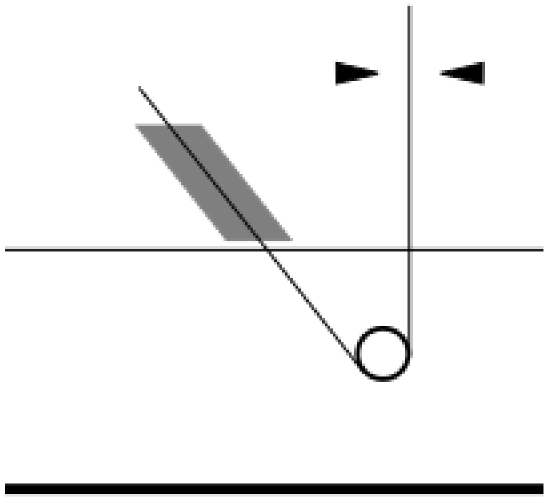
Stability + Uniformity

Advantages:

Safe, Efficient, Economical to operate

Challenges:

- Sensitivity of nozzle to strip
- Splashing phenomenon
- **Skimming** formation (**$$**)



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

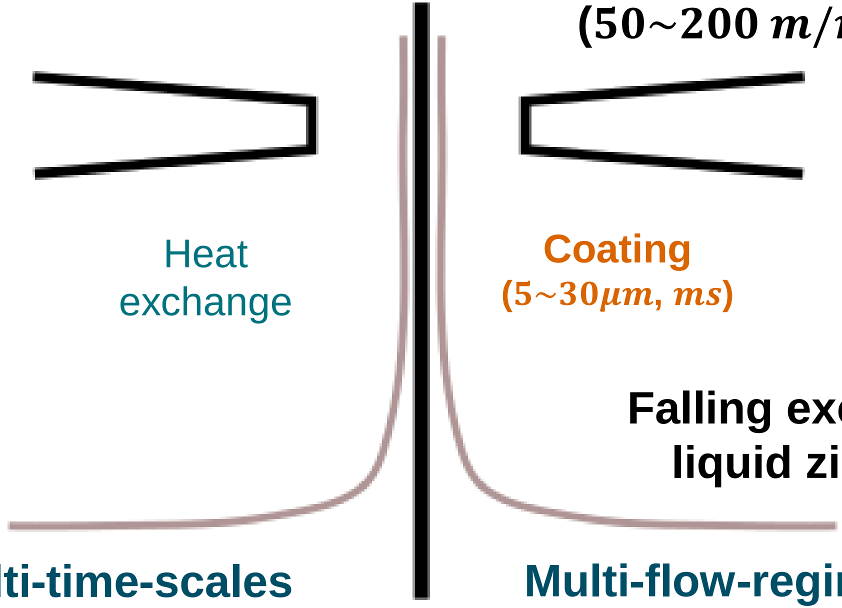
Impinging gas jet from the air-knife

Moving steel strip at high speed ($50\sim200\ m/min$)

High velocity gas flow

Sheet stability

Interaction gas-liquid-solid



Flow of falling zinc

Formation of skimming

Characteristics

Mechanism

Falling excess liquid zinc

Flow of zinc near surface

Multi-time-scales

Multi-flow-regimes

Bath $(m,\ s)$

Multi-length-scales

Multi-phases

Numerical model is useful to gain deeper insights of complex physical phenomena

Non trivial to balance Model complexity vs. Cost

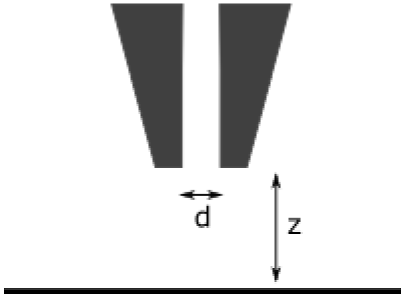
Objective: to model the KEY physical phenomena for top skimming study (3D), being accurate and efficient

Very effective to approach studies in a step-by-step manner

Findings from literatures suggest that the wiping gas jet flow fields and the adhered liquid zinc profile near the bath surface are not very strongly coupled

Air knife ⇔ Liquid zinc film ⇔ Zinc bath surface

Wiping jet gas model



Efficiency of the wiping process

$\Leftarrow$ Pressure + Shear Stress Distribution

$\Leftarrow$ Geometry, Stand-off distance z/d, Angle, Inlet conditions

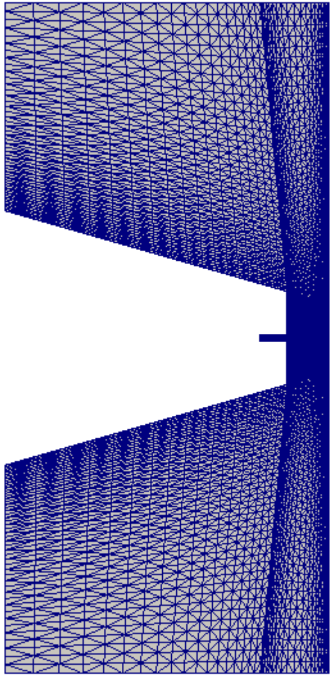
Compressible subsonic flow ($Ma > 0.3$)

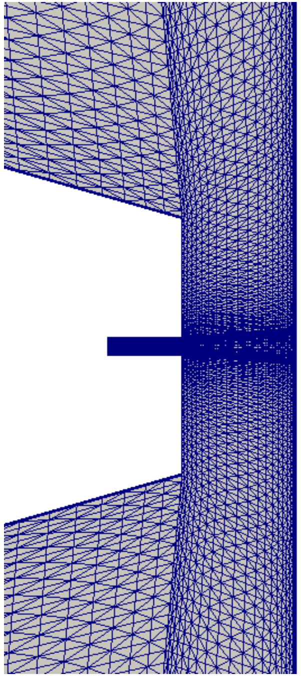
In-house FEM incompressible flow solver is extended for compressible flow, providing possibility to improve the solver-coupling efficiency

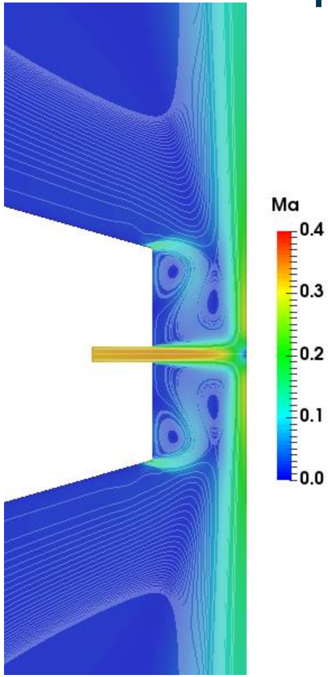
Numerical results are validated using the experimental values Alibeigi (2013)

$$\boldsymbol{Re = 11000; \quad Ma = 0.33; \; V = 113\, m/s; \quad z/d = 6}$$

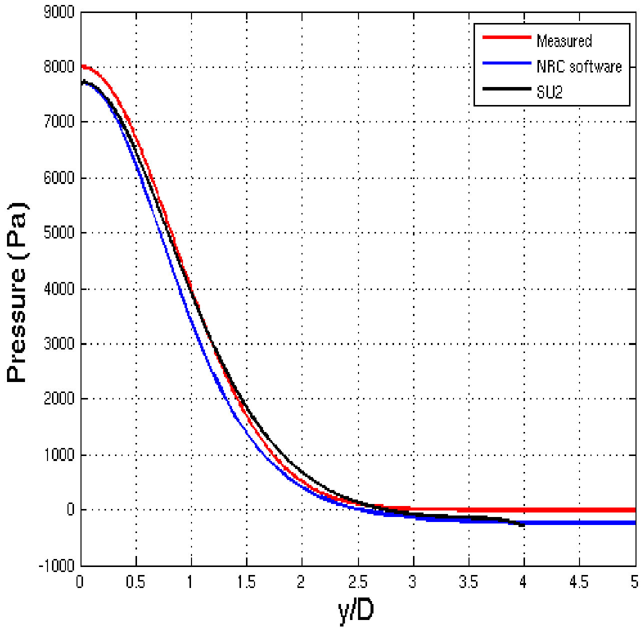
The in-house FEM compressible solver are in good agreement with the experiment & previous SU2 results.







much easier + faster to couple solvers from the same framework



 # Node: 33,480; # Elem: 128,640

How strong is the coupling between the gas jet flow field and the liquid zinc coating?

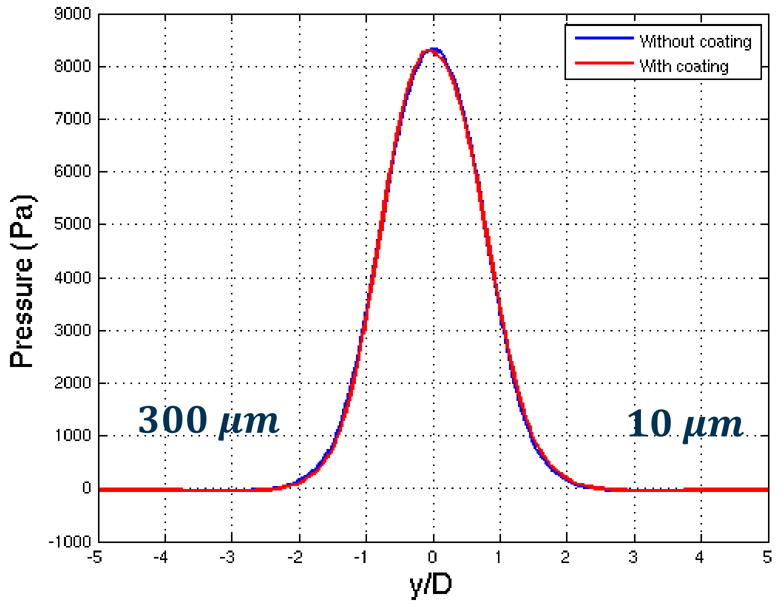
The level of interaction determines if the two domains can be treated as weakly coupled.

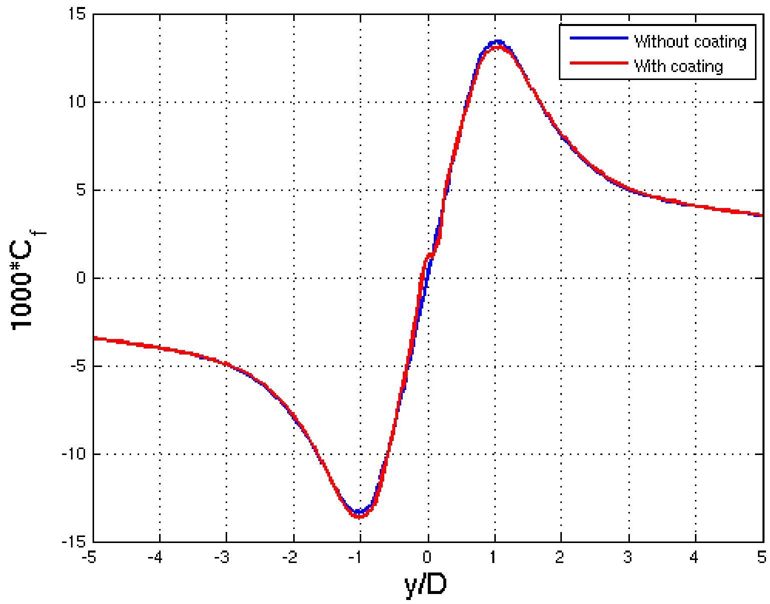
Two particular factors are considered:

1. Presence of the zinc coating,
2. Influence of the moving strip.

The gas jet impinges on a flat static surface will be used as benchmarking condition.

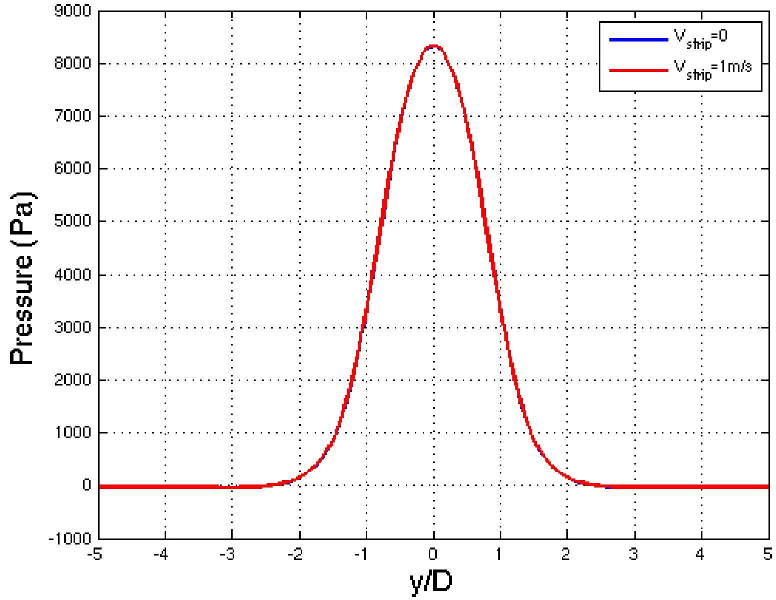
The presence of the liquid zinc film on the steel strip does not induce strong differences

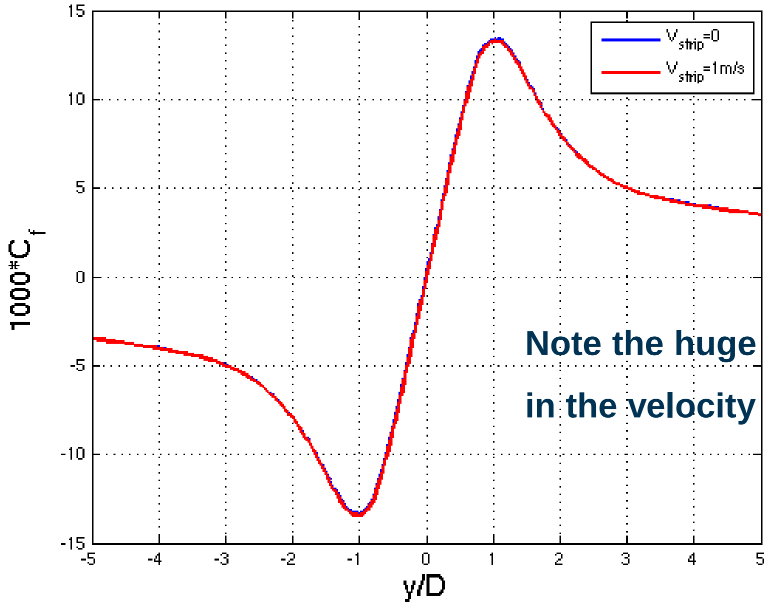




Only a small feedback is exerted from the liquid zinc film onto the gas flow.

Essentially, no feedback difference is observed for the case of the moving the steel strip at 1 m/s.





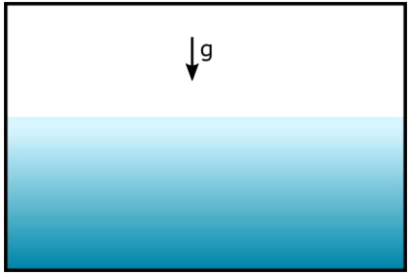
Note the huge difference in the velocity $O(\sim 100)$

The interaction is practically unidirectional from the gas field to the liquid zinc.

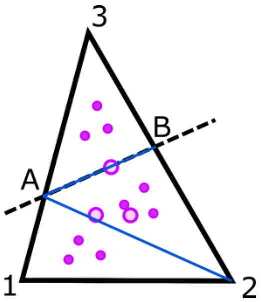
Thus, it is acceptable to employ the proposed weak coupling scheme.

Modeling the liquid zinc film requires a numerical scheme capable to describe free surface flow.

Overview



- Liquid and gas: incompressible
- Solved in parallel using in-house FEM solver
- Free surface tracking: Explicit level-set approach
- Method of discontinuous pressure enrichment is employed to resolve the challenge of discontinuous density and pressure



New development

- Improve force coupling (**pressure** + **shear**) on the liquid zinc with free surface
  Much improved stability is achieved
- Treatment of elements with high aspect ratio (300) are implemented.
  Needed due to a large difference in length scale (μm vs. m)
- For a 3D mesh, it saves about $300 \times 20 \times 10$ elements per cm of sheet length.
  So, for a sheet-length of 60cm, about $3{,}600{,}000$ elements are saved.

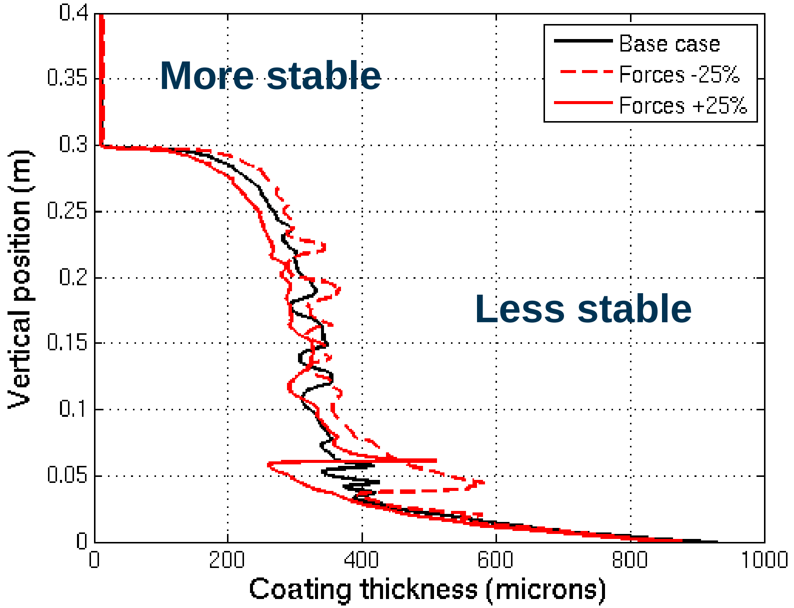
To minimize the coating thickness, one may consider $\Uparrow F_{air\text{-}knife}$, $\Downarrow V_{strip}$ and to some extends $\Uparrow T_{bath\text{-}zinc}$.

Case			Average coating thickness (μm)		Relative thickness to the Base (%)	
			$\Downarrow$	$\Uparrow$	$\Downarrow$	$\Uparrow$
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**

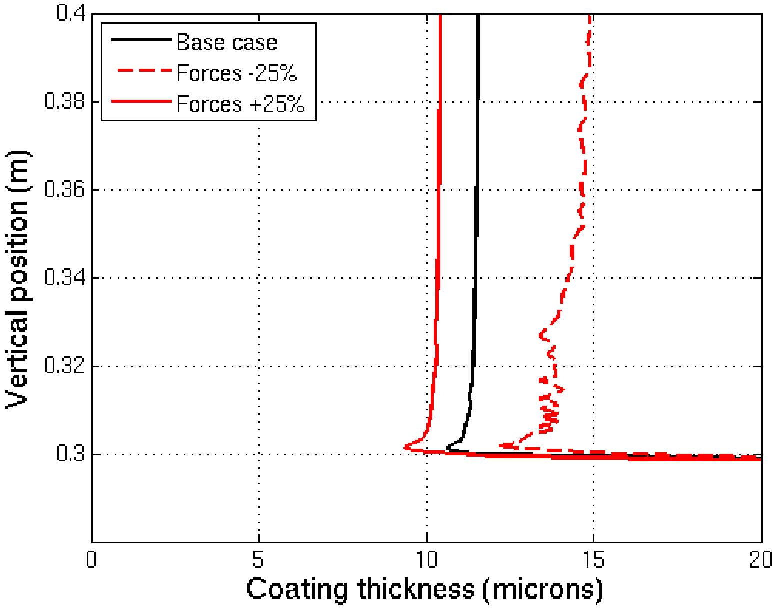
Linear response; *Non-linear response*

The wavy free surface below the air-knife jet greatly augments the contact area, promoting oxides formation.

Non-linear response



Overview

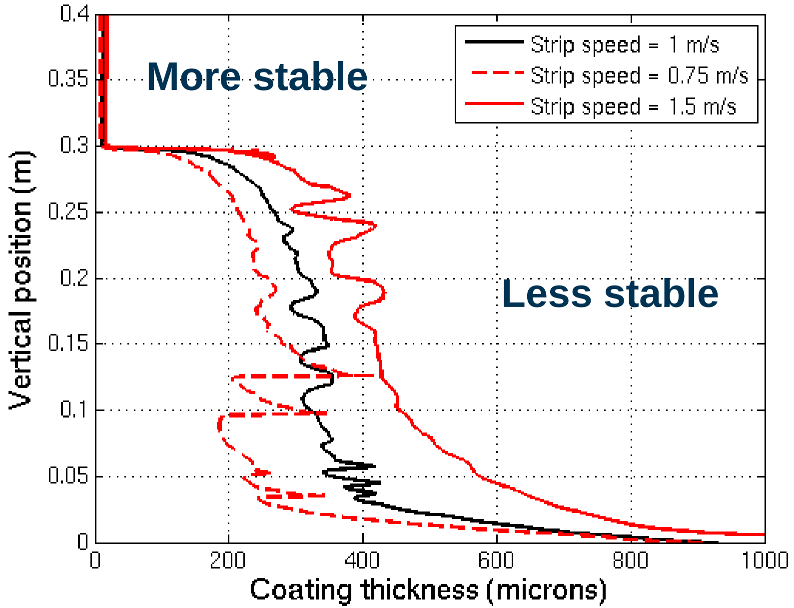


Zoom

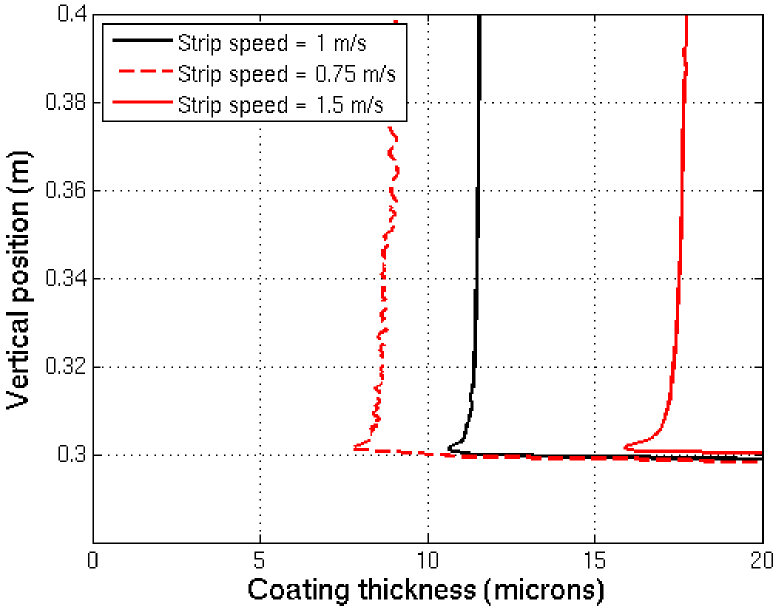
Note: Shear force and strip movement are different below and above the nozzle.

The wavy free surface below the air-knife jet greatly augments the contact area, promoting oxides formation.

Linear response

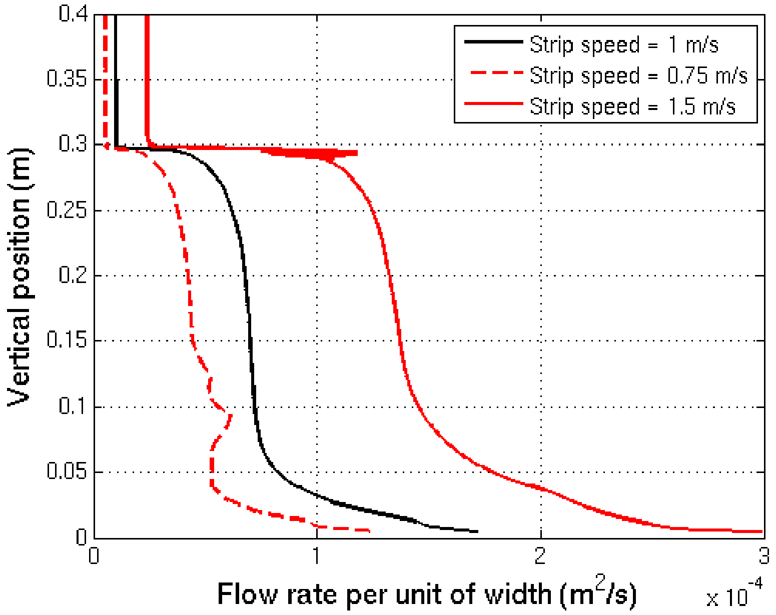


Overview

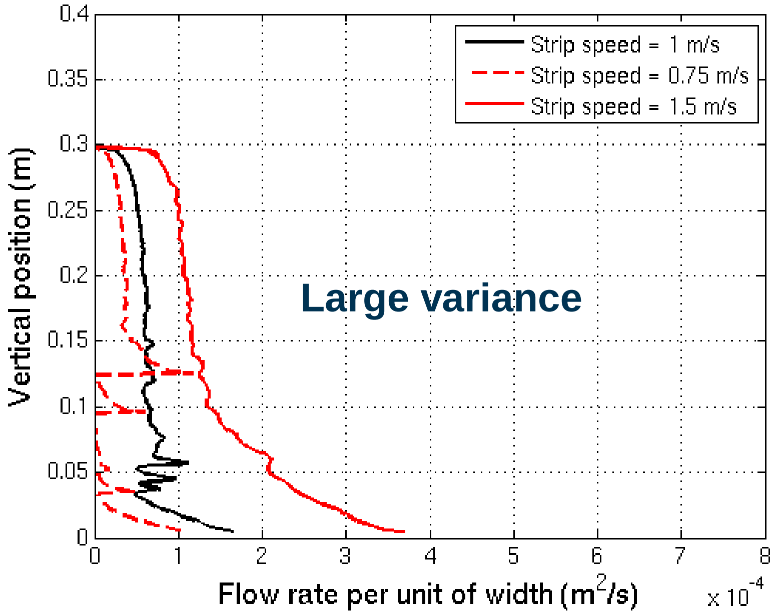


Zoom

The overall vertical flow pattern provides some hints of the shearing from the moving strip and the gas flow.



Upward flow



Downward flow

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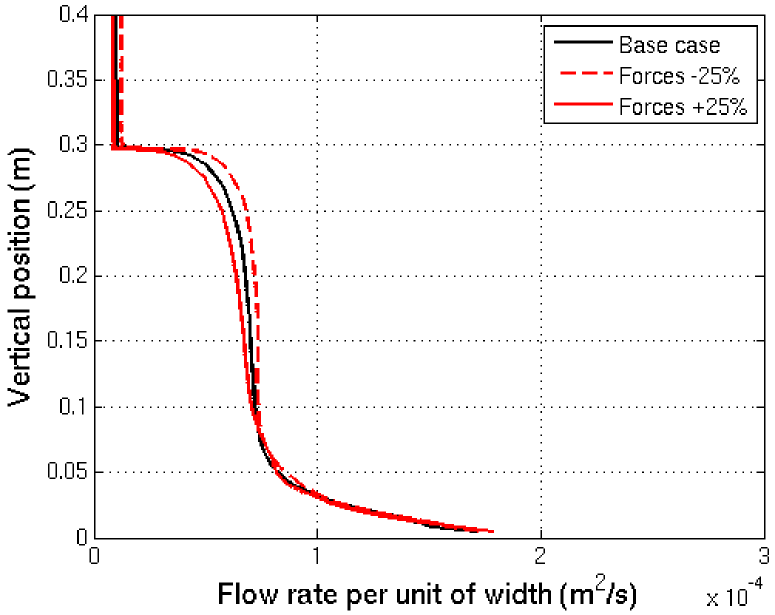

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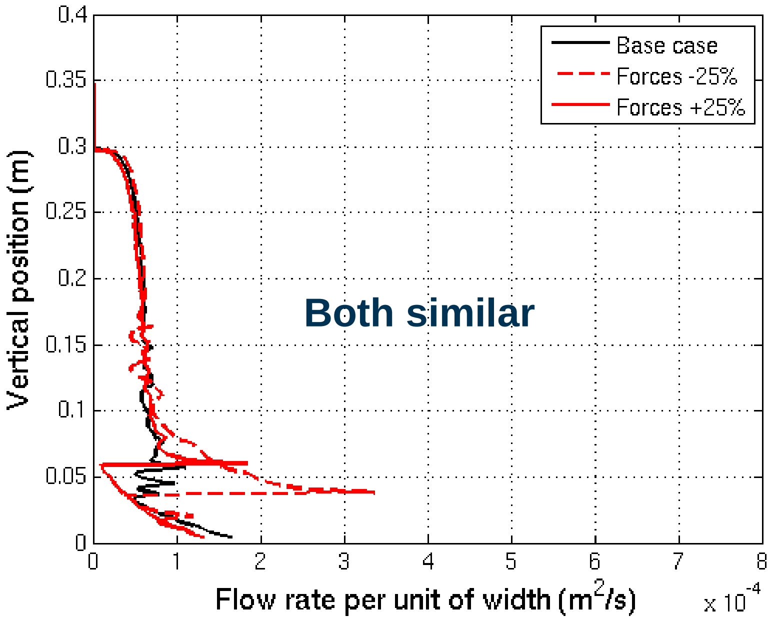

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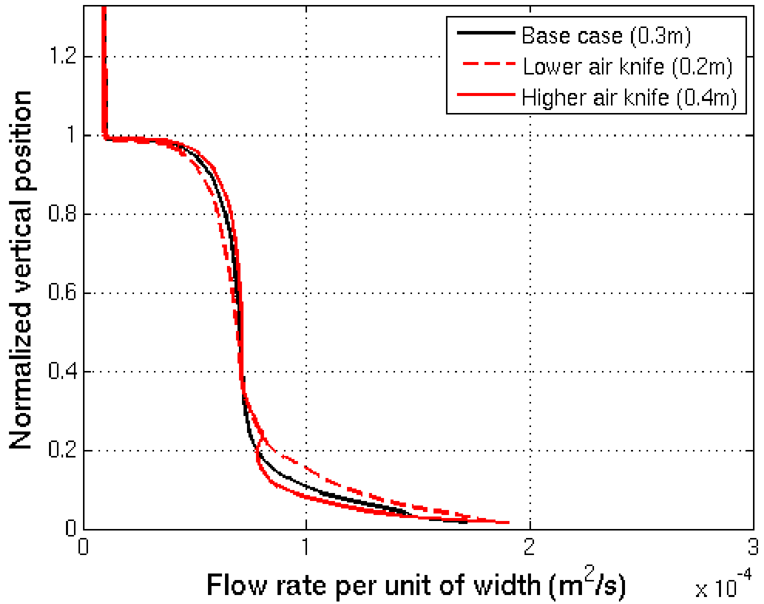
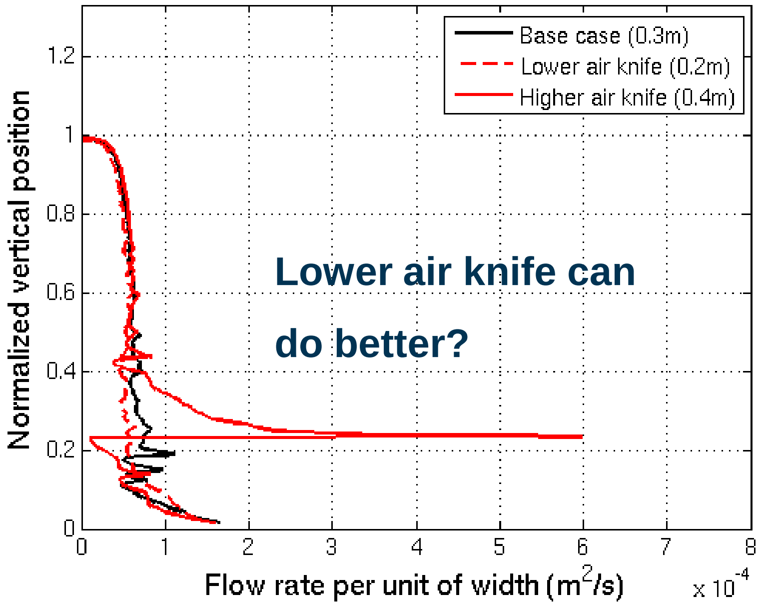


Upward flow



Downward flow

Summary

Previous results confirm that the presence of the zinc coating and the moving strip only have minor feedback onto the gas jet flow field, thus weakly coupled.

Recent developments (compressible and free surface flow solvers) greatly enhance the efficiency of the gas jet wiping model for the investigation of skimming formation.

Sensitivity analyses reveal that certain parameters influence the coating thickness more effectively than the others. Some behaves nonlinearly.

Development and results published in AISTech 2019

The model would 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

Dross skimming generation

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)

Scum / top skimming is a “mushy” foam containing metallic Zn, Zn and Al oxides and porosities in a close mixture.

Skimming increases linearly with **Line speed** and **Wiping Pressure**.

There are conflicted findings on certain parameters (e.g. Sheet width).

Literature review

Goodwin and Dubois (2012)

- Skimming is a foamy oxide-metal mixture.
- The oxide content is not high.
- The foam may be formed under the nozzle, in the back flow or on the pot surface.
- The formation rate is not strongly reduced by using N2.
- The key factors include: line speed, coating thickness and type.
- Higher gas flow is believed to induce higher skimming productions.

Dubois (2004)

- studied the production of skimmings for a 3 month periods from 4 production lines. Could be interesting to follow the process for 6 months.

Literature review

Thiounn et al. (2008)

- Skimmings = scum + top dross + liquid bath
- Scum and Skimmings do not have big differences composition:
  96-98 wt% Zn, 0.02-1.0 wt% Fe, 0.4-1.0 wt% Al, 0.5-2.0 wt% O
- Density of Scum ≈ 5.5 < 7.1 g/ml for Zn ⇒ Float and Solidify!
- Porosity (2D): Scum ≈ 30%, Skimmings ≈ 50%. The porosity size also seems to be larger for skimmings than scums.
- Statistical analysis suggests:

$$\uparrow \boldsymbol{Scum} \propto \uparrow \boldsymbol{Speed} + \uparrow \boldsymbol{Pressure} + \uparrow \boldsymbol{Width} + \downarrow \boldsymbol{Nozzle\ Height}$$

- With all factors kept constant, rate of scum formation is linear in time.
- Also agree that the scum is created at around the exiting strip area under the influences of the air-knife jet flow.

Literature review

Strutzenberger and Pree (2012)

- Scum is a “mushy” foam containing metallic Zn, Zn and Al oxides and porosities in a close mixture.
- It is created around the exiting strip caused by the interaction of the gas jet from the wiping nozzles with the liquid Zn along the emerging strip.
- The thickness of the scum layer increase approximately linearly from the front side of the pot towards the emerging strip.
- The formation rate increases linearly with line speed and wiping pressure. Other studied data include: the strip width, nozzle height, nozzle tilting, coating weight, and bath temperature.
- Scum sampling for 26 cases, and ~140 scum growth periods studied

Dross skimming generation

Survey

- Little published data is available, so a survey was prepared to better understand the dross and skimming production for GA, GI and ZnAlMg
- Data from **13** lines are received, and there were great variations in the data collection frequencies, qualities and practices.

Set goal → **Get data** → **Clean data** → Analyze → Report → Set next goal

Methodology

- Use statistical / data analytics / machine learning workflow
- Data are further cleaned and averaged to a minimum duration of **half a day up to a day**.
- Only **24** data points are obtained for all GA, GI and ZnAlMg conditions.

Will need more data to develop a robust generic statistical model, but probably not so easy to collect them due to the busy production schedule and the large difference in skimming practices.

A few considerations on the statistical model

Low data volume (Dimension p >> No. of records n)

Can only employ a subset of models: the Penalized Linear Regression family, to reduce / shrink the contribution of less “important” variables

Phenomenon complexity

Demands more advanced models like Random Forest, Gradient Boosting;
They need a lot more data for training and testing.

Do we really know which parameters are important? How do they appear in the equation?

Possible solution

Use **Feature Engineering** to develop useful **Interaction features** (e.g. $A_i x_1 x_2 x_3$) to consider higher order characteristics using Generalized Linear Regression.

Linear Regression Model

Assumption

1. Linear* relationship
2. Multivariate normality / Gaussian like for all variables
3. No or little multi-collinearity / Not too highly correlated with each other / Redundant information
4. No auto-correlation* / i.e. y(t+1) also depends on y(t)
5. Homoscedasticity / i.e. residuals are more or less the same across the regression line

Data

1. Need ~ 30 points **per independent variation** in the analysis, like proper Design of Experiment
2. Sensitive to outliers and large variation in feature scales
3. May need variable transformation to get more normal distribution

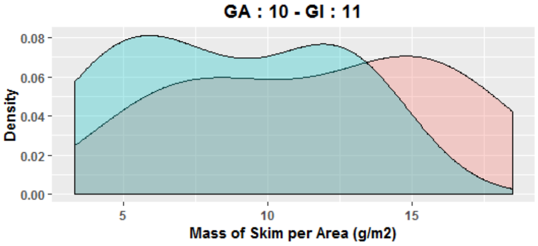
Let’s take a closer look at the data to better prepare the data collection at the later time

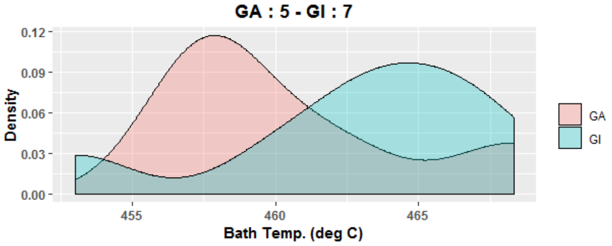
Total 24 records: from ½ day to a day duration

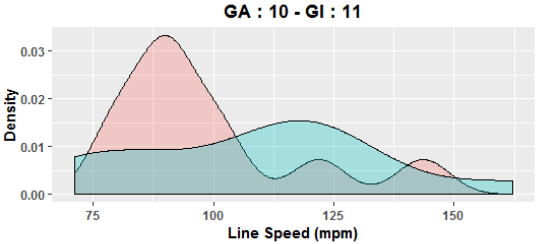
GA	GI	ZAM / ZM	NA
10	11	2	1

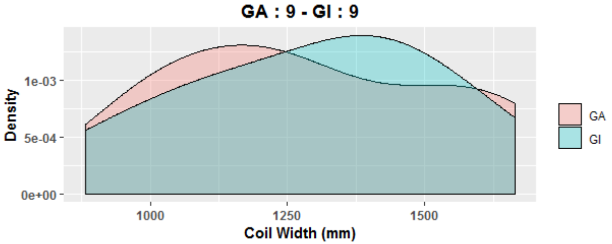
Use N_2 for Wiping			
GA: 0%	GA: 100%	GI: 0%	GI: 100%
7	3	6	3

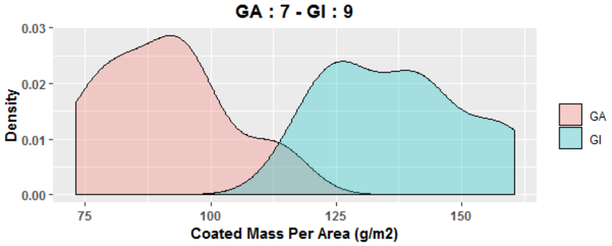
Use	Yes	No	NA
Pre-melt	5	4	15
Baffle	1	3	20
Robot	7	8	9

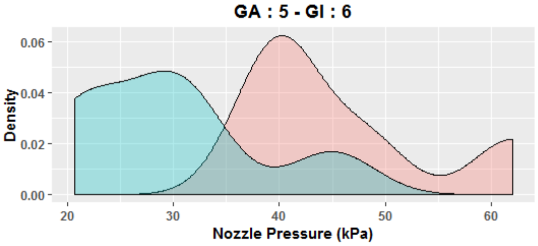


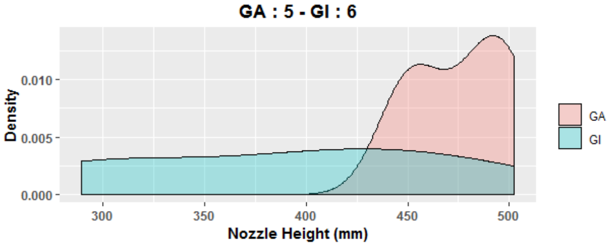




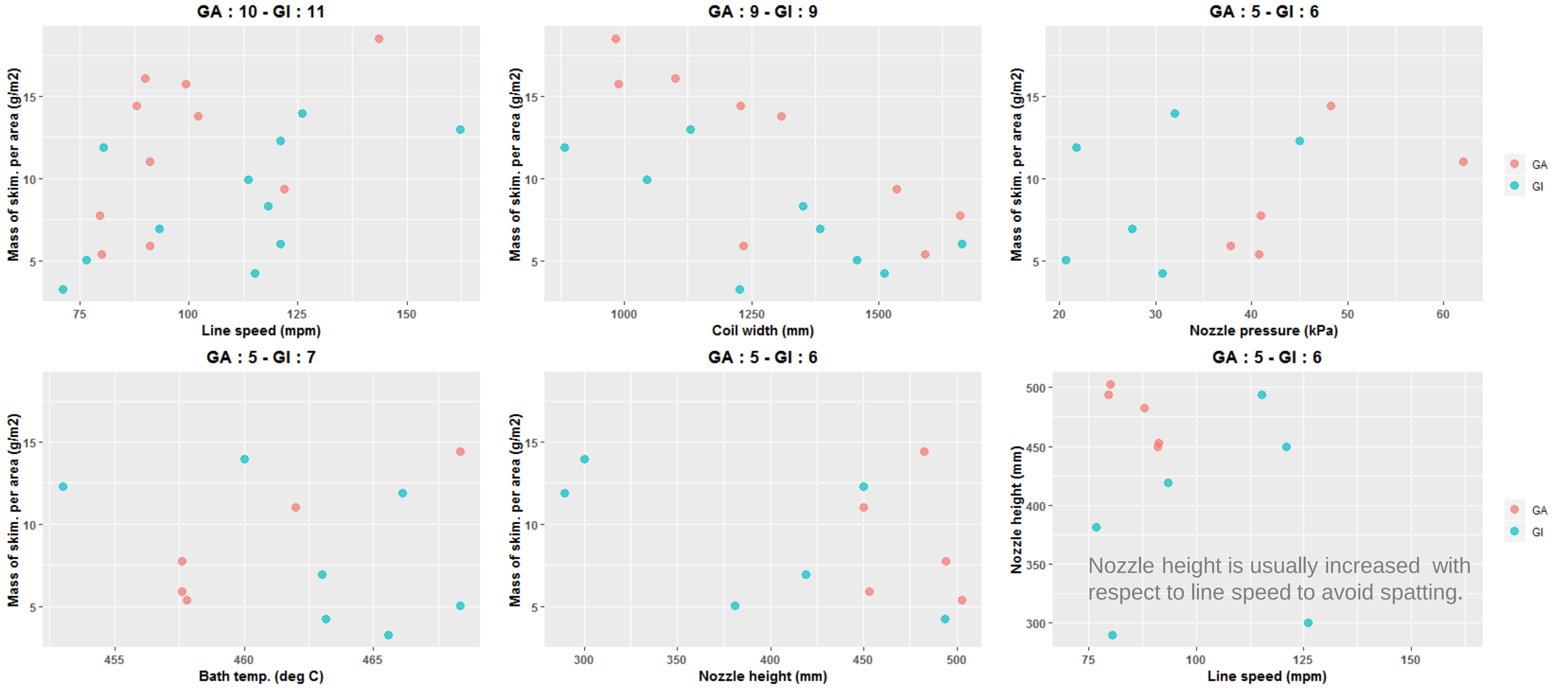




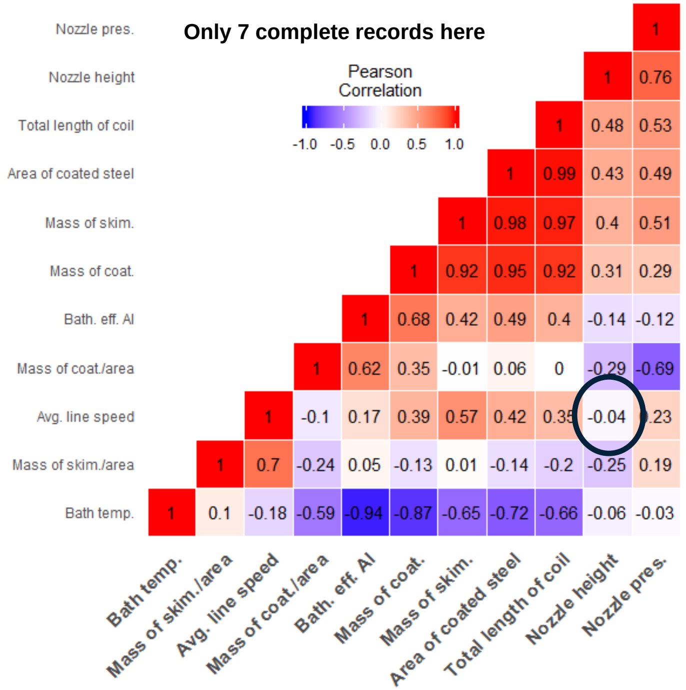


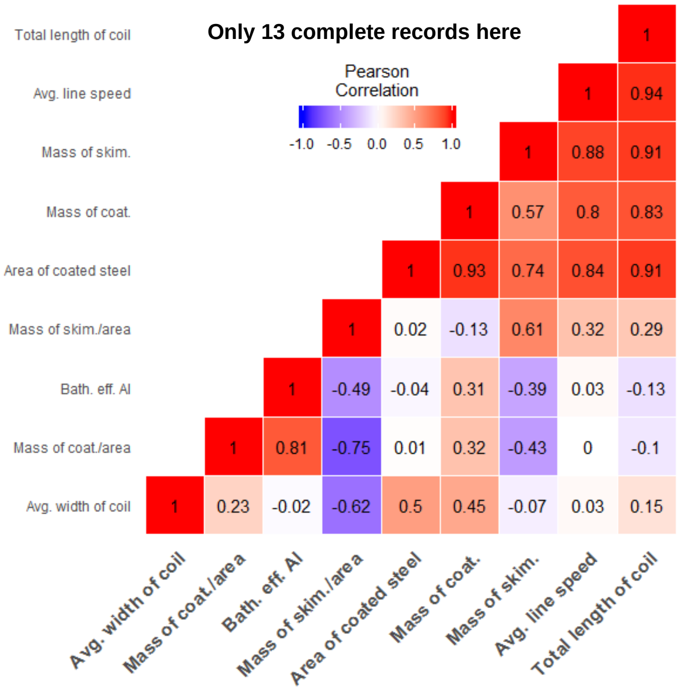


Scatter plot can be used to verify if the data pairs are “linear” and homoscedastic.



Correlation heat map of numeric fields can shows if there are multi-collinear variables

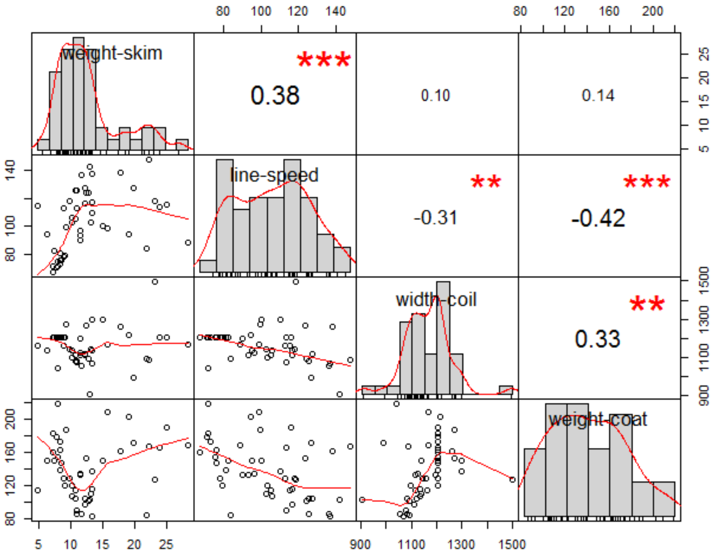


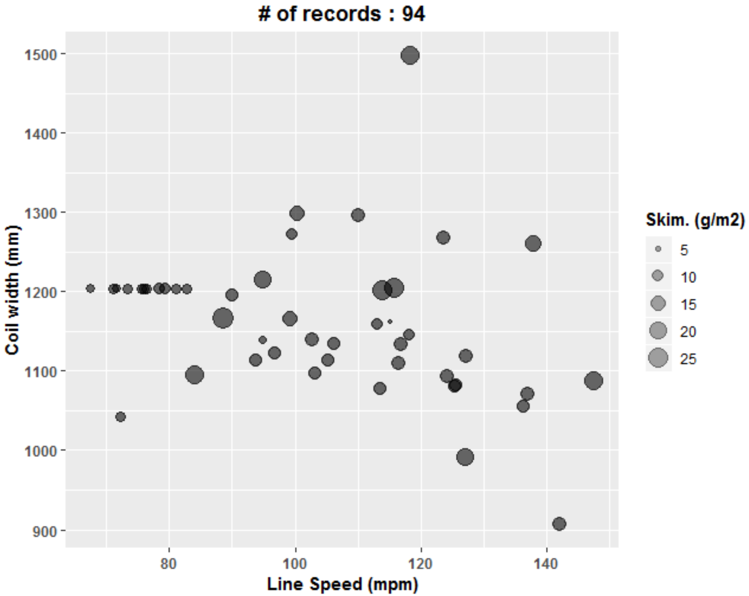


When the data set is more complete (volume and normality), should use Penalized-Linear-Regression / Stepwise methods for feature selections.

Normality is as important as the data volume

All GI here, averaged data from day to a whole month, but with less information.





Although here seems to have enough data points, the relationship is still unclear due to non-normality in the data. It may need to have designed experiments for such purpose.

Phenomenological model: reaction-kinetics-like

Reaction

$$Zn + O_2 \longrightarrow skimming$$

- Top dross ($\boldsymbol{Fe_2Al_5}$) helps like a catalyst, which lowers the activation energy.

Rate

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

- Abundant in Zn, so assume zero-order reaction
- Reaction constant k may consider temperature using Arrhenius equation.

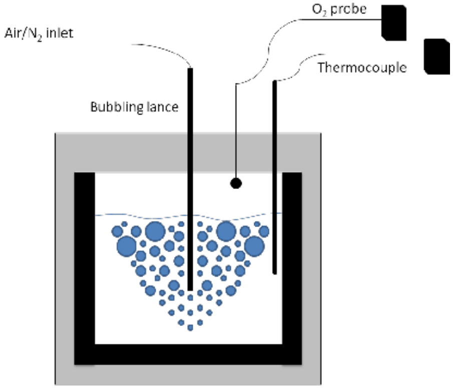
Overall rate

$$R = rF_AF_LF_F$$

Bench scale bubbling experiment

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



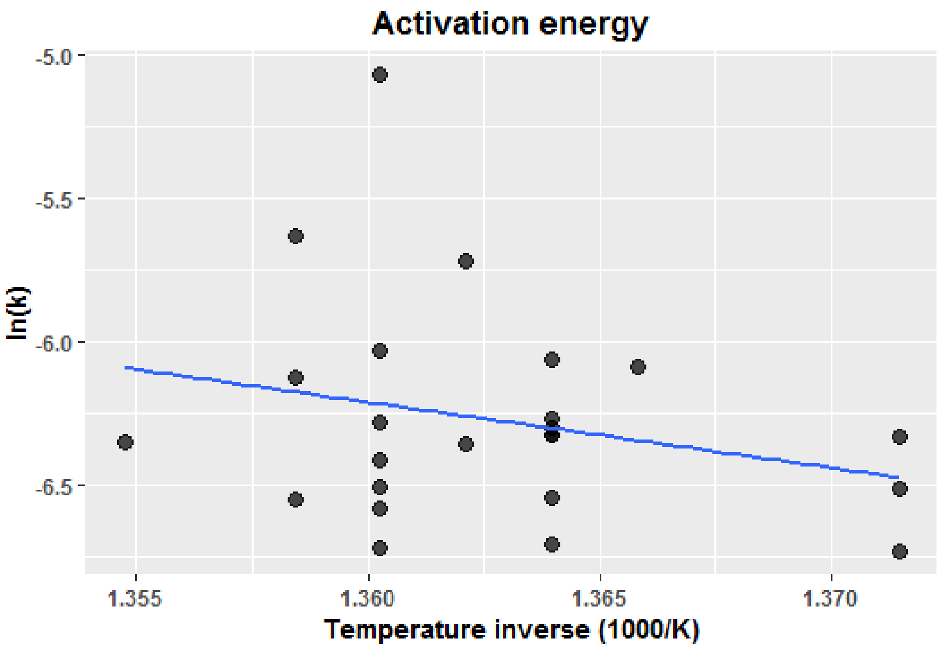
$$r = k[Zn]^0[O_2]^X$$

$$X \approx 2$$

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

ZCO 55: Koutsaris (2011)

Bench scale bubbling experiment



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

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

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

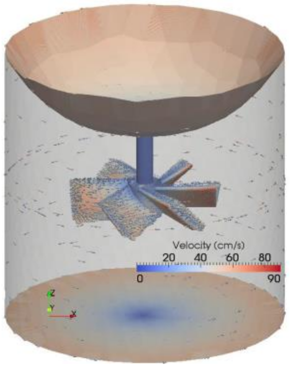
Not very nice fit: $r^2 = 0.065$
Perhaps due to measurement noise &
Narrow temperature range

Better treat temperature as constant for now

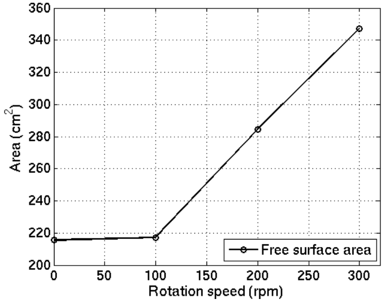
Factors of reactive area and surface velocity

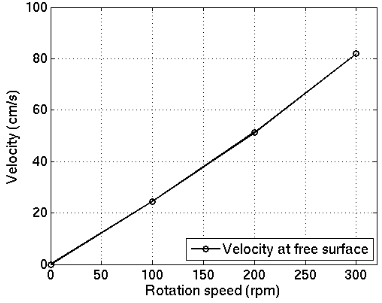
Effect of gas jet not explicitly considered, but the adjusted skimming rate seems to be comparable to the industrial data.

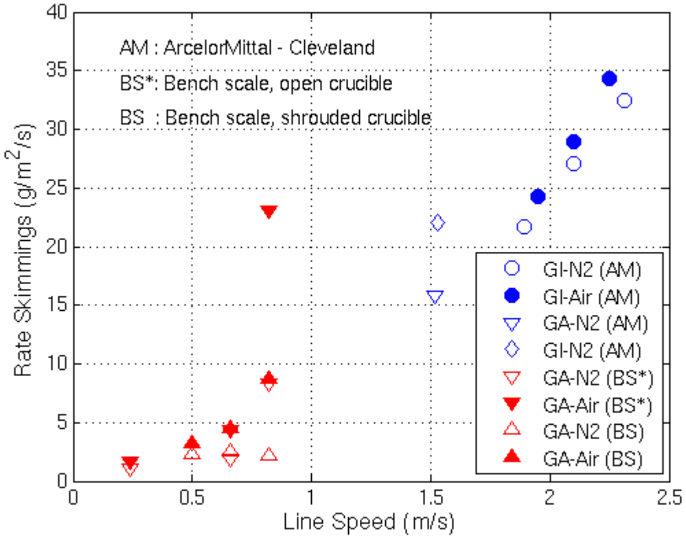
Bench-scale stirring test



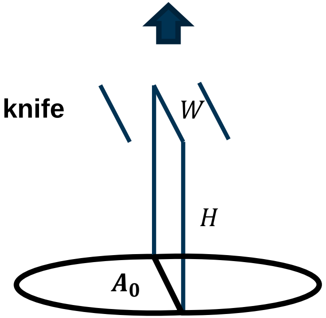
200 RPM







$$R = rF_AF_LF_F = r\frac{A_0{}^{*}}{A_b}\frac{V_L}{V_b}\ (1)$$



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

Bubble Experiment

$A_b = 190 \sim 230\ cm^2$ *(50~60)*

$D_b = 1.1\ cm$

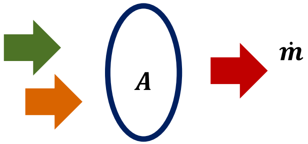
Rising velocity

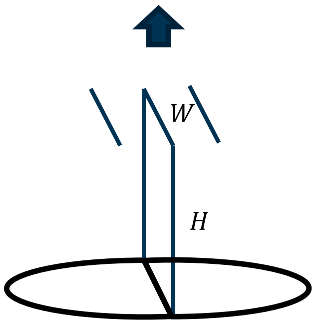
$V_b = 0.164\ m/s$

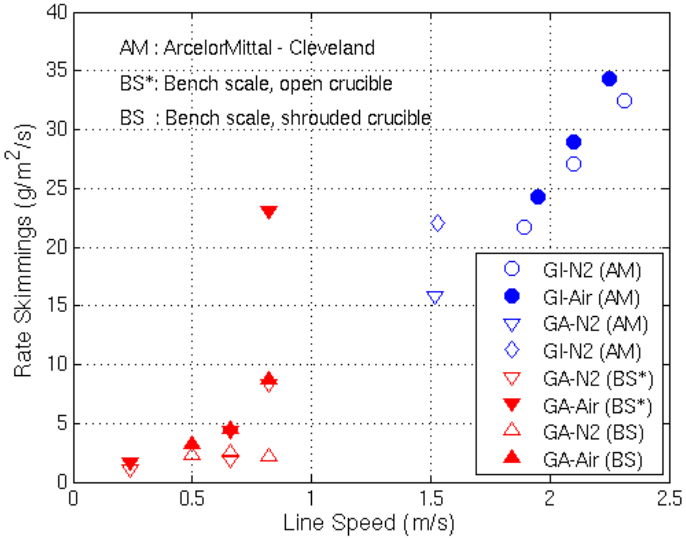
Phenomenological model: Dimensional analysis

Skimming specific production rate (S_{sp}) has the unit: $S_{sp} = \frac{kg}{s \cdot m^2}$

It has the form of **mass flux**.







$$\rho^* = \left[\frac{kg}{s \cdot m^2}\right]\left[\frac{s}{m}\right] = \left[\frac{kg}{m^3}\right]$$

$$\dot{S} = \left[\frac{kg}{s}\right] = \left[\frac{kg}{m^3}\right][m^2]\left[\frac{m}{s}\right] = \rho^* A V_L$$

A geometric factor

$$AV_L = WH\frac{H}{t} = (2W)\left(\frac{H}{2}\right)\left(\frac{H}{2t}\right)$$

Same area in same time,
But slower line speed!

Will a lower H change ρ^*? **Is there any data to check this?**

Summary

Strategies for data analysis and model development framework are well established for top skimming generation.

Need further data collection and/or experiments to enrich the data set, so that it will be sufficient for the model, i.e. to identify critical parameters and to determine the model coefficients.

A simple phenomenological model, inspired from reaction kinetics, is formulated. Dimensional analysis suggests the importance of the form factor of the sheet. Need data to validate these ideas.

Next, examine the difference between the skimming for GA and GI, then link to the skimming generation model

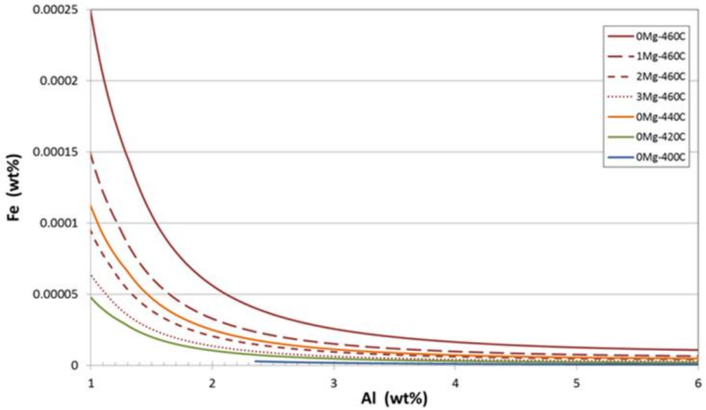
ZnAlMg DROSS FORMATION

Coming work plan

ZnAlMg dross generation model

Components:

1. Zn-Al-Mg-Fe phase diagram (Al at 1-3%, Mg at 1-2%)
    - To couple with the FEM flow solver, need to develop a computer function to represent and shift among these curves.
    - An exponential-decay-like curve can fit well here.
2. Fe dissolution rate at such condition
    - Plan to adapt the work of Giorgi et al. (2005) on interfacial reactions between solid Fe and liquid Zn-Al alloy to determine the averaged Fe dissolution rate.
    - Involve 3 steps: a) Dissolution of Fe, b) Lateral growth of Fe_2Al_5, c) Uniform growth
    - Solve the reaction kinetics equations with Finite Difference method.



Thanks to Daniel Liu (Tech Metals Ltd.)

With the dross generation model, the dross formation characteristics can be determined like in ZCO-66, together with the in-house FEM flow solver.

Acknowledgement

Zinc ...essential for life

international zinc association

Sponsors of the Galvanized Autobody Partnership program

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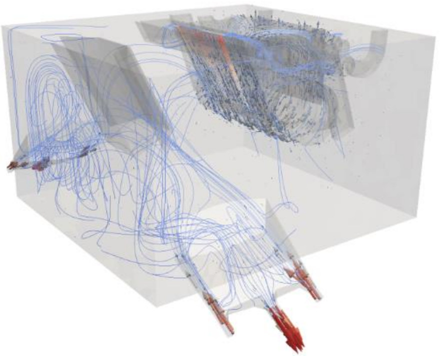

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THANK YOU

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