Planar Jet Stripping of Liquid Coatings: Numerical Studies Using Basilisk

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Film formation on a moving plate:

- Found in photography, material forming, metal industry, automotive...
- L & L films,[1] High Re withdrawal by Groenveld;[2]
- Regime study:,[3] Snoeijer;[4]
- Waves studies by the Kapitzas.[5]

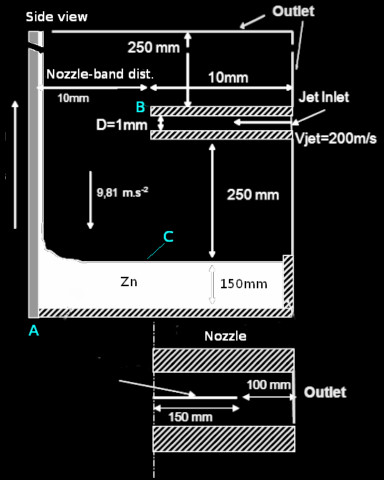
All this is useful only to a certain degree in e.g. zinc coating: $\mathrm{Re}\,(\rho_l, h_{00}, u_w, \mu_l) \approx 2300$. **Flat jet wiping of thus formed film:**

- Flat 'airknife' jets (200m/s) used to control film thickness and edges of the product;
- Analytic studies of ∇p influence by Ellen & Tu;[6] simplified model numerically solved by Hocking;[7]
- Large Eddy Simulations (all 2D) by S. Vincent & Co., e.g. Lacanette[8] or Myrillas et al..[9]

Established opinion is that above-jet film thickness h_c is thinner than $0.1h_{00}$ for glycol, it can be as thin as $0.01h_{00}$ for zinc.

[1] L.D. Landau and B.V. Levich. "Landau-Levich Film". In: Acta Physicochim. URSS 17 (1942).
[2] P. Groenveld. "Laminar withdrawal with appreciable inertial forces". In: Chemical Engineering Science 25 (1970), pp. 1267–1273.
[3] R.P. Spiers, C.V. Subbraman, and W.L. Wilkinson. "Free Coating of a Newtonian Liquid Onto a Vertical Surface". In: Chemical Engineering Science 29 (1973), pp. 389–396.
[4] J.H. Snoeier et al. "Thick films of viscous fluid coating a plate withdrawn from liquid reservoir.". In: Physical Review Letters 100 (2008), pp. 24502–24504.
[5] Hsueh-Chia Cheng. "Wave Evolution on a falling film". In: Annu. Rev. Fluid Mech. 26 (1994), pp. 103–136.
[6] C.H. Ellen and C.V. Tu. "An Analysis of Jet Stripping of Liquid Coatings". In: Journal of Fluids Engineering 106 (1984), pp. 399–404.
[7] G.C. Hocking et al. "Deformations during jet-stripping in the galvanizing process". In: Journal of Engineering Mathematics 70 (2011), pp. 297–306.
[8] D. Lacanette et al. "Macroscopic analysis of gas-jet wiping: Numerical simulation and experimental approach". In: Physics of Fluids 18 (2006).
[9] Konstantinos Myrillas et al. "Numerical modelling of gas-jet wiping process". In: Chemical Engineering and Processing: Process Intensification 68 (2013), pp. 26 –31. ISSN: 0255-2701.

Problem Specification



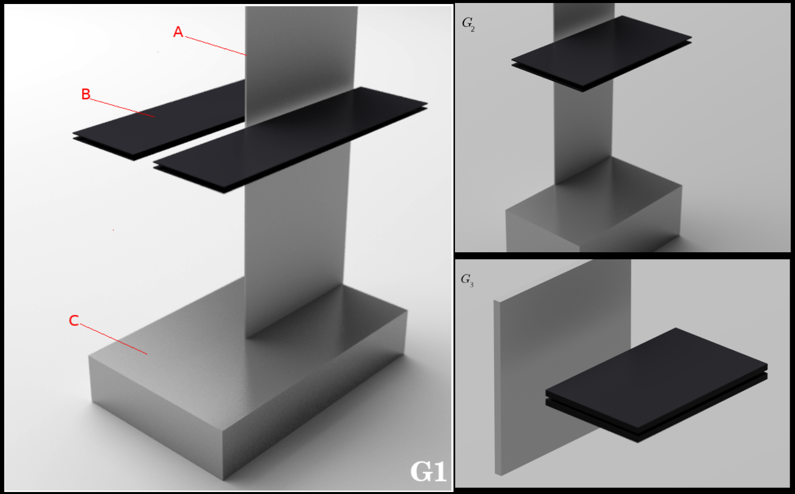


Figure: The coating configuration in two (left) and three (right) dimensions. A - upward moving band; B - the "airknives" or flat jet nozzles; C - liquid zinc containers (walls are invisible in 3D rendering). G_1 full configuration, G_2-half geometry, G_3 $5 \times 5 \times 5$cm subdomain "zoom" config.

Figure 1: the nozzle-band distance d_{nb} is measured at 10mm in industrial configuration.[10] Nozzle diameter D is 1mm. Liquid is drawn from the reservoir C at the bottom, which coats the moving band A. Subsequently, air injected from nozzle(s) B collides with the coated band A and leaves the flow domain Ω below and above the nozzle(s); outlets are drawn in Figure 1 (left) with grayed lines.

[10] Myrillas et al., "Numerical modelling of gas-jet wiping process".

Governing Equations In all cases presented here, full Navier-Stokes equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \otimes \mathbf{u}) = \frac{1}{\rho} \left(\nabla \cdot (\mu \mathbf{D} - p \mathbf{I}) + \sigma\, \mathbf{n} \kappa \delta_S \right) + \mathbf{f}_g, \tag{1}$$

are solved, assuming also incompressibility of the flow:

$$\nabla \cdot \mathbf{u} = 0. \tag{2}$$

where $\mathbf{u}$ velocity, p pressure, μ and ρ for viscosity and density, respectively. $\mathbf{I}$ and $\mathbf{D}$: unitary and rate-of-strain tensors, respectively. Gravity $\mathbf{f}_g$ (along y). Surface tension (1) by $\sigma \mathbf{n} \kappa \delta_s$ where σ is a coefficient, κ is the curvature of the interface S while δ_S is Dirac distribution centered on it.

Properties of ${}_{30}$Zn and air:

- surface tension $\sigma = 0.7[N/m]$
- density $\rho_l = 6500[kg/m^3]$, air $\rho_a \approx 1[kg/m^3]$
- viscosity $\mu_l = 3.17 \cdot 10^{-3}[Pa \cdot s]$., air $\mu_a = 2.1 \cdot 10^{-5}[Pa \cdot s]$.

Boundary conditions

- $0.65 \times 0.25 \times 0.05$m
- steel thickness $1 - 5 \cdot 10^{-3}$
- reservoir depth 0.15m
- band upward velocity 2 m/s.
- $z-$: symmetry ($z+$ band edge is coated)

Ensuring Momentum Conservation in Two-Phase Flow

The momentum-conserving methods:[11][12] special treatment of the advective term in eq. 1 that ensures (numerical) mass and momentum consistency of solution using Volume of Fluid fraction function C.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \wedge \frac{DC}{Dt} = 0 \wedge \rho = \rho_l C + (1 - C)\rho_g \tag{3}$$

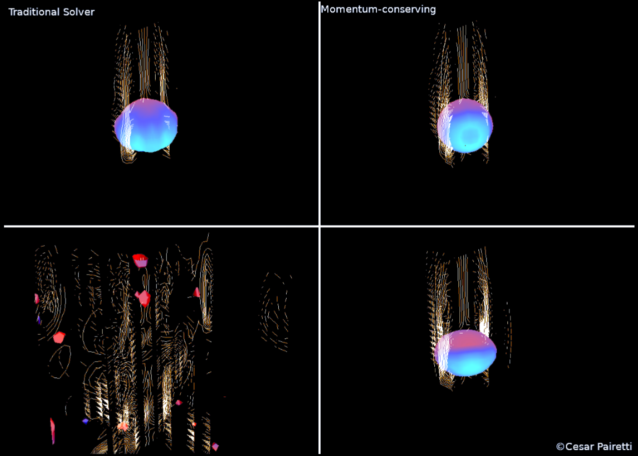


Figure: “Raindrop” case: Momentum-conserving VOF method (right) and traditional M-A-C VOF(left). (In this regime, the drop should survive).

[11] M. Rudman. “A Volume-tracking Method for Incompressible Multifluid Flows With Large Density Variations”. In: International Journal for Numerical Methods in Fluids 28 (1998), pp. 357–378.

[12] G. Vaudor et al. “A consistent mass and momentum flux computation method for two phase flows. Application to atomization process.”. In: Computers and Fluids 152 (2017), pp. 204–216.

Planning of the Simulations

1. Two-dimensional film formation;
2. Three-dimensional film formation;
3. Free jet dynamics, dynamics of the jet impinging on flat plate (two dimensional);
4. ~~Above problem in three dimensions;~~
5. Full configuration (film formation with subsequent jet interaction) in two dimensions with ”relaxed” set of parameters;
6. Full configuration in two dimensions with real parameters;
7. Both above problems (with ”relaxed” and real parameters) in three dimensions.

Case	ρ_l, ρ_g (kg/m^3)	μ_l, μ_g (Pa·s)	u_w (m/s)	d_{nf} (m)	u_{inj} (m/s)
Relaxed	$650, 1.22$	$3.17 \cdot 10^{-2}, 1.7 \cdot 10^{-5}$	4	0.01	75
Real	$6500, 1.22$	$3.17 \cdot 10^{-3}, 1.7 \cdot 10^{-5}$	2	0.01	200

Table: Parameters for the discussed simulations in both presented variants (“real” and “relaxed”).

Grids: We have used 2^{11}-2^{13} grids in 3D, and up to 2^{14} in 2D.

In Groenveld's analysis[13] T and Q at 0.52 and 0.47, respectively, yields $h_G = 163\mu m$.

$$\mathrm{Re}_f(h_G) = \frac{\rho_l h_G u_w}{\mu_l} \approx 672. \quad (4)$$

One could expect the film to be at least in the intermittent regime.

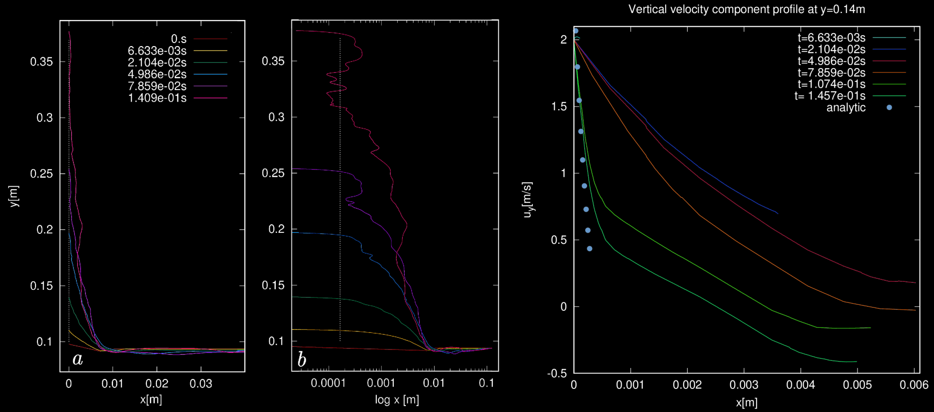


Figure: Left: Configuration $G_{2,14}$ (no air injection). Interface geometry at chosen t values (with x in (a) dec and (b) log). The dashed line is $h_G = 163\mu$ m. Right: Configuration $G_{2,14}$ (two-dimensional, no air injection). (a) $u_y(x)$ profiles through the film at varying t values taken from Fig. 3 (lines), Groenveld's prediction using $u_y = \frac{\rho_l g x^2}{2\mu_l} + \mathscr{C}\frac{x}{\mu_l}$ (points).

[13] Groenveld, "Laminar withdrawal with appreciable inertial forces".

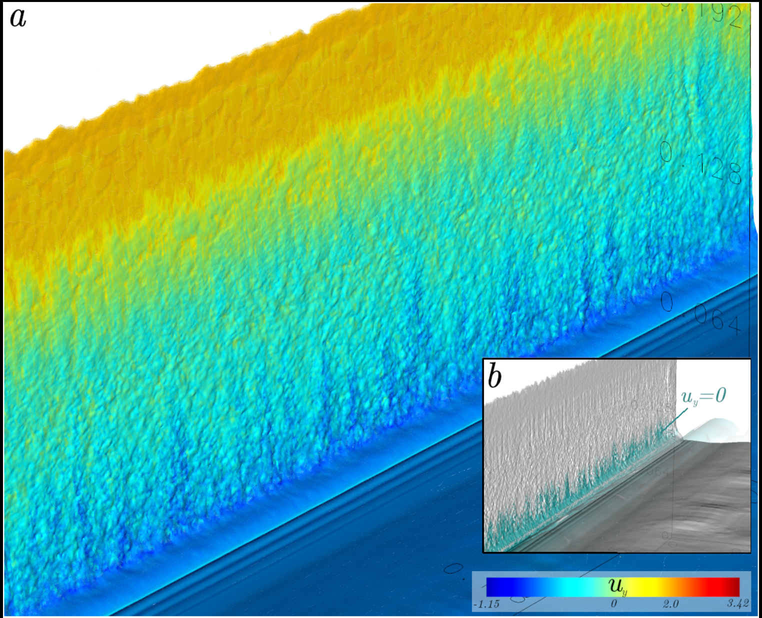


Figure: Configuration $G_{2,12}$ film formation study; the flow at $t = 0.148$s. (a) Actual VOF-reconstructed liquid-gas interface geometry, colored by the u_y velocity component. Inset (b): liquid-air interface shown in gray with the $u_y = 0$ isosurface drawn in turquoise to approximately delimit the stagnation height.

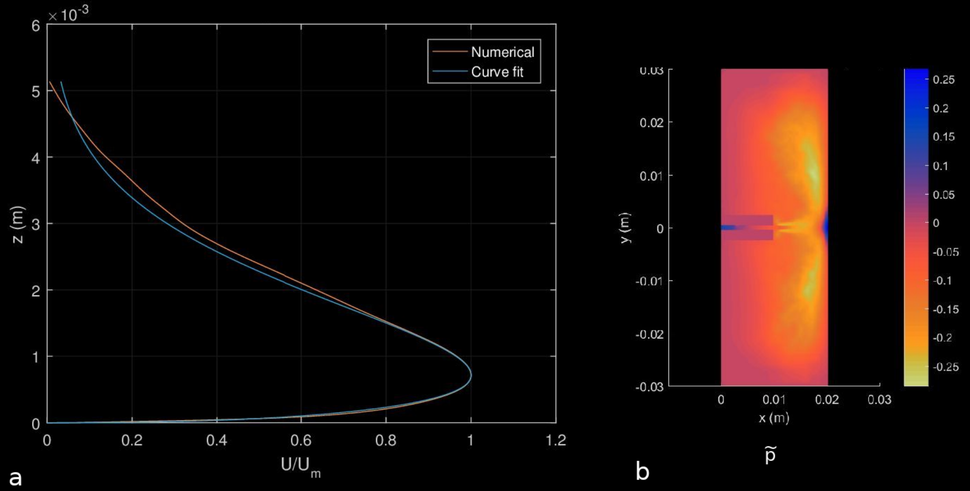


Figure: Study of an impinging jet (single-phase flow): (a) Velocity profile near the wall, simulation (ensemble averaged, blue) and Ozdemir & Whitelaw[15] ((5) brown); (b) Ensemble-averaged mean pressure in the same simulation.

$$\frac{u}{u_{max}} = \frac{\gamma}{\beta}\left(\frac{y/y_{0.5}}{\beta}\right)^{\gamma-1} \cdot \exp\left(-\left(\frac{y/y_{0.5}}{\beta}\right)^{\gamma}\right), \quad (5)$$

[14] Bedii Ozdemir and J.H. Whitelaw. "Impingement of an axisymmetric jet on unheated and heated flat plates". In: Journal of Fluid Mechanics 240 (1992), pp. 503–532.

Airknife: 2D Injection Simulations

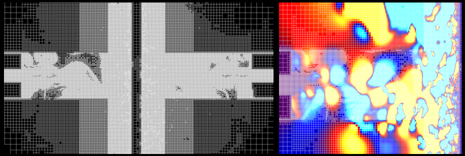


Figure: (left)The 2^{14} 2D simulation: grid structure (right) The 2^{14} 2D simulation: examples of resolution inside the nozzles. (Color: u_x.)

Even though AMR is used, we have to limit maximum refinement level spatially to further decrease CPU cost. (**SRR** Spatially Restricted Refinement). Full resolution in 2D (up to 2^{14}, $\Delta x \approx 31\mu$m, 32 cells in nozzle diameter ($D = 1$mm)).
Thus, even if locally resolved, this is a two-phase "Implicid LES" (or "failed DNS").

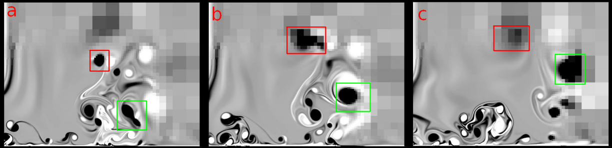


Figure: Dissipation of the vortical structures (marked by red and green boxes) by the grid in the impact zone. Time progression from left to right.

We (eagerly) use "numerical dissipation sponges" i.e. filtering discretisation effect.[16]
Figure 7 shows an example of structure damping (from (a) to (c)).

[16] B. Geurts and F. van der Bos. "Numerically induced high-pass dynamics in large-eddy simulation". In: Physics of Fluids 17 (2005).

Airknife: 2D Injection Simulations - Momentum-Conserving Simulations presented here also used a slightly smaller domain size of $L = 0.512$m, resulting in $\Delta x \approx 31\mu$m$< h_c$.

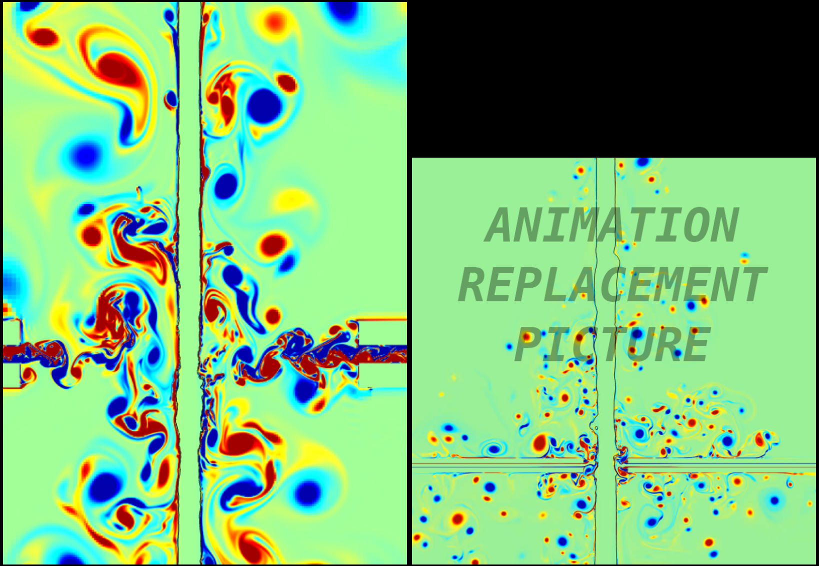
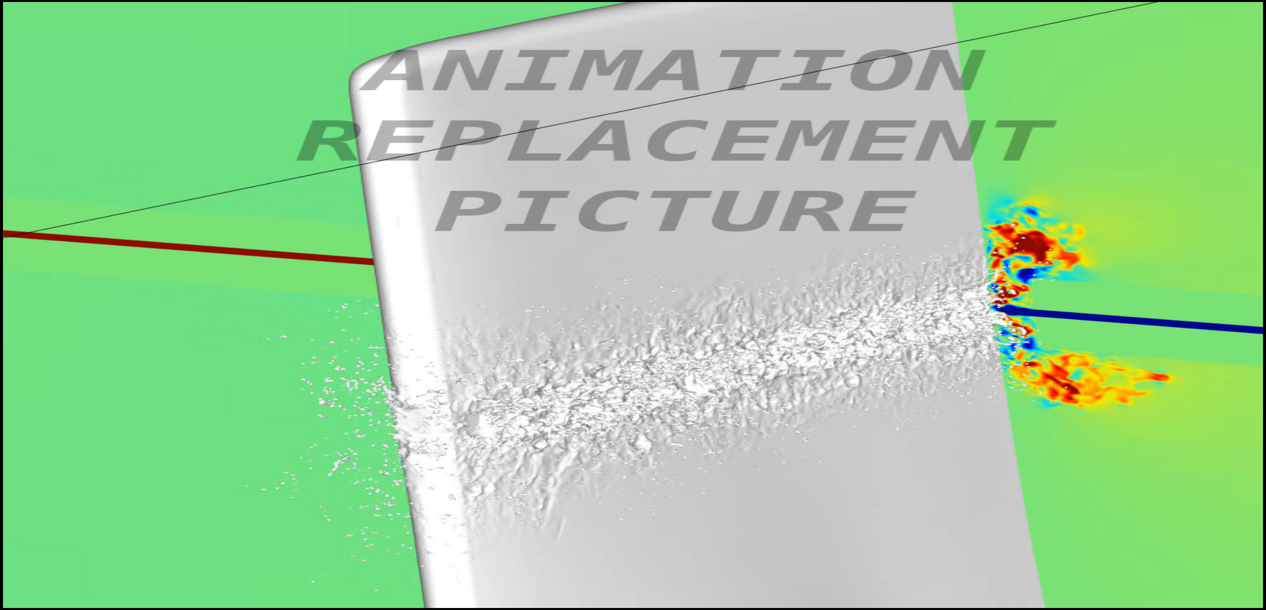


Figure: (left) 2D, momentum-conserving simulation at 9ms after the injection. Apparent lack of strong atomization visible. (right) “Relaxed” parameters simulation, vortical structures sliding on the interface.

Total computational cost of the simulation presented in Figure 8 was 69120 CPUh, divided between 576 nodes (in five 24-hour runs).

Airknife: 3D wiping simulations

Let us start with the "relaxed" parameters set:



Evolution of the system for $t \in [0, 0.16304]s$. This uses an ultra-simplified version of Immersed Boundary Method[17] to represent solids (plate, nozzle walls). Nozzle walls are invisible in this animation.

[17] Zhu Lin-Lin, Guan Hui, and Wu Chui-Jie. "Three-dimensional numerical simulation of a bird model in unsteady flight". In: Comput Mech 58 (2016), pp. 1–11.

Real parameters: preliminary results

This includes geometry specification visible in Figure 1a: dimensions for nozzle diameter ($D = 1 \cdot 10^{-3}$m), nozzle-film distance ($d_{nf} = 0.01$m), coated band/plate thickness ($L_w = 1 \cdot 10^{-3}$m) and similar thickness for nozzle walls. Resolution, at the moment

$$\Delta x = \frac{0.512}{2^{12}} = 1.25 \cdot 10^{-4} m, \tag{6}$$

or 8 cells in nozzle diameter. This is not sufficient to resolve the h_c thickness, however zero-flux thickness h_{00} of 163 microns is in reach. Still this is 'equivalent' to $(2^12)^3 = 4096^3$ domain (or would be without SRR).

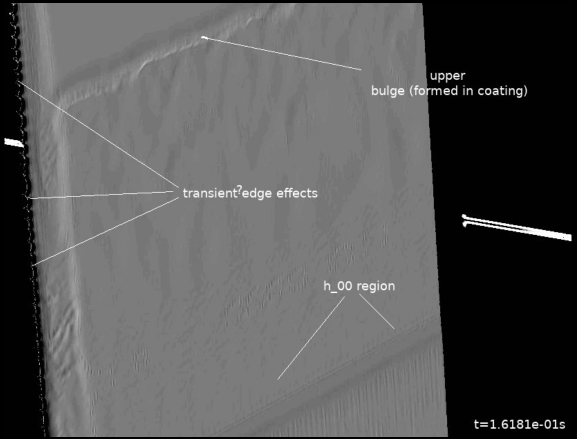


Figure: 3D, 2^{12} simulation, momentum-conserving: film formation just prior to gas-liquid contact (enhanced image). Upper bulge (formed in coating) visible.

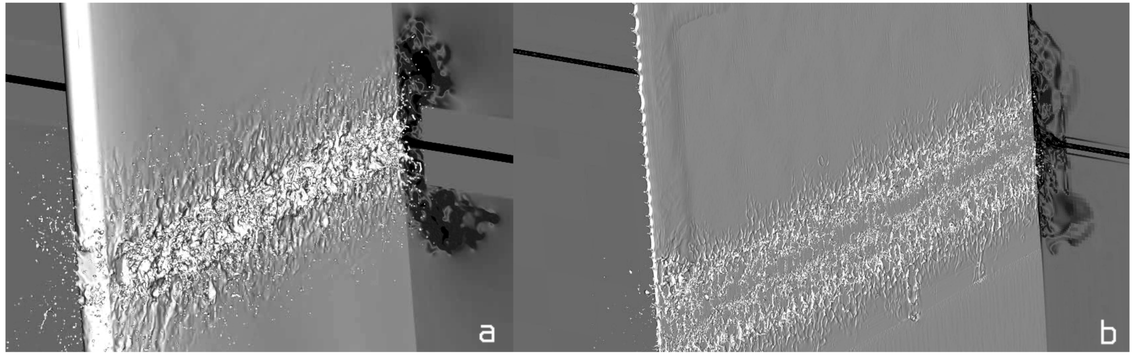
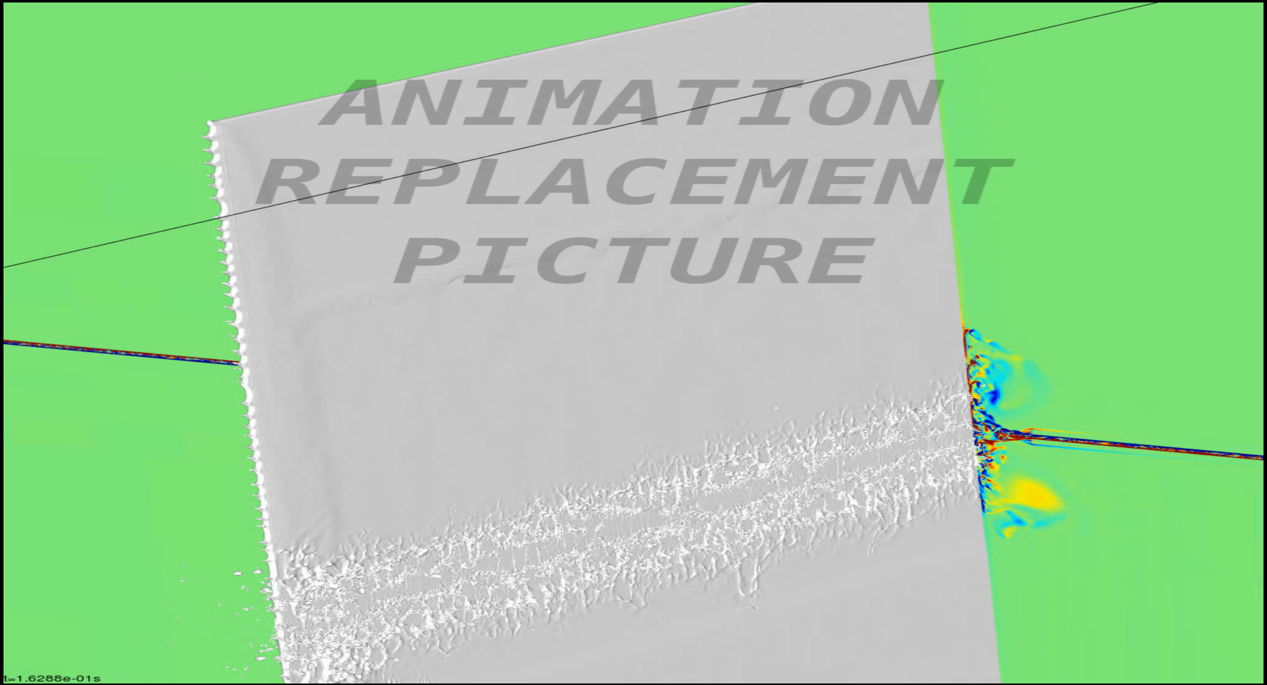


Figure: The 2^{12} three-dimensional simulation. (a) The "relaxed" parameters (classical N-S Basilisk solver, centered grid) (b) real parameters (momentum-conserving).

- Relaxed parameters ($\rho_l = 650, u_{inj} = 75, \sigma = 7.0, D_{nf} = 2.5mm$) vs real parameters ($\rho_l = 6500, u_{inj} = 200, \sigma = 0.7, D_{nf} = 1mm$)
- Different timescales: matched basing on the impact zone width
- Re (based on D) :5380 (a) versus 14300 in (b) ("optimistic" estimation based on nozzle diameter) or
- Re 633 (a) versus 2240 (b) for the film (based on h_{00} and u_w).
- "Optimistic" $\mathrm{We} = 2.79$ (a) vs $\mathrm{We} \approx 5$ (b) based on h_c.
- Less optimistic $\mathrm{We} \approx 40$ for (b) based on h_{00}.

The zero-film-thickness based $\mathrm{We} \approx 40$ seems better adjusted to the atomized character of real case (b).



Real case: Evolution of the system for $t \in [0, 0.16304]s$. The injection occurs at 0.16s. Grid is (up to) 2^{12}.

“Academic remix”: symmetric problem reformulation.

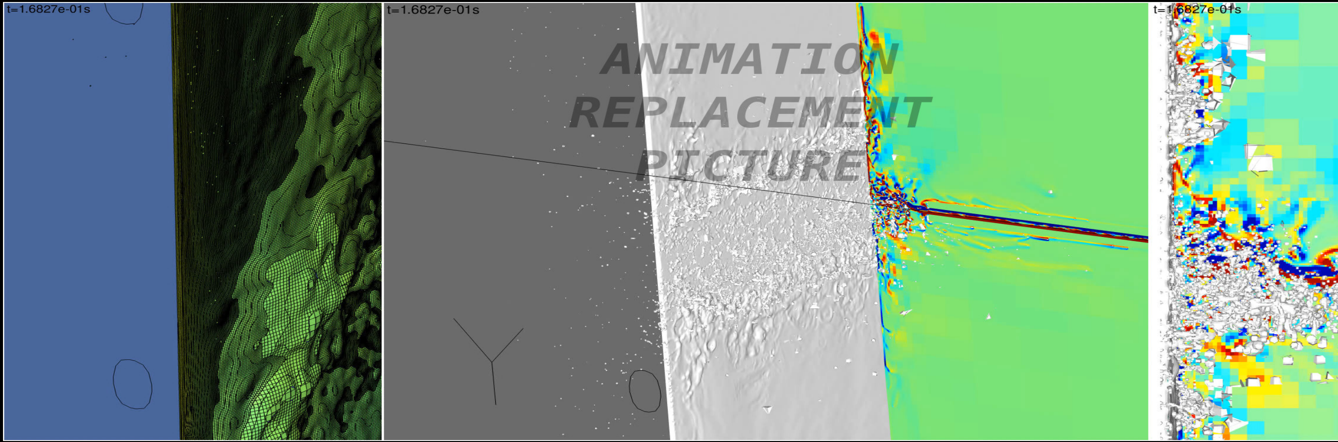


Figure: 3d Real parameters study for half-geometry. Views: bottom isometric (left); isometric impact area (center); $+z$ impact area (right).

Visible[18]: onset of nozzle flapping (could extract a characteristic timescale based on that). Initial disintegration of deposit seems to be followed by a “steady” pressure distribution akin to predictions of Hocking.[19]

[18](Note: due to the limitations of the wall-projector, some features (droplets) in this movie are sub-pixel!)

[19]Hocking et al., “Deformations during jet-stripping in the galvanizing process”.

“Discussion”: is observed atomization physical?

Could we discern between “physically justified” atomization and an effect induced numerically?

Some dimensionless numbers:

- Zero-flux film thickness (reference point below the impact zone): $h_{00} = 5.46 \cdot 10^{-4}$m.[20]
- Groenveld’s thickness $h_G = 5.46 \cdot 10^{-4}$m
- $\mathrm{Re}\,(h_{00}, u_{wall}) \approx 2.24 \cdot 10^3$
- $\mathrm{We}\,(h_{00}, u_{inj}) \approx 40$
- $\mathrm{We}\,(h_G, u_{inj}) \approx 1.6.$

At $\mathrm{We} = 40$ atomization seems justified. Ideally, we could decrease it and check again...

...so, we repeated the simulation at We=1.6.

[20] On a 2^{12} mesh this is barely resolved, $\Delta x \approx h_{00}/5$.

“Discussion”: is observed atomization physical?

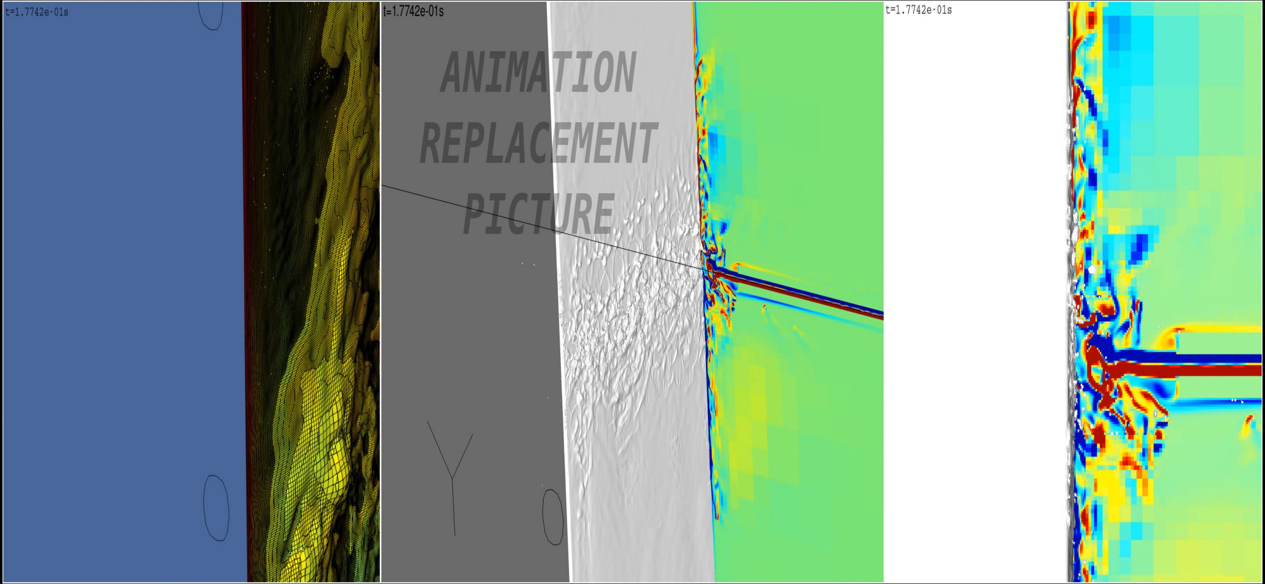
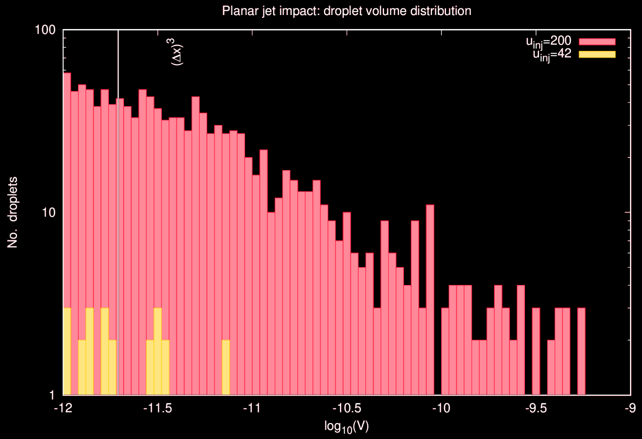


Figure: The $u_{inj} = 42$ m/s flow in a motion picture.

We (have) perform(ed) simulations aiming at comparison of atomization physics at $u_{inj} = 200$ (all previous slides) and $u_{inj} = 42$ m/s.

Is observed atomization physical?



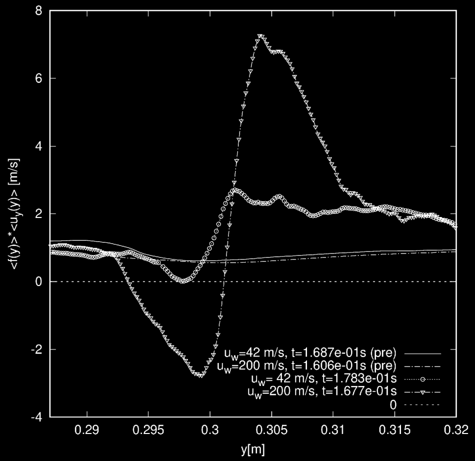


Figure: (left)Droplet volume distribution in the G_2 configuration for varying air injection density. (right) Average liquid velocities (u_y component) in the impact zone.

We (have) perform(ed) simulations aiming at comparison of atomization physics at $u_{inj} = 200$ (all previous slides) and $u_{inj} = 42$ m/s. All $V < \Delta x$ is actually Volume-of-Fluid “debris” (non-reconstructed volumes) recognized as small volumes.

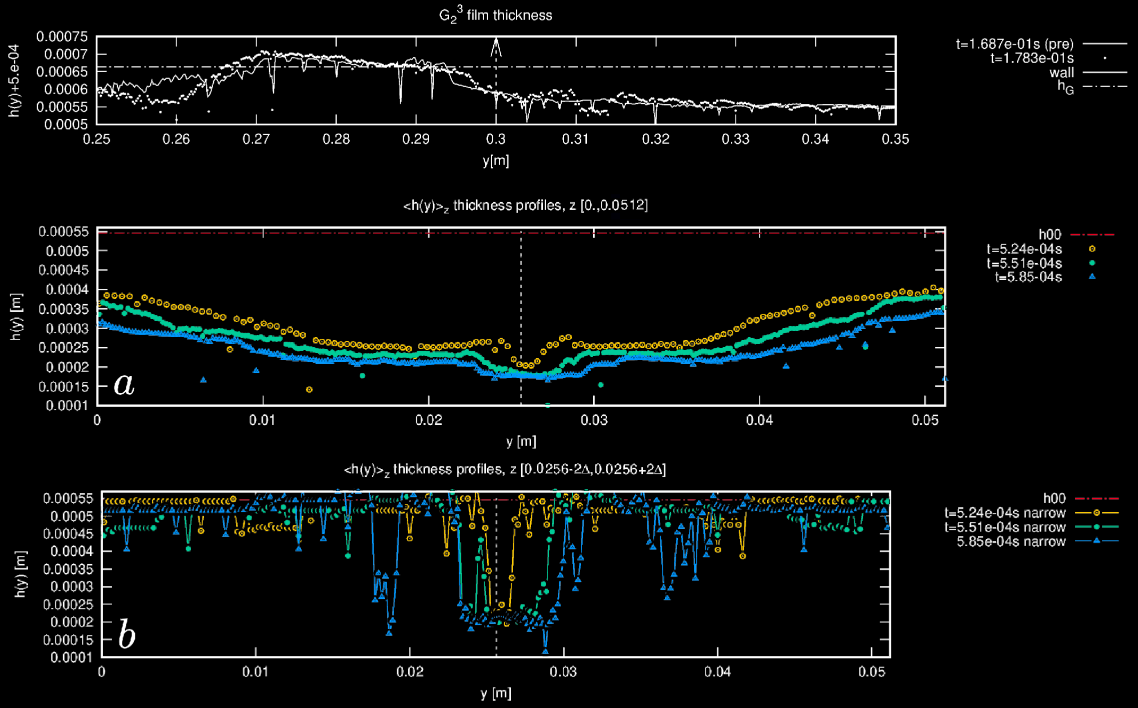


Figure: Film thickness profiles for the $G_{2,12}(u_{inj} = 42)$ simulation. Above: G_2 (half-geometry), below: G_3 (zoom geometry)

G_3 inside story: such a beautiful failure

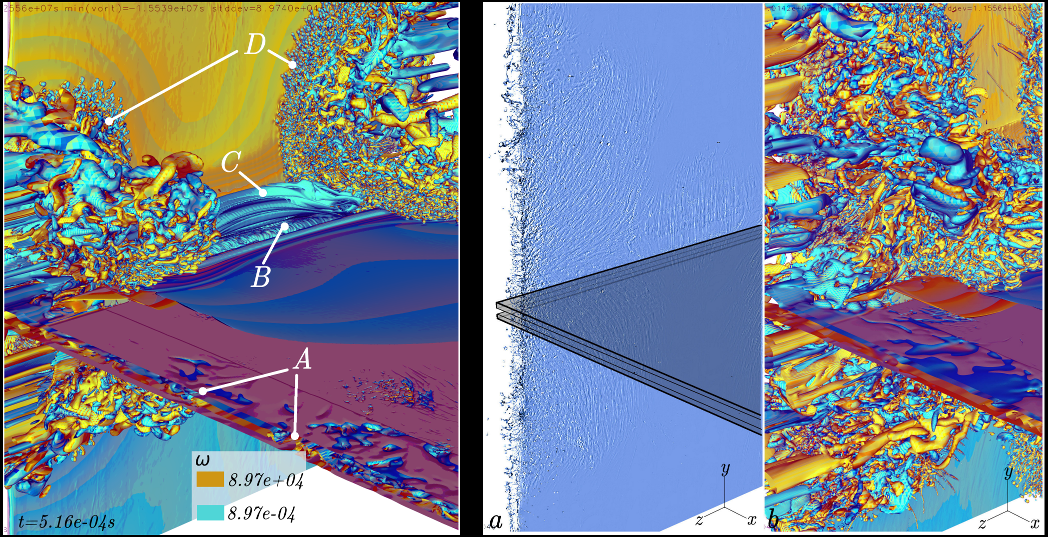


Figure: $G_{3,11}$ simulation: vortical structures in the air phase. *A* - incoming airflow, *B* rotating transverse structure at the nozzle exit, *C*- elongated, rotating 'strip' structures impacting the film in the centre region, *D*- small structures associated with nozzle side wall boundary layers.

Conclusions

1. We have performed a series of simulations of the air knife jet-wiping process in hot-dip coating, with a parameter study using Basilisk
2. Momentum transfer from gas to liquid causes a significant degree of atomization of liquid layers influenced by steep pressure gradient in the impact zone. This is a departure from low-resolution results currently available.[21]
3. It is only feasible to observe edge effects in 3D simulation, up to now grid resolution is lacking in this aspect. However the 2^{12} simulation already captures rudimentary physics.
4. For the atomization part of the process, perhaps it's enough to resolve Hinze[22] scale $L_h \approx \left(\frac{\rho}{\sigma}\right)^{-3/5} \epsilon^{-2/5}$? (Estimated at below 1mm...)
5. Simulations are planned using forms of SRR (coulpled with Level-Set), half-geometry and at up to 2^{15} resolutions (or 32768^3) making it feasible to resolve $\Delta x \approx 15\mu$m.

Thanks!

The paper: *Planar Jet Stripping of Liquid Coatings: Numerical Studies* (Aniszewski, Zaleski, Popinet, Saade) available this month on arXiv/HAL.

[21] Myrillas et al., "Numerical modelling of gas-jet wiping process"; Ellen and Tu, "An Analysis of Jet Stripping of Liquid Coatings".
[22] J.O. Hinze. "Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes". In: AIChE J. 1 (3) (1955), 289–295.

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