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# High-fidelity CFD simulations to understand the physics of the jet wiping process in galvanization

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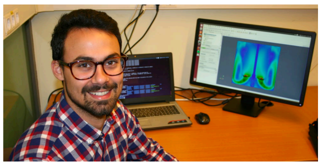
## Work team



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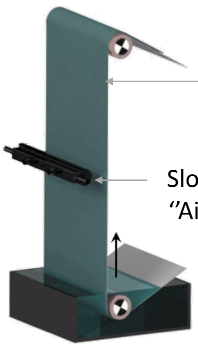
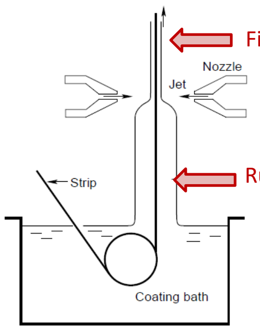
# Outline



# 1. Industrial context

## The jet wiping process in galvanization




- Jet wiping is a coating technique used in photographic, paper and **galvanization** industries.
- Liquid film dragged from a liquid bath by a substrate moving upwards.
- A slot gas impinging jet is used to reduce and control the coating thickness, leading the formation of two regions:
  - Runback flow back to the bath.
  - Final thin film flow.

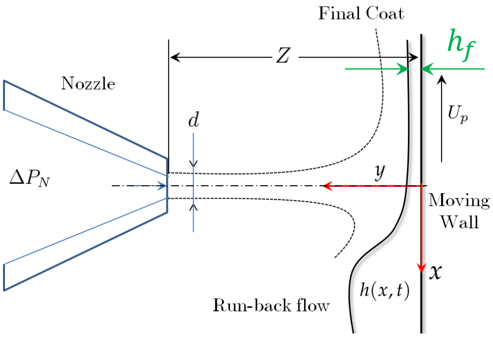
## 1. Industrial context

### The jet wiping process in galvanization

Hot-dip galvanization

550 process lines for over 100 millions of tons per year [ZIC, Cominco ltd]

Liquid zinc ~460°C




Contactless technique

Accurate control of process lines

$$h_f = f(Z, d, \Delta P_N, U_P, \rho_l, \mu_l)$$

## 1. Industrial context

### The jet wiping process in galvanization

Hot-dip galvanization

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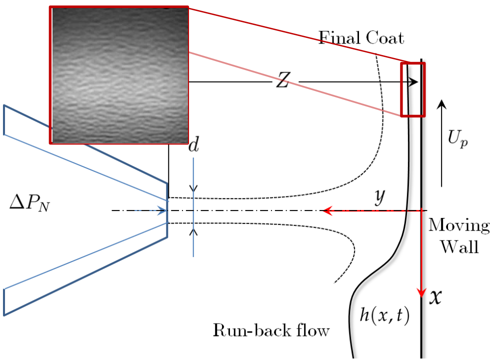



Instability of the final coating film: **Undulation**

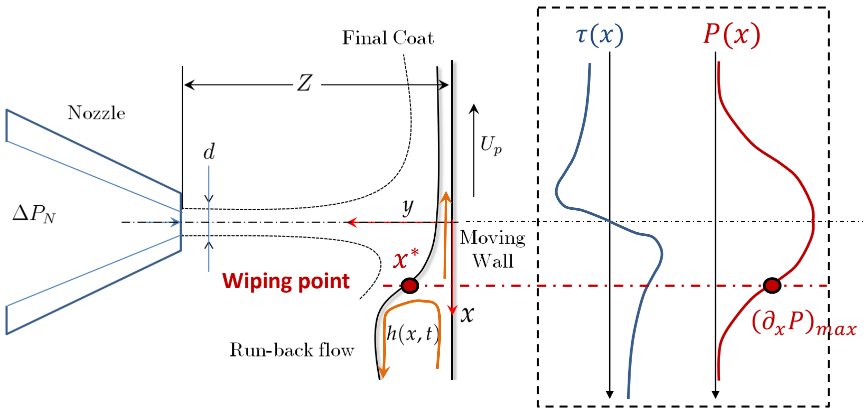
Degradation of the coating quality

Automotive Industry

# 1. Industrial context

Physical mechanism

- Process parameters
  - ✓ $U_p$ : substrate speed
  - ✓ $Z$ : standoff distance of the jet
  - ✓ $d$ : nozzle slot opening
  - ✓ $\Delta P_N$ : nozzle pressure
- Fluid properties
  - ✓ $\rho_l, \rho_g$ : density of liquid and gas
  - ✓ $\mu_l, \mu_g$ : kinematic viscosity
  - ✓ $\sigma$ : liquid surface tension

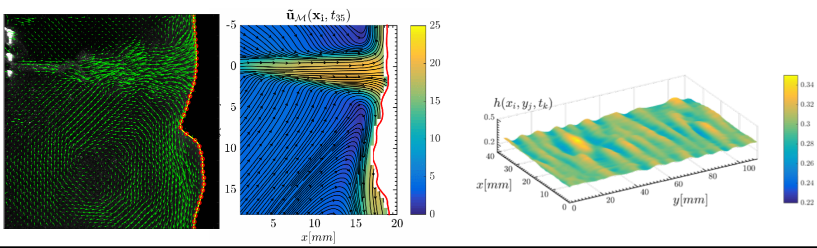



# 1. Industrial context

State of the art

Different hypotheses for the origin of undulation:

- Intrinsic hydrodynamic instability of the film [Tu & Ellen, 1986] [Hocking, 2011]
- Substrate vibration [Gosset, 2007] [Peng, 2013]
- Jet buckling instability [Yoon, 2010]
- **Gas jet- liquid film interaction** [Gosset, 2007] [Myrillas, 2011]
  - Jet bending due to a large recirculation close to the runback. [Pfeigel et al., 2017]
  - Experimental characterization of the wave patterns. Gosset, Mendez, Buchlin (2019) Exp Therm Fluid Sci 103:51-65.
  - Time resolved analysis of the two-phase flow: pulsation of the runback flow, unsteadily confining the wiping jet. Mendez, Gosset, Buchlin (2019) Exp Therm Fluid Sci 106:48-67.



## 2. Objectives

### Objectives of the present work

Assess the capability of high-fidelity simulations to reproduce the dynamics of the jet wiping process:

- Carry out an extended validation of two-phase CFD simulations with high quality experimental data for the first time.
- Understand the mechanism of undulation formation
- Collect data for the further investigation of the problem with integral film models.

- Use of open source Finite Volume libraries OpenFoam v5.0

## Outline

1. Industrial context
2. Objectives
3. **Numerical modeling and setup**
4. Results
5. Conclusions and perspectives

## 3. Numerical modeling and setup

Equations of conservation

**One fluid, two-phase NSE**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$F_{st} = \sigma \, \kappa \, \nabla \alpha$$

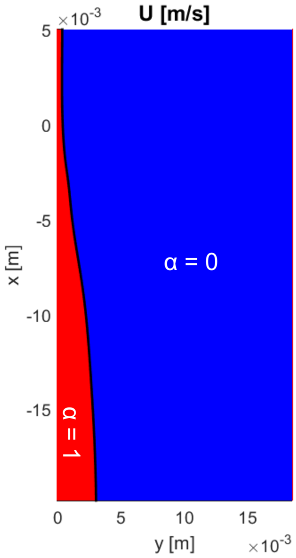
$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \nabla \cdot \tau + \rho g + F_{st}$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{v}) = 0 \longrightarrow$$ **Volume of Fluid (VOF)**

$\alpha$ : liquid volume fraction

- $\alpha = 0 \rightarrow$ gas
- $0 < \alpha < 1 \rightarrow$ free surface
- $\alpha = 1 \rightarrow$ liquid

$$\phi = \phi_l \alpha + \phi_g (1 - \alpha)$$




## 3. Numerical modeling and setup

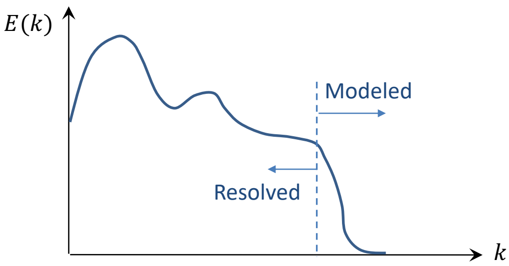
Turbulence modeling

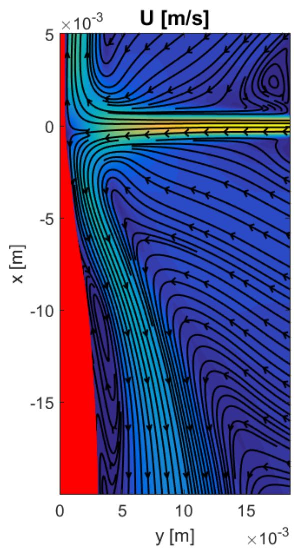
**Large Eddy Simulation (LES)**

Turbulence filtering

Modelling of the smaller scales

Large scales fully resolved



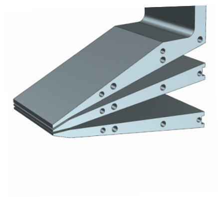



# 3. Numerical modeling and setup
## Test cases

**Liquid properties** (Dipropylene glycol)
- **ρ** = 1023 kg·m$^{-3}$
- **μ** = 0,0799 Pa·s

**Gas properties** (Air)
- **ρ** = 1,2 kg·m$^{-3}$
- **μ** = 1,48·10$^{-5}$ Pa·s

- **σ** = 0,032 N·m$^{-1}$



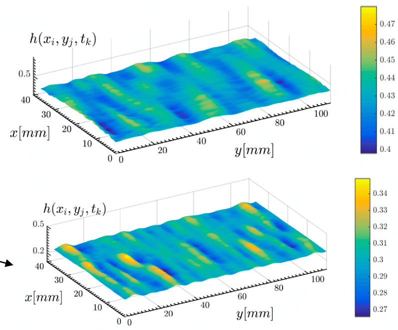
$d = 1.3\ mm$

$U_p = 0.35\ m/s$

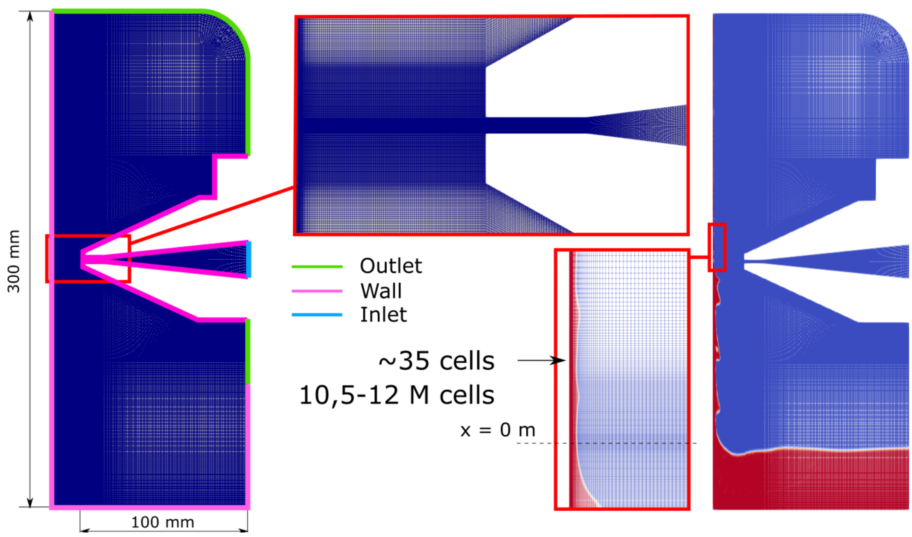
$\hat{Z} = Z/d$

| $\hat{Z}$ | $Z\ [mm]$ | $\Delta P_N\ [Pa]$ |
|---|---|---|
| 19,4 | 25,22 | 425 |
| 19,4 | 25,22 | 875 |
| 14,2 | 18,46 | 425 |
| 14,2 | 18,46 | 875 |

$25 \leq V_{jet} \leq 37\ m/s$




# 3. Numerical modeling and setup
## Discretization of the domain



# 3. Numerical modeling and setup

Solver parametrization

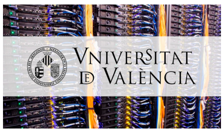
OpenFOAM

"**Open**-source **F**ield **O**peration **A**nd **M**anipulation"
C++ toolbox for the development of customized numerical solvers, and pre-/post-processing utilities for the solution of continuum mechanics problems, including CFD

## Numerical setup

- **3D VOF**
- **Solver:** interFoam
- **Smagorinsky LES** ($C_S$ = 0,158)
- **CFL** = 0,96.
- **Time**: Euler
- **Convective terms**: Gauss linear.
- **Gradient terms**: Gauss linear.
- **Diffusive terms**: Gauss linear corrected

## Computational cost



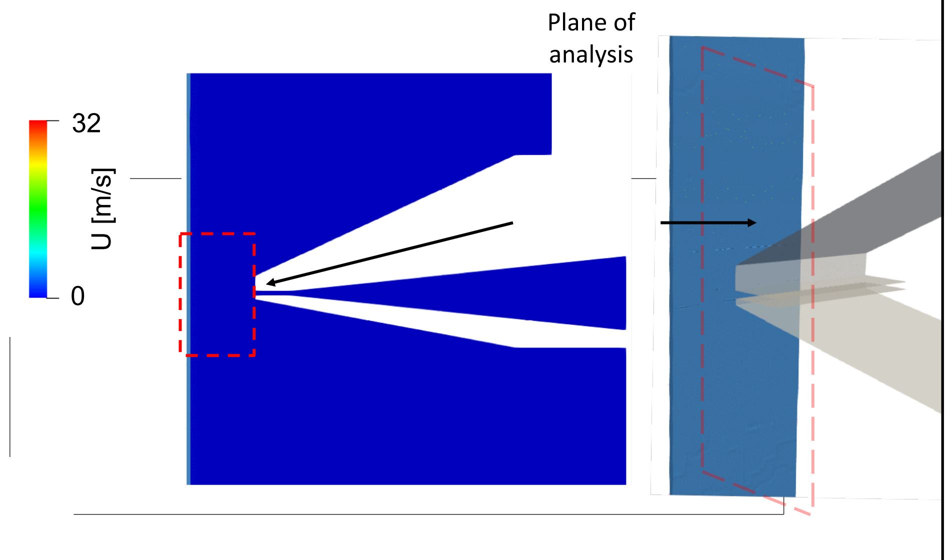

- **Finisterrae II (CESGA).**
- **Tirant (UV).**
- **288 cores.**
- **10 – 12 M cells.**
- **300 – 700 hours CPU / s of real flow.**
- **275 GB of data / s of real flow.**


# Outline

1. Industrial context
2. Objectives
3. Numerical modelling and setup
4. **Results**
5. Conclusions and perspectives

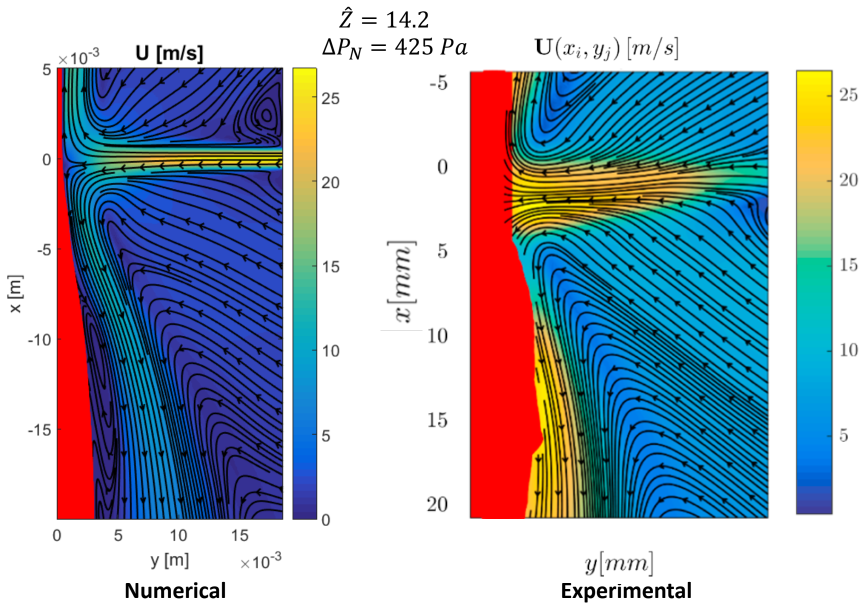
# 4. Results

Flow visualization




# 6. Results

Gas jet characterization

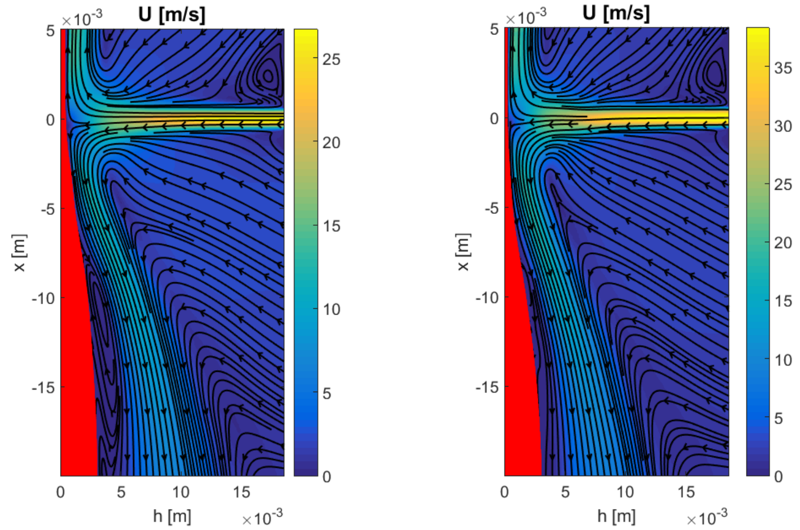


# 6. Results

Gas jet characterization

$\hat{Z} = 14.2$

$\Delta P_N = 425\ Pa$ $\Delta P_N = 875\ Pa$




# 6. Results

Gas jet characterization

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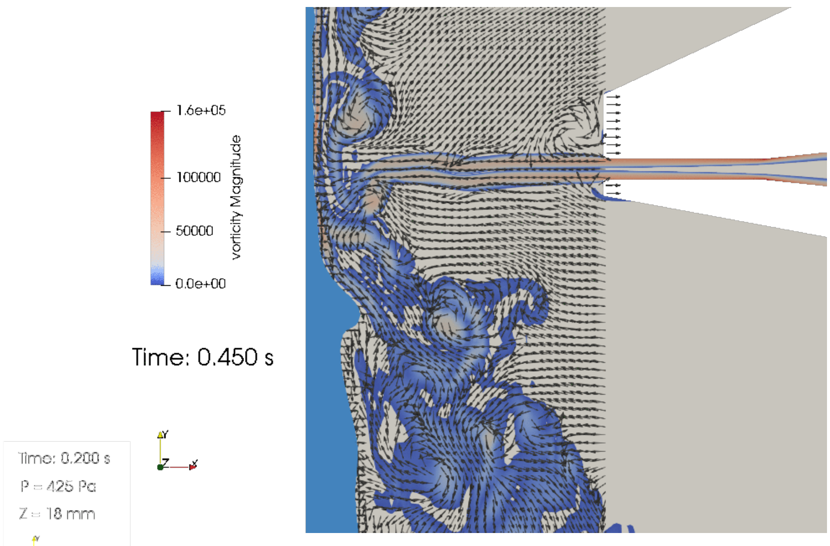
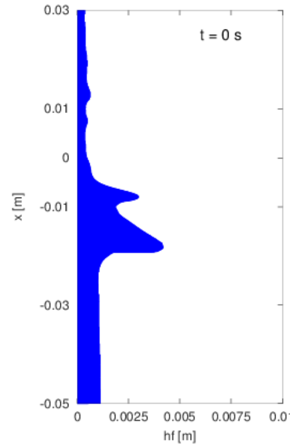
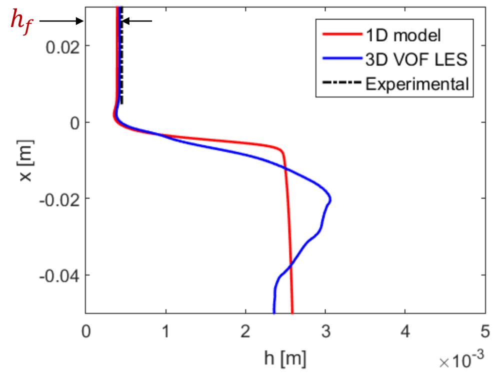


# 4. Results

## Liquid film characterization




Time range for statistical analysis: $1 \leq t \leq 3\ s$
Sampling frequency: $1\ kHz$

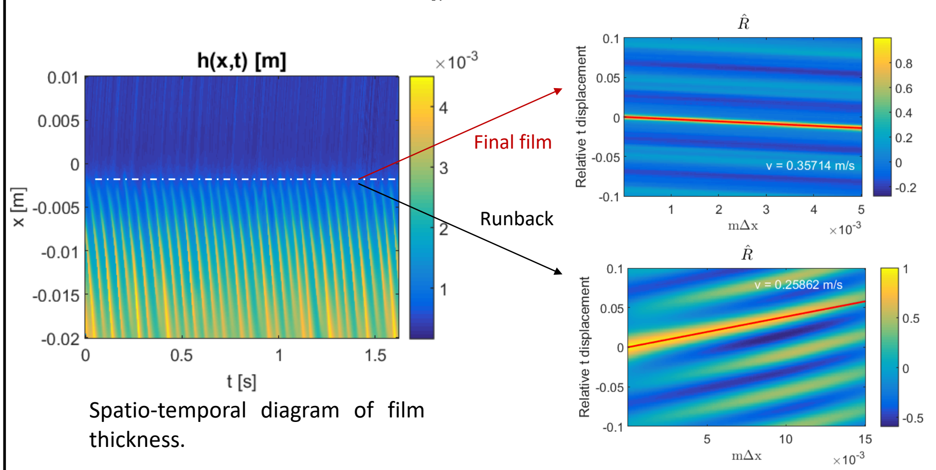
Base test case

| | | $h_f\ [\mu m]$ | |
|---|---|---|---|
| $Z/d$ | $\Delta P_N\ [Pa]$ | Experimental | Numerical |
| 19,4 | 425 | 607 (± 5%) | 513 |
| 19,4 | 875 | 399 (± 5%) | 327 |
| 14,2 | 425 | 449 (± 5%) | 431 |
| 14,2 | 875 | 310 (± 5%) | 265 |

# 4. Results

## Liquid film characterization

$\hat{Z} = 14.2$
$\Delta P_N = 425\ Pa$

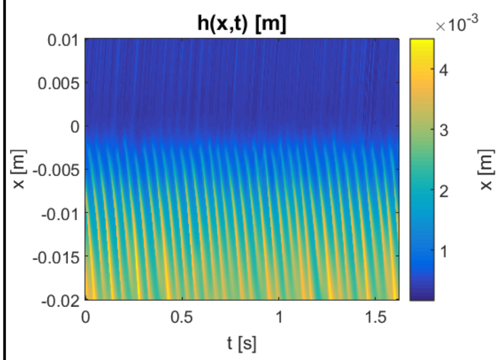



Spatio-temporal diagram of film thickness.

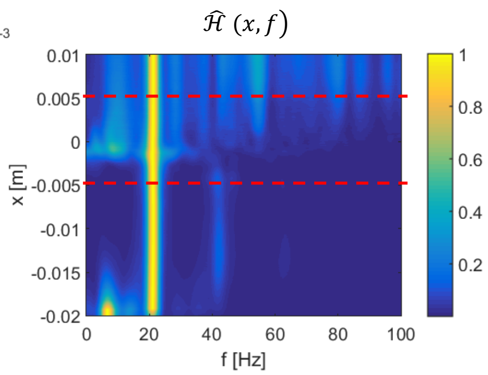
Signal auto-correlation in space and time → Wave velocity

## 4. Results
Liquid film characterization

$\hat{Z} = 14.2$
$\Delta P_N = 425\ Pa$




Spatio-temporal diagram of film thickness.

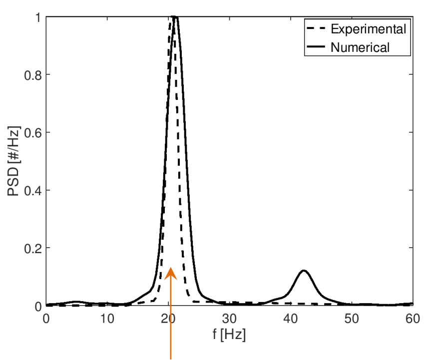



Power spectral density of the thickness along the x axis.

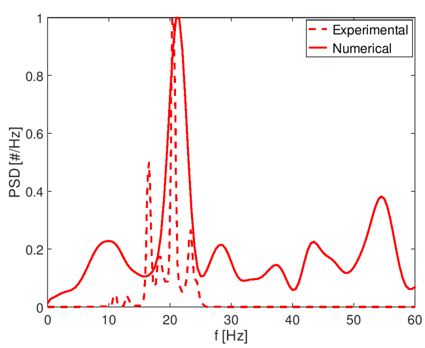
## 4. Results
Liquid film characterization

$\hat{Z} = 14.2$
$\Delta P_N = 425\ Pa$

Runback $x = -0.005\ m$




Final film $x = 0.005\ m$



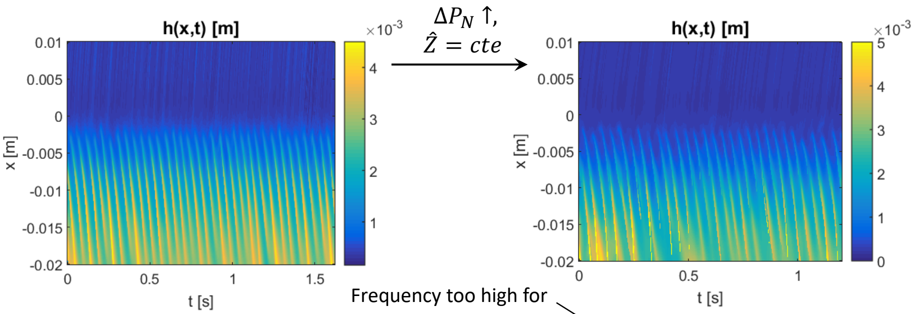

Frequency of jet oscillation!

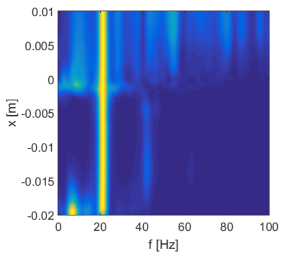
Mendez et al. (2019) Exp Therm Fluid Sci

$f = 21.4\ Hz \rightarrow \lambda = 15.5\ mm$

# 4. Results

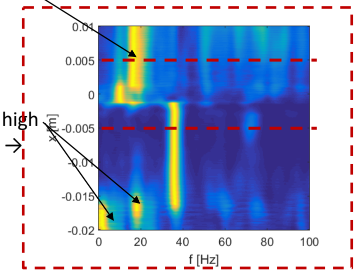
Liquid film characterization




Frequency too high for the film to reverse direction → Wave merging

Wave frequency too high for full development → Merging

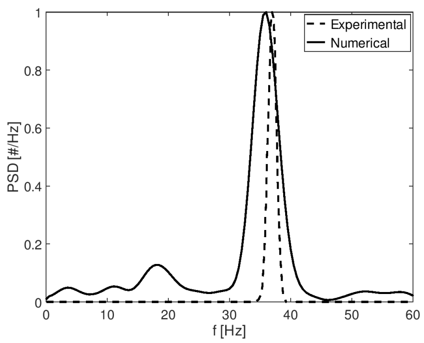



# 4. Results

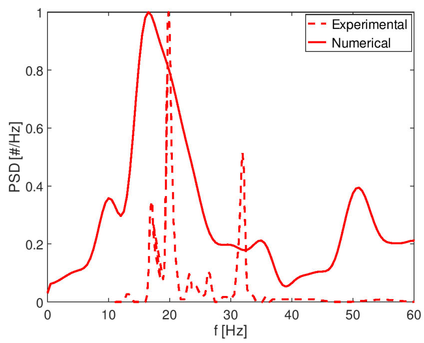
Liquid film characterization

$$Z/d = 14.2$$
$$\Delta P_N = 875\ Pa$$

Runback $x = -0.005\ m$

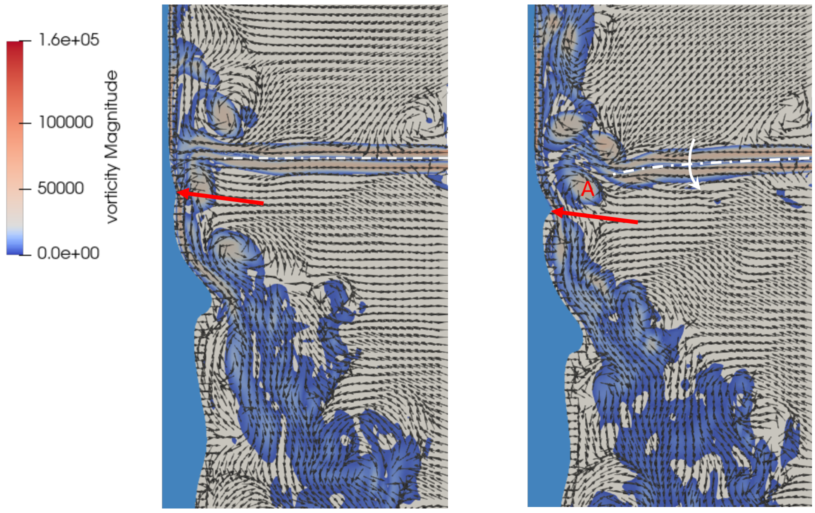



Final film $x = 0.005\ m$



# 4. Results

Gas-liquid interaction

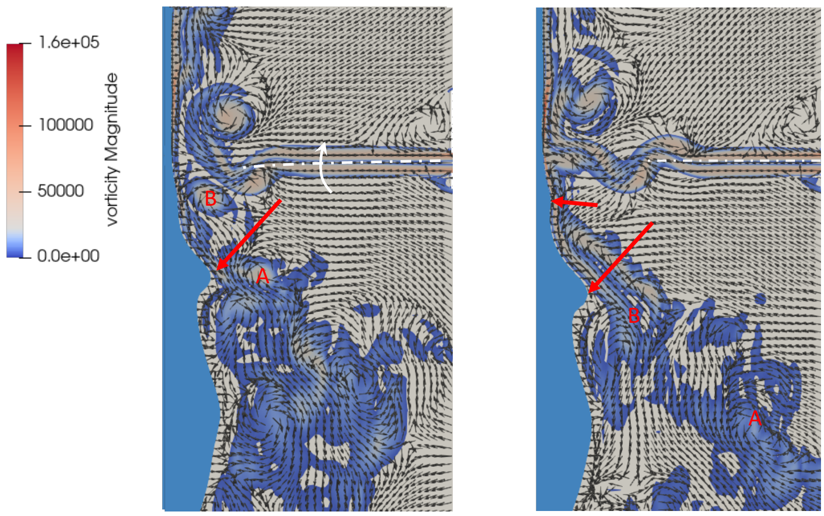



t = 0 s

t = 0.015 s

# 4. Results

Gas-liquid interaction




t = 0.035 s

t = 0.040 s

## Outline

1. Industrial context
2. Objectives
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5. **Conclusions and perspectives**

## 5. Conclusions and perspectives

- 3D VOF-LES simulations are capable to predict reasonably well the main characteristics of the gas and liquid flow in jet wiping.

- Instability mechanism has been decrypted and confirms the hypothesis of a robust coupling between the runback film and the gas jet.
European Coating Symposium 2019, Heidelberg.

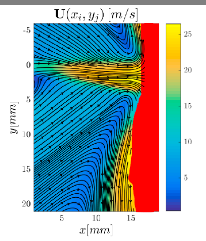
- The computational cost of these simulations makes it prohibitive for industrial purpose.
  - 300 – 700 hours CPU / s of real flow for dipropylene
  - Difficulties in galvanization conditions: Lower coating thickness, higher gas speed, high surface tension

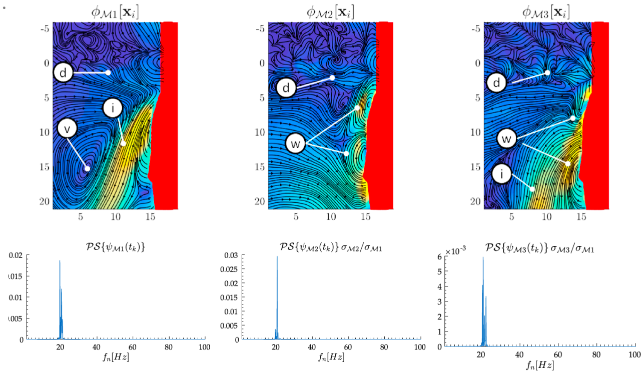
| Zinc | | Dipropylene glycol |
|---|---|---|
| $h_f \sim 5 - 10\ \mu m$ | ⟷ | $h_f \sim 300 - 600\ \mu m$ |
| $150 \leq V_{jet} \leq 200\ m/s$ | | $20 \leq V_{jet} \leq 60\ m/s$ |
| $1.5 \leq U_p \leq 2.5\ m/s$ | | $0.3 \leq U_p \leq 0.5\ m/s$ |

## 5. Conclusions and perspectives

<u>What remains to be done:</u>
Advanced processing of the gas flow field with multi-scale Proper Orthogonal Decomposition (mPOD)

Mendez, Balabane, Buchlin (2019) JFM 870:988-1036.
Mendez, Gosset, Buchlin (2019), Exp Therm Fluid Sci 106:48-67.



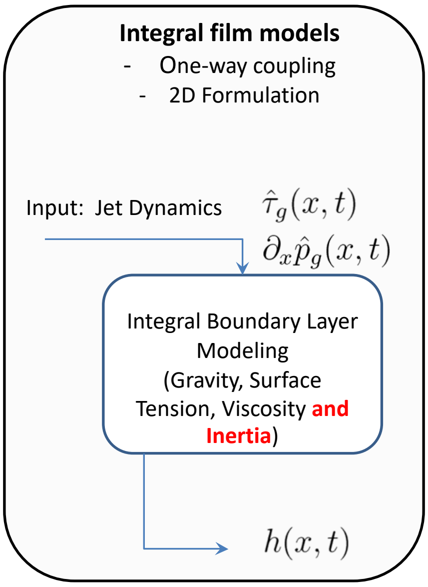




## 5. Conclusions and perspectives

<u>What remains to be done:</u>

- Formal validation of integral film models, a potential alternative with ≈ $10^5$ lower computational cost.

- Application to real galvanization conditions.



## Thank you for you attention!

**Anne Gosset, David Barreiro Villaverde, Marcos Lema Rodríguez, Miguel Alfonso Méndez**

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