ON THE JET WIPING OF HIGH KAPITZA LIQUID FILMS

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The jet wiping is a contactless metering technique used in the hop-dip galvanization process to accurately control the zinc coating weight on steel substrates. A planar gas jets impinges perpendicular to the film, reducing the thickness of the coating dragged by a moving strip, and developing a runback flow as sketched in Figure 1. For some operating conditions, the final product is affected by the appearance of long-wavelength patterns in Figure 1, usually referred to as undulations, due to a two-phase flow instability between the gas jet and the liquid film [1,2].

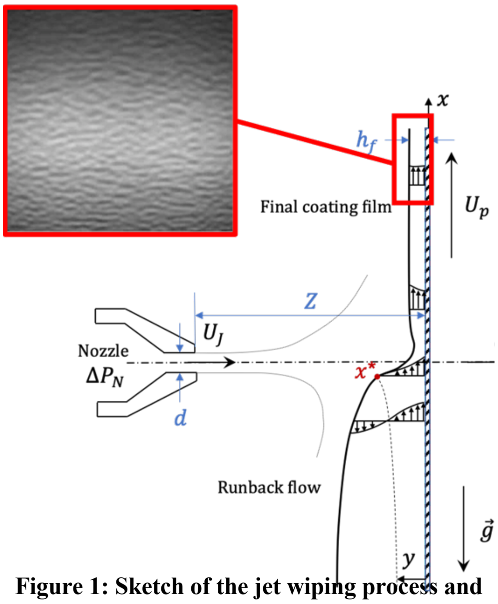


Figure 1: Sketch of the jet wiping process and experimental visualization of the undulations.

CFD simulations have been carried out to investigate the hydrodynamic mechanism responsible for the undulation. Recently, a numerical model in OpenFOAM that combines Volume of Fluid (VOF) and Large Eddy Simulation (LES) has been extensively validated with experimental data for laboratory scale wiping configurations [3,4]. Multiscale modal decomposition and correlation analysis have shown that the undulations emerge from the unsteady wiping efficiency of the gas jet triggered by the periodical formation of large waves in the run-back flow.

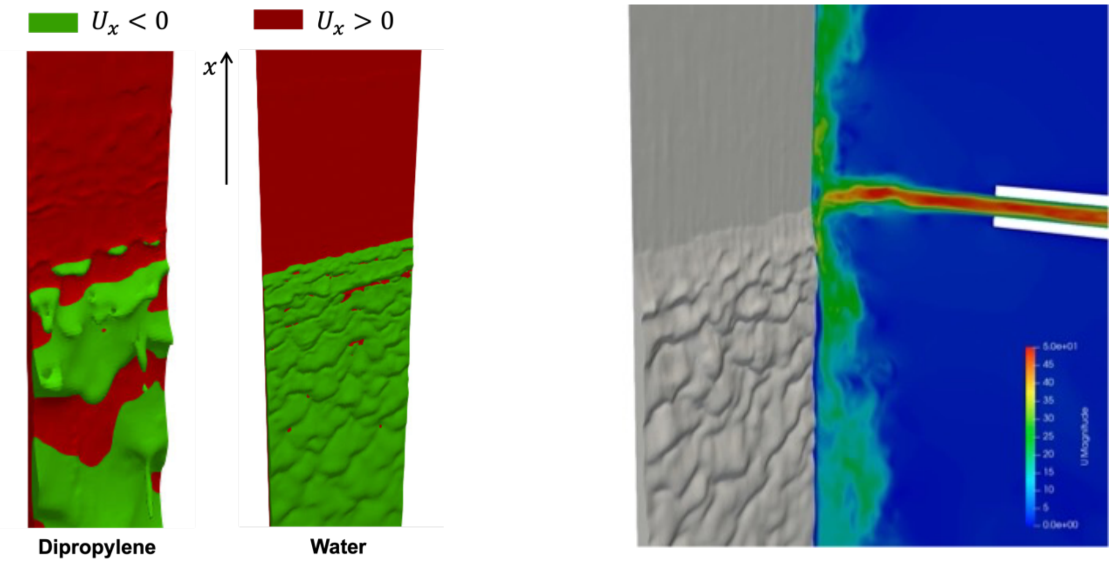
The relevant dimensionless quantities in jet wiping are the following: on the liquid side, the film Reynolds number $Re_f = U_p h_f/\nu_l$, the Capillary number $\mathrm{Ca} = \mu_l U_p/\sigma$, and the Kapitza number $Ka = \sigma/\rho_l g^{1/3} \nu_l^{4/3}$, and on the gas side, the gas jet Reynolds number $Re_j = U_j d/\nu_l$ and the wiping number $\Pi_g = \frac{\Delta P_N d}{\rho_l g Z^2}$, which represents the wiping strength as it is proportional to the pressure gradient generated by the jet at the interface. The comparison in Table 1 shows that the previously investigated lab scale configuration with dipropylene glycol is not expected to represent well the industrial zinc galvanization. The film flow is dominated by viscosity, while surface tension is expected to play a negligible role in the damping of the undulation. On the other hand, the computational cost of simulating the industrial process with molten zinc is hardly feasible according to Aniszewski et al. [5], and our own experience, due to the vastly different scales in the gas and the liquid. In this work, we simulate an air- water wiping characterised by improved similarity conditions: the Ca and Ka numbers are orders of magnitude closer to galvanization and the strength of wiping is comparatively stronger.

The simulations are performed using the validated numerical model based on the two-phase flow solver interFoam of OpenFOAM 9. The working liquid is water, with density $\rho_l = 1000\ \mathrm{kg/m^3}$, dynamic viscosity $\mu_l = 10^{-3}\ Pa \cdot s$ and surface tension $\sigma = 0.072\ N/m$. The coating layer is formed by withdrawing the flat substrate from a liquid bath at a speed U_p=1 m/s, and then impinged by a slot gas jet with a nozzle opening d=1 mm and standoff distance Z=10 mm. The 3D domain is discretized with 20M hexahedral elements using blockMesh. The time step is below 10^{-7} to ensure that the CFL is always below 0.9 and second order schemes are applied in time and space. The computations are parallelized in 512 processors at the Centro de Supercomputación de Galicia (CESGA), requiring approximately 2000 h of computational time per second of real flow and generating more than 10 TB of high-quality data of the flow.

Table 1: Comparison of the dimensionless numbers for three characteristic wiping configurations.

	Dipropylene glycol	Water	Zinc galvanization
Re_f	2.1	28	18
Ca	0.80	0.014	0.0037
Ka	4.8	3400	16440
Re_j	2380	2830	14370
Π_g	0.16	1.02	2.45

A preliminary analysis confirms that the hydrodynamic mechanism responsible for the undulation differs from the one identified with the previous computations with dipropylene glycol. Figure 2 (a) illustrates the effect of the jet wiping strength on the run-back flow, where the image on the right displays a weak wiping in which the run-back flow does not reach a fully developed state with dipropylene. The run-back waves are periodically developed when the amount of liquid at the impact is such that the combined action of the gas jet and gravity overcome the viscous drag imposed by the moving plate. On the contrary, the wiping action of the jet with water is stronger, as the runback is established, and the position of the interface below the gas jet is steadier. Therefore, we do not expect the undulation to be a confinement-driven instability as in the previous computations, but more related to the high frequency flapping of the jet. The jet tip is highly distorted as shown in Figure 2 (b), introducing small scale disturbances in the wiping efficiency –and therefore in the coating thickness– that propagate towards the final coating and the run-back flow.



(a) (b)

Figure 2: 3D representation of the liquid film where the areas of the streamwise velocity Ux>0 are shown in red and areas of Ux<0 in green for the simulations with dipropylene glycol [3] and water (a); and flow visualization of the velocity field at the midplane of the domain (b).

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References

[1] Gosset, A., Mendez, M. A., & Buchlin, J. M. (2019). An experimental analysis of the stability of the jet wiping process: Part I – Characterization of the coating uniformity. Experimental Thermal and Fluid Science, 103, 51–65.

[2] Mendez, M. A., Gosset, A., & Buchlin, J. M. (2019). Experimental analysis of the stability of the jet wiping process, part II: Multiscale modal analysis of the gas jet-liquid film interaction. Experimental Thermal and Fluid Science, 106, 48–67.

[3] Barreiro-Villaverde, D., Gosset, A., & Mendez, M. A. (2021). VOF-LES simulation of the jet wiping process: validation and multiscale modal analysis. 16th OpenFOAM Workshop.

[4] Barreiro-Villaverde, D., Gosset, A., & Mendez, M. A. (2021). On the dynamics of jet wiping: Numerical simulations and modal analysis. Physics of Fluids, 33(6).

[5] Aniszewski, W., Saade, Y., Zaleski, S., & Popinet, S. (2020). Planar jet stripping of liquid coatings: Numerical studies. International Journal of Multiphase Flow, 132, 103399.