MULTISCALE ANALYSIS OF 3D VOF LES SIMULATIONS OF THE JET WIPING PROCESS

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1 INTRODUCTION

Jet wiping is a metering technique used in the hop-dip galvanization process to control the zinc coating weight on steel substrates. As sketched in Figure 1 (a), a slot gas jet impinges on the liquid film dragged by the solid substrate, reducing the coating thickness and developing a run-back flow. It is the most widely used technique because it is contactless and energy-efficient, although the violent break-up of the run-back flow (splashing) and the formation of undulations in the final coating limit the range of operational windows. The final coating thickness is a function of the stand-off distance Z, the nozzle opening d, the substrate speed Up, and the gas jet velocity Uj; the latter being determined by the static pressure in the stagnation chamber of the nozzle ΔP_N. The momentum exchange between the gas jet and liquid film is described by the wiping actuators, namely the streamwise pressure gradient $\partial_x p_g$ and shear stress at the interface τ_g.

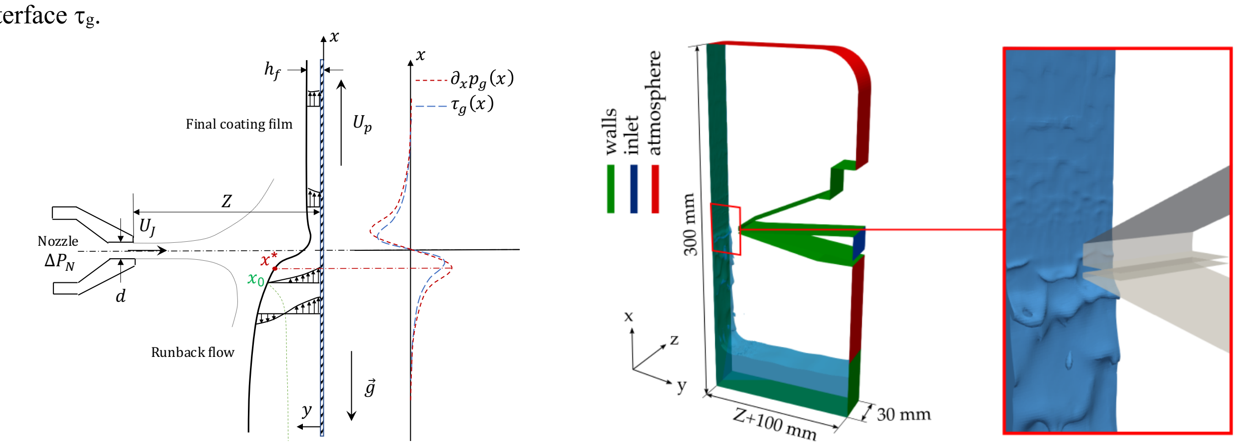

Figure 1. Sketch of jet wiping (a) and 3D domain with the boundary conditions with a snapshot of the liquid film (b).

An experimental campaign allowed the characterization of the gas and liquid film simultaneously for a wide range of wiping regimes (Mendez et al., 2019a). The spectral matching between the gas and film flows suggested that the mechanism of wave formation results from a two-phase coupling instability. Numerical investigations using Large Eddy Simulation (LES) and Volume of Fluid (VOF) also reported jet oscillations at temporal scales compatible with the undulations in the film using dipropylene glycol as working liquid (Myrillas et al., 2013).

This work aims at modelling the jet wiping process with 3D VOF LES simulations for a complete description of the undulation mechanism. The numerical model has been validated with experiments in terms of mean final thickness (Barreiro-Villaverde et al., 2019). We apply the multiscale Proper Orthogonal Decomposition (mPOD) to identify the main undulation patterns in the film. An extended mPOD based on correlation analysis is implemented to isolate the associated structures in the gas.

2 NUMERICAL METHODS

The CFD simulations combine Large Eddy Simulation (LES) for the turbulent gas flow and Volume of Fluid (VOF) to account for the two-phase nature of the problem. Three simulations were performed with interFoam, an incompressible two-phase flow solver of the OpenFOAM package that implements an algebraic VOF formulation. The LES methods involves a low pass filtering of the Navier-Stokes equations, modelling the effect of sub-grid scales with an additional turbulent viscosity given by the Smagorinsky model. The three configurations reproduce two standoff distances and two nozzle pressures (Case 1: Z=18 mm, ΔPN=425 Pa | Case 2: Z=18 mm, ΔPN=875 Pa | Case 3: Z=25 mm, ΔPN=875 Pa) using air and dipropyleneglicol (ρl=1023 kg/m3, μl=0.075 Pa·s, σ=0.032 N/m). The computational domain with the boundary conditions is shown in Figure 1(b), and the time step is of the order of 10^{-6} to ensure that the Courant number is always below 0.95. The entire project consumed 3.5 M CPU hours of priority access in the Spanish Supercomputing Network (RES).

The flow fields are post-processed with the multiscale Proper Orthogonal Decomposition (mPOD) to isolate the different spatio-temporal scales in the film flow (Mendez et al., 2019b). The decomposition breaks the datasets as a linear combination of elements (r-modes) characterized by a temporal evolution ψr, spatial structure ϕr, and amplitude Σr. The spectral content of the modes is constrained to a specific frequency range imposed with a filter bank. First, we compute the modes in the liquid to detect the most dominant undulation patterns. Second, we use the temporal structure of these modes to project the gas flow fields, namely the velocity fields and wiping actuators. This step allows detecting correlated structures between the undulations and the seemingly chaotic gas flow.

3 RESULTS AND CONCLUSIONS

As shown in Figure 2, the spatial structure ϕ_2 associated to one of the leading modes preserves most of the flow features observed in the snapshot of the normalized film thickness $\check{h}$. The reconstruction built from these dominant modes portrays two-dimensional wave patterns that originate close to the impingement and propagate in opposite directions along the final film and run-back flow. Moreover, the frequency peaks of these modes match perfectly the one in the gas jet, proving that it must result from a two-phase coupling interaction. The same holds for the rest of the cases, even when the liquid film shows strong three-dimensional patterns. We refer to this pattern as the *2D coupled undulation*.

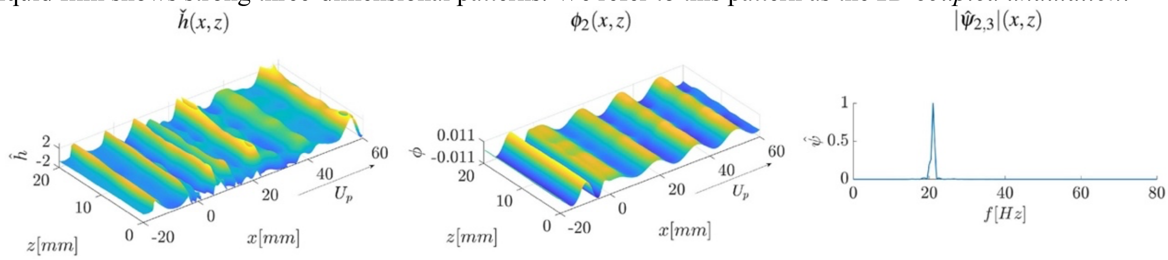

Figure 2. Snapshot of the normalized thickness $\check{h}$ (left), spatial structure of one of the leading modes in the liquid ϕ_2 (middle), and associated frequency spectra $|\hat{\psi}_{2,3}|$ (right).

The extended mPOD allows revealing the structures in the gas jet correlated with the 2D coupled undulation. Figure 3 illustrates the fluctuating velocity field and wiping actuators distributions associated to the undulation and taken at a z constant midplane. The vortical structure below the nozzle axis indicates a periodical deflection of the lower side jet and airflow detachment associated to the formation of the run-back waves. The effect of this mechanism on the wiping actuators is a pulsation of the pressure gradient at this location that modulates the wiping efficiency periodically, producing the undulation. An exhaustive analysis of the three investigated cases with the full description of the mechanism is provided in (Barreiro-Villaverde et al., 2021).

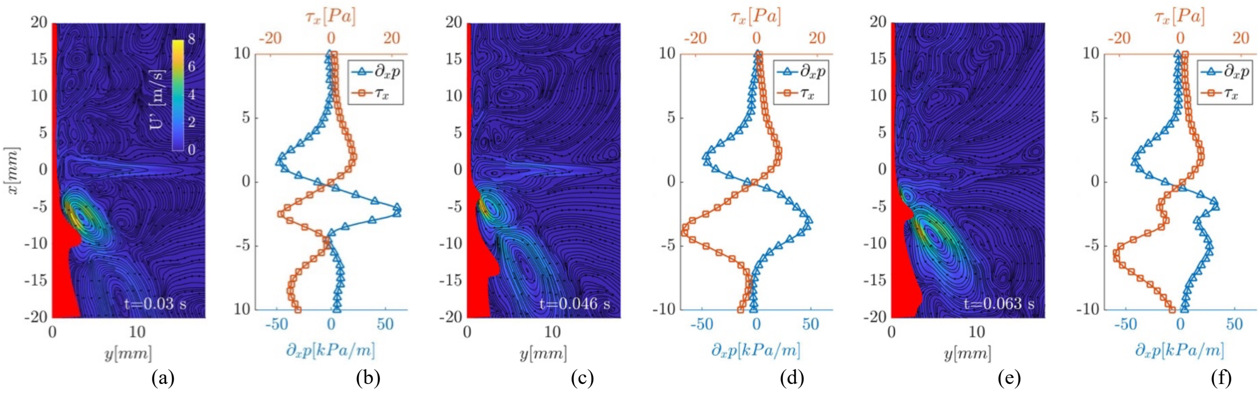

Figure 3. mPOD filtered fluctuating velocity field (a,c,e) and wiping actuators (b,d,f) for three different time steps.

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