VOF-LES SIMULATION OF THE JET WIPING PROCESS: VALIDATION AND MULTISCALE MODAL ANALYSIS

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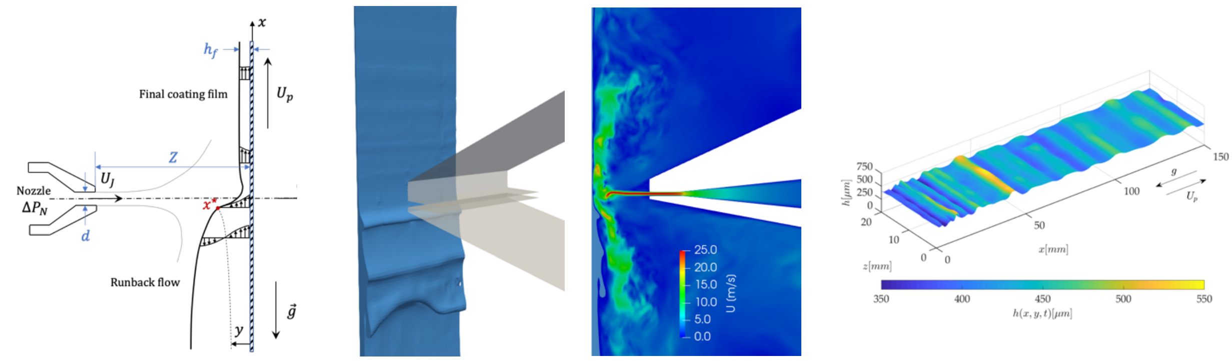
Jet wiping is a coating process in which a liquid is dragged by a flat substrate moving upwards after dipping in a coating bath. In order to control accurately the thickness of the liquid film deposited on the surface, two slot gas jets impinge on both sides of the film, acting literarily as “air-knives”: the final coating thickness is reduced and the excess liquid flows back to the bath as a *runback,* as shown in Fig.1(a). In spite of its undeniable advantage to be contactless, the process is limited by the appearance of large amplitude waves on the final product after solidification, known as *undulations*, of main concern for quality standards. The experimental investigations conducted by Gosset et al. [1] and Mendez et al. [2] suggest that their origin is a hydrodynamic feedback mechanism between the gas jet and the liquid film. The objective of this work is twofold: first, it aims at resolving numerically the liquid-gas coupling with the Volume Of Fluid (VOF) method and Large Eddy Simulation (LES) for turbulence modelling, and validate the results with experiments. Second, it seeks to identify the basic mechanism of wave formation using a novel modal analysis decomposition technique [3,4], and link it with the jet behaviour.

Three wiping test cases experimentally characterized in Mendez et al. [2] are simulated with the VOF formulation implemented in the *interFoam* solver, while a Smagorinsky LES model is used to accurately predict the gas jet behaviour. The Multiscale Proper Orthogonal Decomposition (mPOD) [3] is used to identify the coherent patterns in the liquid and gas dynamics, characterized by a wide range of spatial and time scales. mPOD is a data-driven decomposition that combines the advantages of energy (Proper Orthogonal Decomposition) and frequency (Dynamic Mode Decomposition) based methods: the spectral content of the modes is restricted to a certain frequency range by using Multi Resolution Analysis (MRA). The decomposition is performed using the open-source package MODULO [4].

An overview of the results for one test case is shown in Fig.1, with the 3D reconstruction of the liquid film interface (b), the contour map of the gas velocity field in the midplane (c), and the final film thickness distribution after post-processing of the volume fraction fields (d). In this wiping condition, the liquid film features two-dimensional wave patterns in both the final film and runback flow. It can be seen how the gas jet, after impingement, divides into two side jets, the bottom one being substantially deflected by the large waves on the runback.

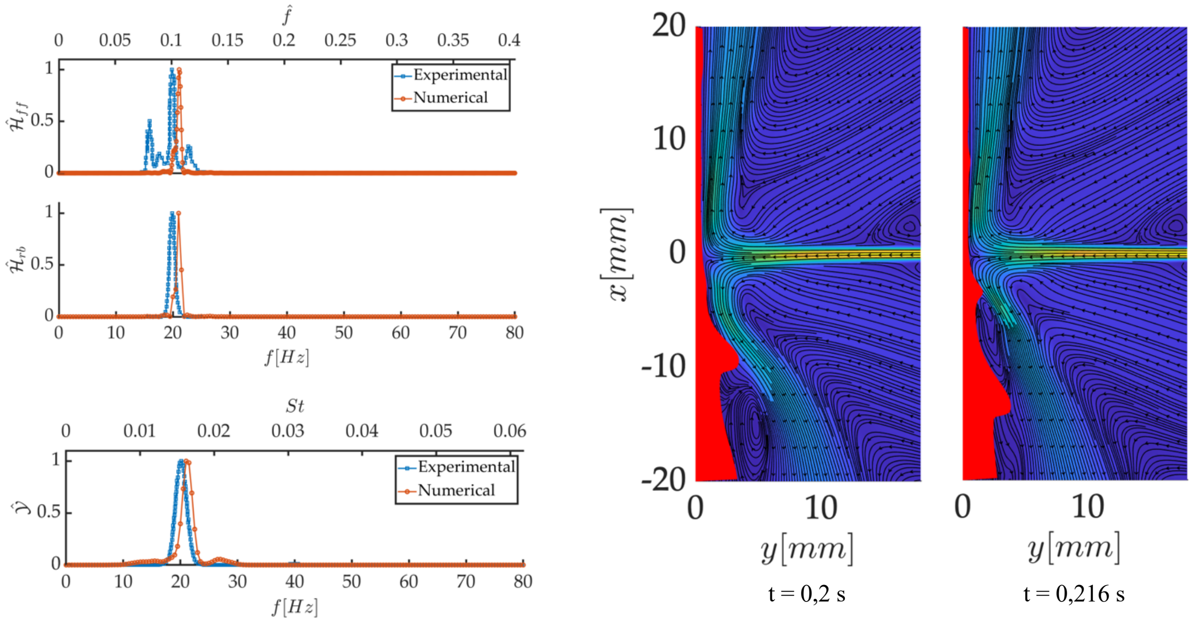


(a) (b) (c) (d)

Figure 1: Sketch of the jet wiping process (a), 3D film reconstruction (b), contour map of the velocity field in a midplane (c), and the final film thickness distribution (d).

The numerical model is successfully validated in terms of final film mean thickness and liquid/gas frequency content. The spectra in Fig.2(a) are computed from the leading mode obtained in the multiscale analysis of the final film $\hat{\mathcal{H}}_{ff}$, the runback flow $\hat{\mathcal{H}}_{rb}$ and the gas jet $\hat{\mathcal{Y}}$. The agreement between the experimental and numerical data is remarkable, as is the fact that the same frequency peak is detected in the three quantities. This is clearly the proof that the undulations are produced by a coupling mechanism in which the film and the gas jet are locked onto a certain frequency, as suggested in the hydrodynamic feedback hypothesis. In the other two test cases, characterized by more three-dimensional wave patterns, the gas jet and runback wave frequencies are also in good agreement. In spite of a slower convergence of the mPOD decomposition, i.e. more modes are needed to describe the film dynamics, the same basic 2D mechanism is detected, in which the jet motion is coupled with the large runback waves: the *2D coupled mode*.

An extended modal analysis is also performed using the temporal structure of the most dominant modes in the liquid dynamics to detect the correlated flow structures in the gas jet. This allowed linking the formation of the waves on the runback flow with the deflection of the side jet attached to the interface in the region $x < 0$, as it can be seen in the reconstruction of the velocity field using only the 2D coupled mode in Fig.2(b). Most importantly, this motion is found to be accompanied by a pulsation of the pressure gradient generated by the jet at the film interface, just below the jet axis. The undulation originates from the resulting unsteady wiping efficiency, and then propagates through the entire domain due to the advection nature of the system. The mechanism seems thus to be triggered and self-sustained by the unsteady confinement of the jet produced by the waves of the runback flow.



(a) (b)

Figure 2: Spectral content of the most dominant modes in the liquid film and gas jet for the CFD simulations and experiments (a) and reconstructed velocity field in for two snapshots in a midplane using the pair of modes correlated with the main undulation pattern (b).

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