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High and low fidelity models to investigate the instabilities in jet wiping

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The jet wiping process is applied in hot-dip galvanization to control the coating thickness dragged by a moving strip, by means of an impinging gas jet. We analyze this flow configuration using high-fidelity two-phase simulations and low fidelity analytical models to investigate several aspects of the flow such as the formation of non-uniformities on the final product. The high-fidelity model combines the Volume of Fluid (VOF) and Large Eddy Simulations (LES) methods, while the low fidelity model simplifies the system of equations for the liquid film based on the long-wavelength approximation. In this work, we discuss the application of these two models to investigate the physics of jet wiping, in particular to understand the flow instabilities that lead to the appearance of wave patterns on the final product.

INTRODUCTION

The jet wiping process is used in many different applications in the paper, photographic and galvanization industries to control the thickness of a coating layer attached on a moving substrate, by means of 2D impinging gas jets. Figure 1 illustrates the flow configuration encountered in hot-dip galvanization: the coating layer is dragged by a flat steel strip withdrawn at a speed U_p from a molten zinc bath at 460 ºC. The high-speed gas jet interacts with the coating film (still in liquid state) in such a way that the excess liquid forms a runback flow back to the bath, leaving the substrate covered with the desired coating mass. However, in a wide range of process conditions, this liquid-gas interaction leads to the appearance of wavy patterns in the coating, usually referred to as undulation. The latter affects the surface finish of the galvanized strips when dry.

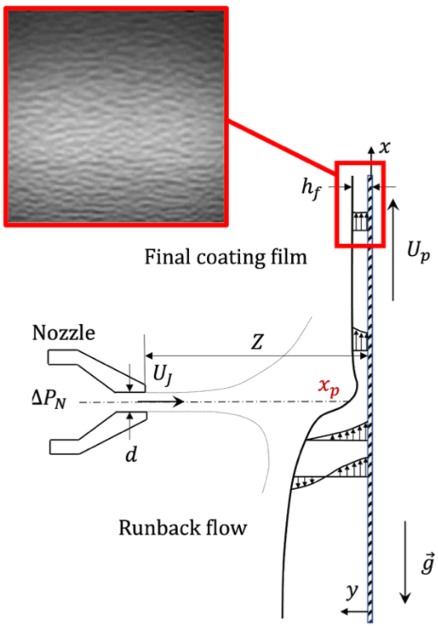

FIG 1. Sketch of the jet wiping process and experimental visualization of the undulation.

In this work, we investigate the application of high and low-fidelity models to understand the hydrodynamic mechanism responsible for the undulation.

NUMERICAL METHODS

The high-fidelity model is based on a full resolution of the two-phase flow combining the VOF and LES models. This approach has been recently validated with experimental data in Barreiro-Villaverde et al [1] for laboratory scale conditions. The simulations are performed using OpenFOAM 9 on a 20M structured mesh. The time step is of the order of 10^{-7} s and requires approximately 4000 CPU hours per second of real flow using 1024 cores in parallel.

On the other hand, the low-fidelity approach is based on an integral model for the liquid film, which relies on the long-wavelength approximation. In this approach, the liquid flow equations are integrated across the film thickness, reformulating the problem as a function of thickness and flow rate [2]. The model is one-way, in the sense that it assumes the gas jet flow is not affected by the film dynamics. The effect of the gas jet on the film is introduced through the spatio-temporal distributions of the pressure gradient and shear stress at the interface. A three-dimensional formulation implemented in python [3] has been validated for its application in jet wiping to predict the final film dynamics [4]. The computational cost of this model is considerably lower than the high-fidelity CFD; although it requires realistic distributions for the pressure gradient and shear stress, which can be difficult to obtain when the liquid-gas coupling is strong.

RESULTS

The configuration analyzed here uses water as a coating fluid, with density ρ_l=1000 kg/m^3, dynamic viscosity μ_l=10^{-3} Pa·s and surface tension σ=0.072 N/m. The nozzle pressure is set to ΔP_N=1 kPa and the substrate speed is U_p=1 m/s. The slot nozzle opening d=1 mm and the jet standoff distance is Z=10 mm. Those conditions ensure improved similarity with respect to galvanization [4].

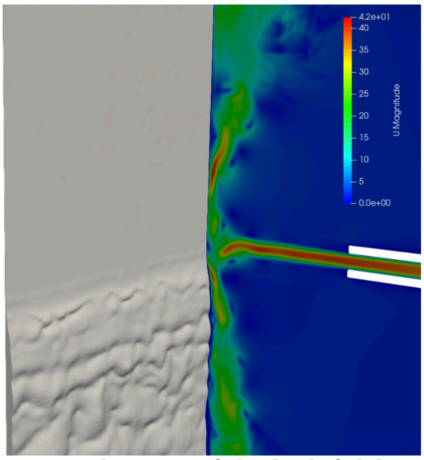

FIG 2. Flow visualization of the high fidelity CFD simulation: 3D reconstruction of the liquid film and contour plot of the velocity field for a midplane in z.

Figure 2 shows the film interface and the velocity magnitude field in the midplane obtained in the two-phase CFD simulations. The impingement of the turbulent gas jet contributes to reducing the thickness of the film ($h_f \approx 30\,\mu m$) and developing a wavy run-back flow ($h_{rb} \approx 500\,\mu m$). Note that the undulations are not visible here due to the extremely reduced thickness of the final film. In contrast with more viscous fluids [1], the coupling between the gas jet and the liquid is weaker because of the film is less intrusive. However, it is interesting to see that the waves on the runback are qualitatively similar and are in both cases responsible for the time fluctuation of the wiping efficiency, which leads to the undulation.

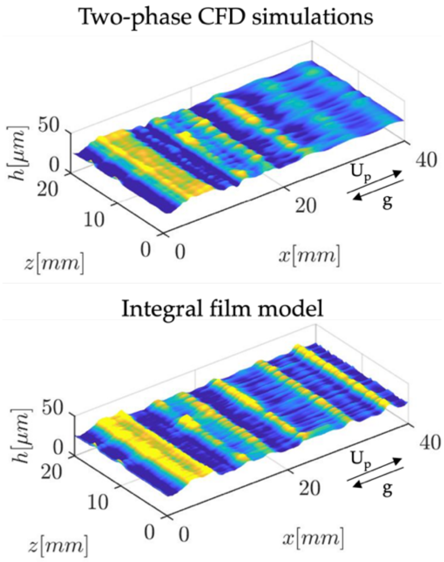

FIG 3. Comparison of the undulation patterns predicted by the CFD (top) and liquid film model (bottom).

Figure 3 compares the instantaneous undulation predicted by the CFD simulations (top) and the integral model (bottom). The integral model is fed with the data from the CFD computations: the film thickness and flow rate at the inlet of the domain, which corresponds to the impact point denoted as x_p in figure 1; and the interfacial shear stresses and pressure gradients due to the gas jet.

The qualitative agreement is remarkable. The low-fidelity model captures even the small scale structures observed in the CFD computations. The main differences are located downstream wiping, and they are linked to the numerical diffusion produced by large cell aspect ratios at x>20 mm in the final film.

CONCLUSIONS

We have presented the application of high and low fidelity models for the jet wiping process.

The two-phase CFD model allows resolving the full interaction between the liquid and the gas, but its computational cost is prohibitive to be used in industrial conditions. On the other hand, the low fidelity model allows capturing very well the dynamics of the final film at a fraction of the computational cost of the CFD simulations, although the accuracy of the results depends on the quality of the inputs of the model. In this sense, the combination of these two models could be an interesting path for future work.

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