Proceeding Paper

Numerical Simulations and Modal Analysis to Investigate the Defects in a Coating Process †

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Abstract: This work investigates the hydrodynamics of jet wiping, a coating process in which a thin slot gas jet impinges on a coating film dragged by a moving strip; thus, reducing the coating thickness and developing a run-back flow. The interaction between the liquid film and the gas jet is highly unsteady, producing long-wavelength defects on the final product known as undulations. We perform Computational Fluid Dynamics (CFD) simulations of the process using High-Performance Computing (HPC) resources. A multi-scale modal analysis is then applied to decrypt the mechanism of wave formation. The main undulation pattern features two-dimensional waves and is correlated with a large-scale motion of the gas jet.

Keywords: computational fluid dynamics (CFD); high-performance computing (HPC); numerical simulations; multi-scale modal analysis; coating process; multiphase flows

1. Introduction

Jet wiping is a contactless coating technique used to control the thickness of a thin film. It is intensively used in hot-dip galvanization, where the steel substrate is dipped into a molten zinc bath at 460 °C, dragging a coating layer on its surface as it is withdrawn vertically from the bath. The film thickness is reduced and controlled by a slot gas jet normally impinging on the liquid film; thus, acting as an air knife. The final coating mass applied on the substrate is a function of several process parameters represented in Figure 1: the nozzle to substrate stand-off distance, Z, the nozzle slot opening, d, the substrate speed, U_p, and the gas jet velocity, U_j.

Over a large portion of the process operational window, the final coating film displays long-wavelength patterns that alter the quality of the product (Figure 1). In a recent experimental study, the liquid film and gas flows were characterized simultaneously for several wiping conditions [1]. The spectral matching observed between the gas jet and the liquid flow suggested that the undulations are produced by a two-phase coupling instability, although the complete mechanism could not be captured. The present work aims at understanding the two-phase interaction that, ultimately, leads to undulation, using Computational Fluid Dynamics (CFD) simulations and a multi-scale modal analysis.
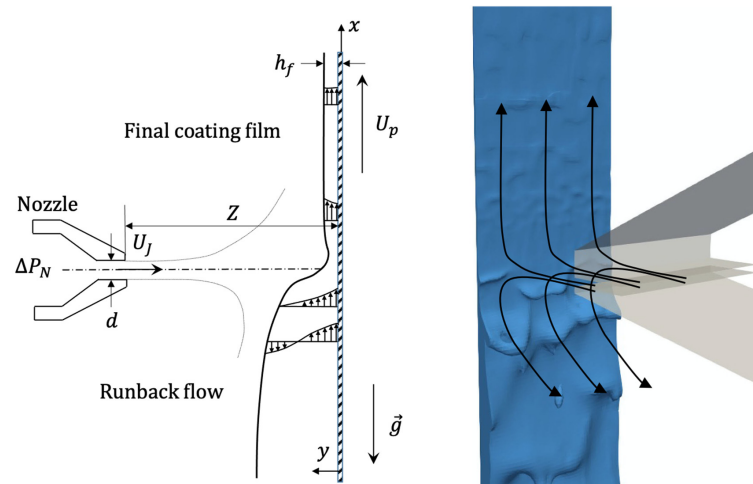
Figure 1. Two-dimensional sketch of the jet wiping process (**left**) and rendering of the flow patterns in the film for laboratory wiping conditions (**right**).

2. Methodology

We performed high-fidelity simulations of the jet wiping process in laboratory scale conditions, as described in Mendez et al. [1]. For that purpose, the incompressible two-phase flow solver InterFoam of the CFD open-source libraries OpenFOAM wass used. The numerical model was based on the Volume of Fluid (VOF) technique, to account for the two-phase nature of the problem, and Large Eddy Simulation (LES) for the treatment of turbulence in the gas jet. Its complete validation has recently been published [2].

The mesh features 10–12 M computational nodes, and the time step ranges between 1.5×10^{-6} and 7×10^{-7} s. The flow governing equations were solved numerically using 288 Intel E5-2680v3 CPUs at the Centro de Supercomputación de Galicia (CESGA), consuming a total of 3M CPU hours of priority access granted by the Spanish Supercomputing Network (RES). The flow datasets were post-processed using Modal Analysis, which consists in splitting the data as a linear combination of elementary contributions (modes). The multi-scale Proper Orthogonal Decomposition (mPOD) [3] is a data-driven decomposition—which means that the basis is built from the data itself—that classifies the modes according to their energy and frequency content; thus, featuring structures that are coherent in time and space. In this work, the mPOD was applied for the analysis of the final film flow in order to isolate the main undulation patterns. In a next step, an extended mPOD was implemented to detect the structures in the gas jet that were strictly linked to the formation of the undulation. The latter was based on the projection of the gas fields onto the temporal basis of the dominant modes of the film flow.

3. Results and Discussion

The modal decomposition of the high-fidelity simulations revealed the most relevant scales in the two-phase mechanism of wave formation. Figure 2 shows a comparison between the original and the mPOD filtered spatial normalized thickness distribution for one time step. This approximation featured a two-dimensional travelling wave pattern built from two of the most energetic modes with comparable energy and delayed $\pi/2$ in both space and time. It was remarkable how well the film flow was approximated using only a pair of mPOD modes.

The filtered gas velocity fields in Figure 3 were retrieved using the extended mPOD. The small scales observed in the original velocity fields were clearly uncorrelated with the coating waves and, therefore, were irrelevant for the mechanism of wave formation. In contrast, the undulations were well correlated with a large-scale deflection of the lower side jet, induced by the passage of large waves on the run-back flow.
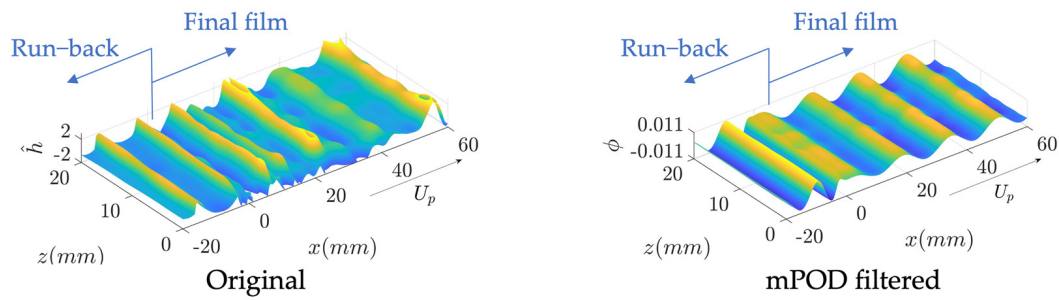
Figure 2. Snapshot of the original and mPOD filtered normalized thickness distributions.
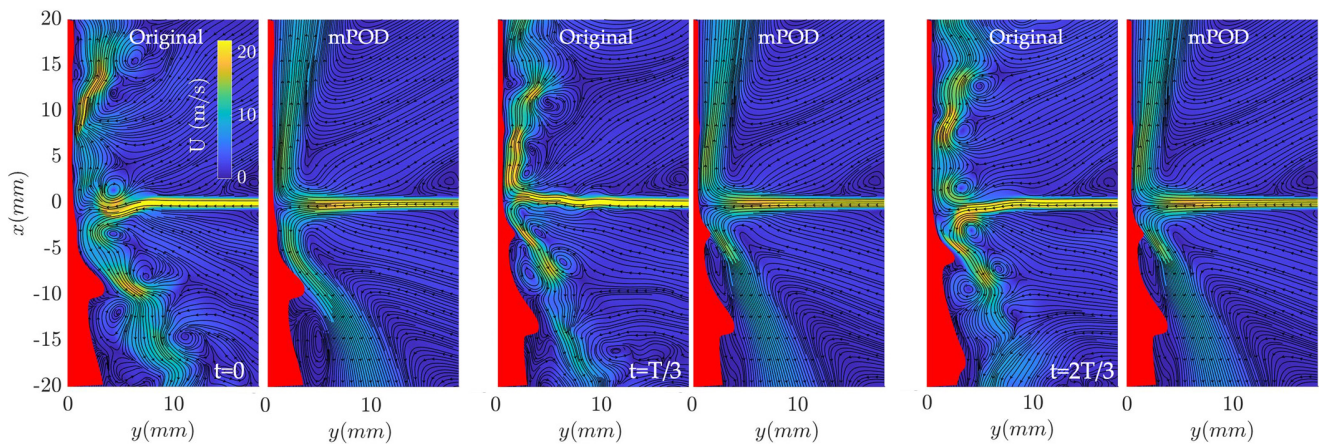

Figure 3. Snapshots of the original and mPOD filtered velocity fields for three time steps in a period T of wave formation. The instantaneous liquid film is represented in red.

4. Conclusions

The combination of high-fidelity CFD simulations and a multi-scale modal analysis allowed decrypting the main mechanism at the origin of undulation defects in jet wiping. For the wiping configuration under study, the final coating exhibited two-dimensional wave patterns originating at the location of the jet impact, due to the unsteady confinement produced by the passage of waves in the run-back flow. The mPOD is an excellent tool to identify coherent patterns in fluid flows; the filtered datasets retained the most relevant features of the flow with only two modes, achieving a compression rate of 1000.

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