Numerical simulations of planar jets stripping of liquid coatings

W. Aniszewski*[1], S. Zaleski[1], S. Popinet[1]
[1]Institut Jean le Rond d'Alembert - CNRS UMR 7190 - Sorbonne Universite, Paris, France
*Corresponding author: aniszewski@dalembert.upmc.fr

Introduction

In the process of *coating* - such as found in photography, lamination or metallurgy, a moving flat sheet of coated material (e.g. steel) emerges -- usually moving vertically -- from a bath of liquid coating material. Depending on parameters the resulting film formation process may be entirely laminar or turbulent [1]. This first stage process of film formation ends before film solidification, thus temperature evolution and energy can be disregarded. In some processes, the coat is complete after gravitational forming - in other applications it is modified.

In this work, we indeed focus on the *second stage*, which is modification of the formed coat/film by airflow, issuing from flat nozzles, known as "*airknives"*. They strip excess coat from the product, resulting in film thickness orders of magnitude smaller than that formed in the first stage via gravity-governed flow. The airflow in the jets is strongly turbulent at Reynolds numbers Re > 15000, imposing high computation costs. Still, pressure profile converges to a bell-shaped curve centered at the impact line [2]. The resulting stresses modify liquid coat flow resulting in thinning of the coat above the impact zone.

Materials and methods

Numerical investigation of the coating mechanism benefit if the deposit is created gravitationally, even in the high-Reynolds number regime. Thus, our simulations include entire liquid coating basin filled with zinc, and the coated band up to the height at which nozzles are located (0.4m) with additional 0.25m - tall zone above to accommodate , resulting in a 0.65m - tall domain. In three dimensions, the upward-moving coated sheet/band is located in 0.2m wide domain's center. This, considering with a 10-100 µm coat thickness results in an extremely large range of scales. For a more precise study, we have also investigated another, more "academic" version of this study, wherein only half of the coated band is considered (with one air-knife present at its side) and a symmetry condition is used. Results from this setup are presented below.

Due to extreme range of scales, we apply the grid-refinement technique (local AMR, [3]) withing the in-house code *Basilisk* [5]**.** which is optimized for high efficiency in serial and parallel execution. The N-S solver uses finite differences, modern time progression schemes and Volume of Fluid method to track the interface. Even with that precautions, the computational cost of such simulation is prohibitive for current computers. We therefore limit the AMR technique in such way, that full resolution can be attained only close to the air-liquid impact zone and inside the nozzle. The former of these areas is where the gas-liquid momentum exchange takes place, and liquid is thinned by the airflow. The latter is obviously crucial as we need turbulence to develop properly inside the nozzle.

Results and Discussion

The simulation involves fully realistic industrial parameters: liquid density ϱ_l and viscosity μ_l correspond to liquid Zinc at ϱ=6500 kg m^3 and 0.00317 Pa s respectively. The upward-moving wall is first coated (the "first stage" mentioned in the Introduction) gravitationally, once it emerges from a bath full of liquid. The upward wall velocity is 2 m/s, which results in a turbulent withdrawal [1] (*Re* based on the zero-flux film thickness reaches 2500). One the coat is formed, airflow in the nozzle begins. The injection velocity u_{inj} is 200m/s, flat profile is injected. The distance between nozzle exit and the coated wall (and, hence, liquid film) is 1 centimeter. Coated wall is 0.512m tall, 0.15m wide (*z* extent) and 0.5mm thick. The nozzle slit is 1mm (measured along *y* axis). The nozzle is 0.25m wide (measured along *z* axis) and 0.511m long (measured along *x* axis). Naturally, the simulation domain is 0.512m^3. It has to be noted that at the moment, the *Basilisk* code supports square/cubic domains only. Masks can be used to limit the simulation region shapes to non-cubic, however to simplify implementation we opt for a non-restricted, cubic domain with entire flow concentrated next to the '*x-'* wall. Since air injection is defined on the '*x*+' wall, air travels through entire domain length before issuing from the nozzle. This ensures - even numerically - a sufficient level of mixing in the airflow before it exits the nozzle.

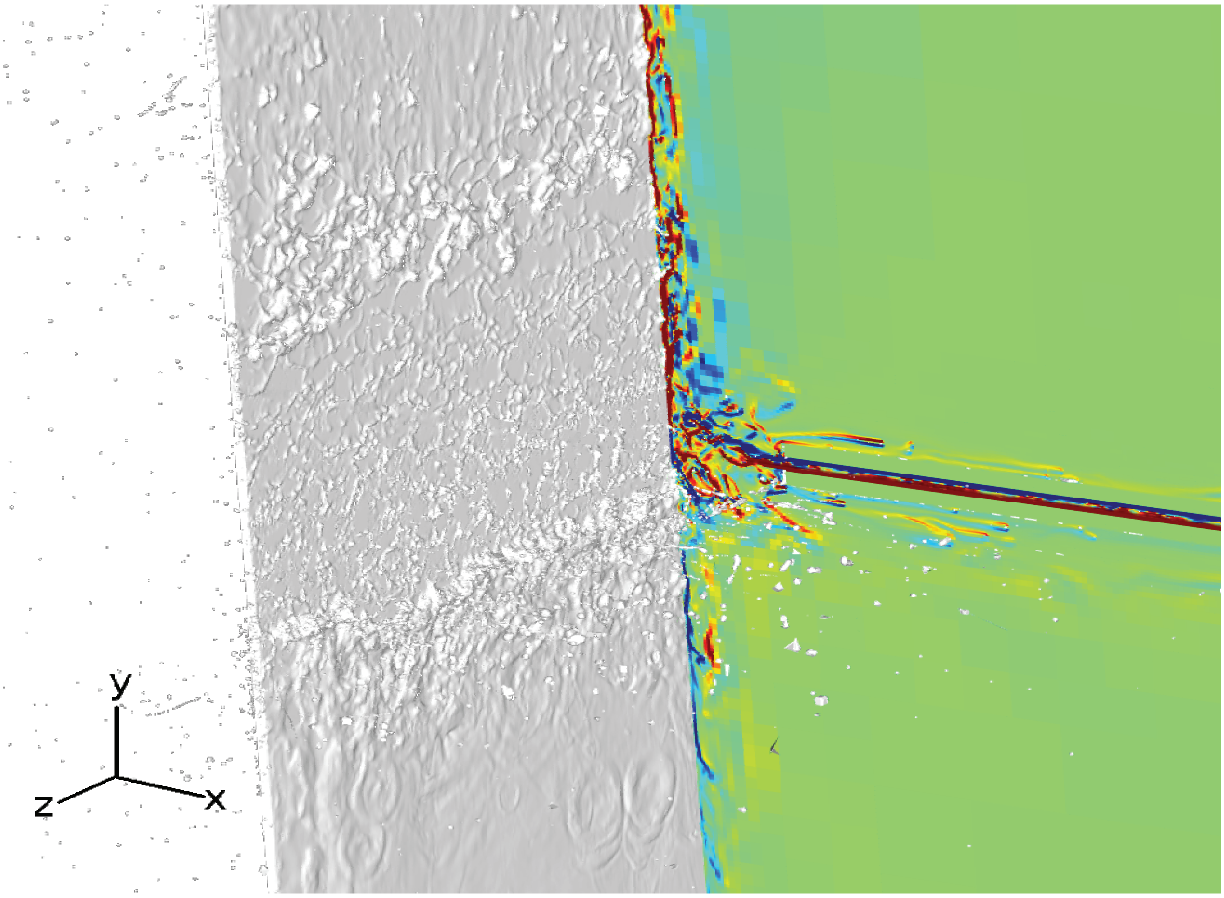

Figure 1. Film geometry at t=0.172s (i.e. 0.008s after impact). The nozzle, invisible in this visualization, extends in *z* direction and has a form of two flat plates (both parallel to *y*) separated by a *d*-sized slit (1mm in the simulation shown above). A cutplane is shown at *z*=0 colored by vorticity.

An example of a 3D coating simulation is visible in Figure 1 at 0.02s after the injection moment $t_{inj.}$ = 0.16s. In Figure 1, the interface is visible as a white/gray surface, with many ligaments and droplets in the impact zone. A cut-plane is placed at the z- wall, colored by vorticity ω. This helps us recognize the location of the "air-knife" (whose solid wall are not visible in Fig. 1 in order to not obscure the flow). We observe flat nozzle flow trace (along z axis). Pressure gradient restricts the flow within the film, so that a coat "bulge" is created below the nozzles with material crumbling down under gravity. Occasionally, the droplets impact back on the coat, resulting in circular wrinkles visible e.g. below the impact zone. The surface of the film is not strongly atomized, although it must be admitted that at the scale of Fig. 1, some small fluid packets might be simply to small to resolve visually, even if they're present in simulation. However, a stable thin film is created above the impact zone at thickness estimated at below 50 μm. This is a slight over-estimation compared e.g. to simplified model results of Hocking [6] and most likely results from lack of resolution.

Computational grid used for this simulation is non-uniform, with highest refinement level 12, which translates to minimal grid-size of $\Delta x=0.512/2^{12}=1.25\ 10^{-4}$m. (Some authors use the notion of grid equivalence between uniform-grids and these locally-refined. In such case, the 2^{12} grid has to be regarded as equivalent to a 4096^3 uniform grid). Despite this low resolution, it is possible using the Volume of Fluid [7] method that a computational grid-cell exists which is only partially filled, thus resolved film thickness may be smaller than Δx. Unfortunately such results have still to be regarded as preliminary and imperfect, since e.g. velocity field in such a thin film can not be correctly resolved. Thus, it is expected that much higher resolutions are needed to resolve the post-impact film thickness.

Figure 2 presents the side-view of the same moment in the simulated coating process as presented in Figure 1. In this view, the nozzle location is marked by semi-transparent dark region. Small liquid parcels are easily seen engulfed in the turbulent flow, some of them aligning with the vortical structures drawn in the back-drop cutplane. Note that Figure 2 is a three-dimensional image, thus we observe all droplets along the *z*-axis extent of the coated band at once. This effect of perspective has to be taken into account when examining Fig. 2, for example, accumulation of droplets is in fact somewhat lower than suggested by this image.

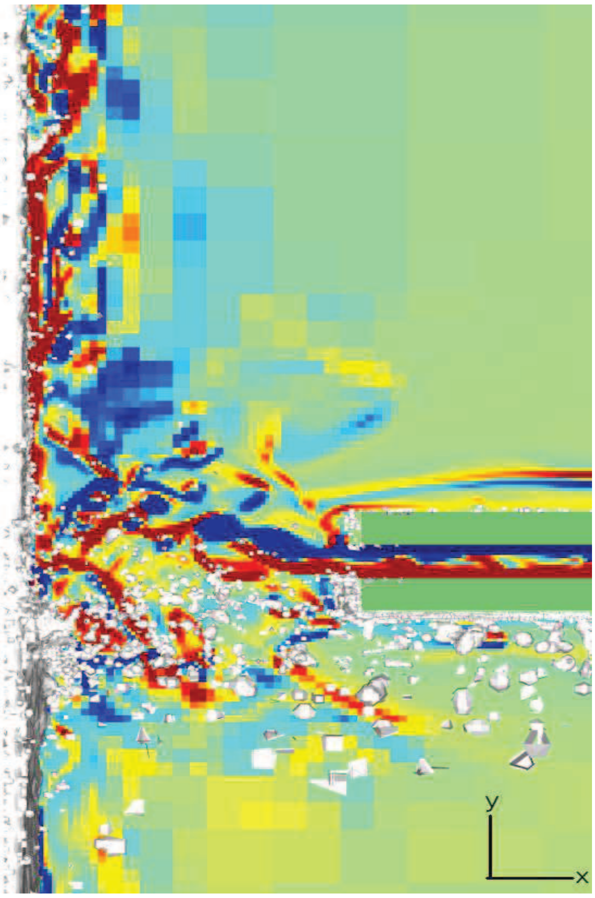

Figure 2. Film geometry at t=0.172s (i.e. 0.008s after impact) i.e. for exact same moment as presented in Figure 1. Lateral view with nozzle location marked by darkening. Decreased resolution far from the film is easily visible in the right hand side, upper part of the image.

Other useful fact that can be derived from Figure 2 is how the liquid packets are treated with lower resolution far from the film. We observe large grid-cells on the green cut-plane (colored by ω), but also, below the nozzle walls, we observe ejecta that is much less resolved that small droplets close to the impact zone. This is a result of intentional decrease of grid resolution far from the region of interest, and is a means to make the simulation feasible.

The simulations here are first of their kind, as the coating and airflow-coat interactions have never been simulated by a DNS approach with such detail in three dimensions. Previous results, e.g by Myrillas et al [8], have only provided time-averaged profiles of film shape. These profiles included no transient effects, and were two-dimensional. Simulations presented in this work are 3D and are eventually intended to reach the DNS resolutions close to the film. Results are expected to improve the control of the process in industrial practice (e.g. edge effects) and validate our analytical predictions for, among others, coat thickness above the injector, or the flow within heavy liquid during film formation. It is believed that by gradually converging the simulation resolution parameters to real-life values - which has to be accompanied by an increase in CPU processing power required - we will be able to achieve full stripping simulation which yields prediction about both film thickness and possible edge effects resulting from the interaction with airflow.

Nomenclature

u	velocity [m s^{-1}]
u_{inj}	gas injection velocity [m s^{-1}]
ω	vorticity [Hz]
ϱ_l	liquid density [kg m^3]
μ_l	liquid viscosity
m	mass [kg]

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