A shallow layer model predicting the zinc film thickness during the continuous hot-dip galvanizing process

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Abstract

The production of galvanized steel strips includes controlling the thickness of the adhered liquid zinc film by a gas jet wiping process. A set of optimal wiping parameters is necessary in order to provide a final thin and regular thickness. From a mechanical point of view, the liquid film thickness after gas jet wiping depends on the maximum pressure gradient and shear stress on the fluid zinc phase boundary. The instability behaviour of liquid film in the hot-dip galvanizing process is studied, since some non-uniformity of the final surface, due to wave presence, is observed and not desired in the industrial products. In this paper the shallow layer equations are used to simulate the evolution of the thin film thickness. The compressible turbulent jet flow field to start with is numerically obtained using an LES turbulence model. The mean pressure gradient and shear stress at the steel strip wall are extracted and introduced as a source term in the shallow layer equations. The effects of the inertia, viscosity, gravity and surface tension are also taken into account. Weak fluctuations are introduced to a numerical scheme to study the stability of the system. It is shown that the model predicts the experimentally observed final film thickness correctly. Finger-shaped waves are developed in the liquid flowing back to the bath. Although the jet source terms are steady, strong irregular waves are predicted in the region before and after the jet impingement line. The present work suggests that the wiping process is inherently unstable. The clarification of the mechanisms behind these instabilities demands further investigations.

Keywords: galvanizing, gas jet wiping, thin film, shallow layer equations, LES, Zinc coating, flow down along a plate.

1. Introduction

The hot-dip galvanizing is a sustainable and economic industrial process. It is important that the zinc coating adheres to the steel surface according to test instructions and that it has a defined and uniform thickness. The thickness of the zinc coating is hydrodynamically adjusted by gas jets which wipe off excess zinc from the moving strip surface (Fig.1). An accurate simulation of the jet hydrodynamic is vital to achieve the necessary pressure and shear stress distribution on the strip generated by jet impingement [1, 2]. Both distributions directly control the wiping efficiency since with higher shear stress and pressure, more zinc is wiped off the strip.

Recently an attempt to perform a two-phase [3] numerical modelling of the process was made. It was shown that the wiping process involves indeed highly coupled physical phenomena, due to the interaction between the turbulent gas jet and the laminar liquid film. The simulation used the VOF method to model the evolution of the thin liquid metal film. However due to high computational time, these simulations were performed in the 2D plane perpendicular to the steel strip surface. Thus wavy structures that develop in horizontal direction cannot be simulated.

In this paper an alternative approach based on the shallow layer equations to simulate the evolution of the thin film thickness [4, 5] is presented. In this approach the simulation of the turbulent gas jet flow and the liquid film are decoupled. The compressible turbulent jet flow is firstly numerically obtained using an LES turbulence model. The average pressure gradient and shear stress at the steel strip wall are extracted and introduced as a source term in the shallow layer equations. This approach allows calculation times that are several orders of magnitude smaller than full 3D VOF calculations.

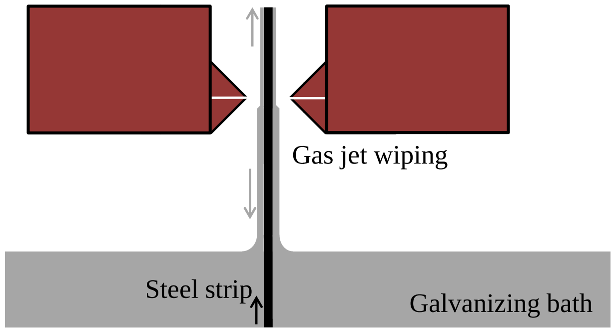

Fig.1. Schematic of the gas jet wiping process [3].

2. LES computation

Mass and momentum conservation in the computational domain were achieved by solving the continuity equation and the Navier-Stokes equations for compressible turbulent Newtonian fluids. The solution yields the pressure and velocity components at every point in the domain. The wiping gas is treated as compressible by applying the ideal gas law, since the density change due to the maximum pressure differences in the domain are high. Therefore, the energy conservation equation is applied to the entire domain. The fluid zinc film is treated as an incompressible phase. For the simulations the commercial computational fluid dynamics software ANSYS® Fluent® was used.

Turbulent eddies, which are smaller than the grid scale, are modelled by a sub-grid-scale model. Compared to a classical wall resolved LES model, the Algebraic Wall Modelled LES approach highly reduces the Reynolds number dependent grid resolution requirements, because the velocity gradient at the wall is modelled by wall functions. An evaluation of the accuracy of various turbulence models and validation to experimental data for impinging gas jets has been performed in former studies by the authors [2]. Figure 2 represents a typical velocity field generated by the gas wiping air jet impinging on a flat upwards moving steel strip without a zinc film attached.

Fig. 3 shows the mean static pressure distributions along the strip around the impingement point. In Fig. 4 the mean shear stress along the strip is shown. In case of shear stress along the fluid film the maximum mean shear stress is reached at distance of about 1.7e-4 m. Below the coordinate -0,01, the mean shear stress becomes weaker. The mean static pressure and the shear stress are used as input for the next step dedicated to the simulation of the thin film thickness.

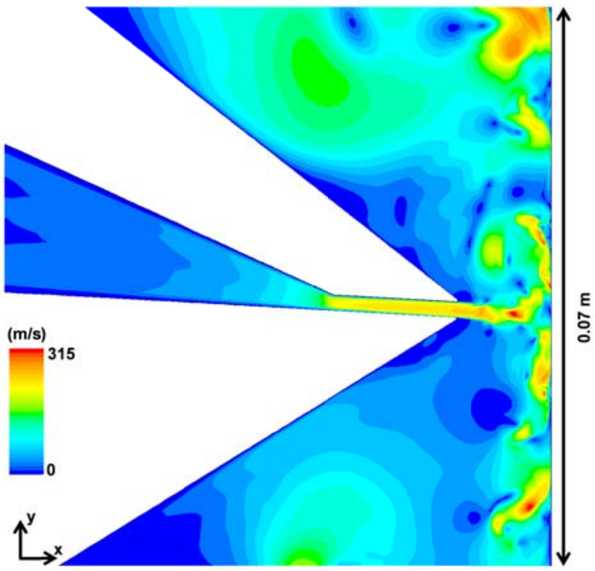

Fig.2. Typical instantaneous gas flow impinging on an upwards moving plane surface at a certain time [3].

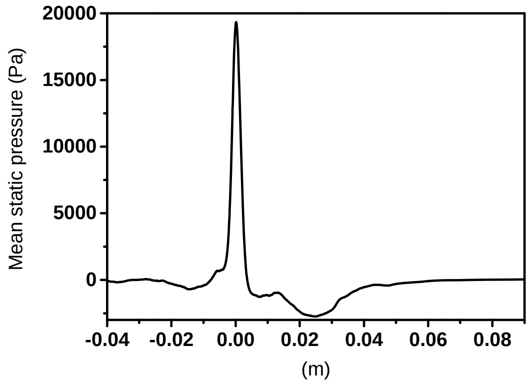

Fig.3. Vertical mean static pressure near the impinging jet (position 0) along the strip.

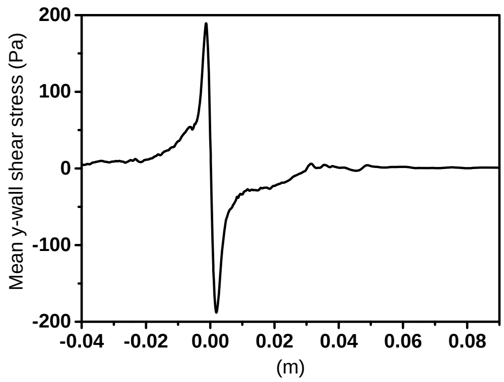

Fig. 4. Vertical mean shear stress near the impinging jet (position 0) on the strip.

3. Shallow layer simulation

By comparing the small thickness of the liquid film (5 -20 μm) to its length (~2 m), we can use the integral method to reduce the simulation of the liquid film flow to a 2D problem. It consists in solving the equations of motion in the thin film approximation neglecting the vertical momentum equation.

The first equation is the continuity equation integrated over the thickness of the liquid metal film:

$$\frac{\partial h}{\partial t} + \nabla \cdot (\vec{q}) = 0 \,, \qquad (1)$$

where *h* is the liquid height and $\vec{q}$ is the 2D flow rate across the height. The height is assumed small enough so that the two horizontal components of the velocity profile can be approximated with second order polynomials: $\vec{f}(z) = (f_x(z), f_y(z))$. These polynomials are uniquely determined by assuming a no slip condition at the wall and a given shear $\vec{\tau}_w$ at the free surface (see Fig.4). The integrated momentum equation is given by:

$$\frac{\partial(\vec{q})}{\partial t} + \vec{u}\nabla(\vec{q}) = \nabla(h\nu\nabla(\frac{\vec{q}}{h})) + \vec{g}h - \nu\frac{1}{h}\frac{\partial \vec{f}}{\partial z}\bigg|_{z=0} + \frac{1}{\rho}\nabla(\sigma h\nabla^2 h) + \vec{F}_{AirJet} \qquad (2)$$

Where σ is the gas/metal interfacial tension, ν the kinematic viscosity and $\vec{g}$ the gravitational acceleration.

The effects of the gas jet on the liquid film is represented in the force $\vec{F}_{AirJet}$:

$$\vec{F}_{AirJet} = -\frac{h}{\rho}(1 + \xi(t))\nabla P_J \qquad (3)$$

Where P_J is the wall static pressure at the wall, together with the shear $\vec{\tau}_w$ are two parameters are given by the time average result of the LES simulation. In order to consider natural fluctuations, we destabilize the system with random waves of amplitude $|\xi| = 0.01$ which are continuously introduced to the gas pressure force. This method allows the physical development of vortices in the steel strip plane.

The boundary condition at the bottom inlet assume a constant flow rate 4.12e-4 m^2/s, and a fluctuating liquid film thickness (± 1%) around an average of *h* = 250 μm. The steel strip velocity is 1.65 m/s. At the top outlet face boundaries the values of *q* and *h* are interpolated from the adjacent cell values.

4. Results

Typical “steady” state results are presented in Fig. (5-8). In Fig. 5, it can be seen that the impinging jet divide the calculation in two, a thick film region and a thin film region. In fact at position 0 we can see a strong decrease of the liquid film thickness from 350 μm at (position -0.06 m) to 10 μm at position 0. This zone is the region where the effects of both the pressure gradient and wind shear stress on the liquid film momentum are the strongest. In industrial conditions, the jet wiping can sometime induce splashing where droplets of zinc are ejected. Since the shallow layer model is a 2D model the splashing cannot be resolved.

In the thick region located further down the free surface shows train of fingers or rings flowing irregularly downward (Fig. 6). These features share some similarities with those observed by Alekseenko et al. [6] and Craster & Matar [7] with water-ethanol mixture flowing down an inclined plate. These waves are generated in the highly stressed region, they are initially small in wave length and their size and amplitude increase during they flow down.

The velocity at the gas/film interface is downward direction in the thick film region (Fig. 7). Due to the non-slip condition assumed at the steel strip, the velocity changes its sign within the film, from positive at the steel strip to negative at the gas/film interface. In the thin film region, the gas jet forces push the liquid in the upward direction, the surface velocity (1.9 m/s) is thus positive and larger than the steel strip velocity (1.65 m/s). Due to the viscous effects within the thin film thickness, at a distance of only 5 cm from the jet impact line the surface velocity becomes almost equal to the wall strip velocity.

In the thin film region the surface irregularities (Fig. 8) show very different patterns compared to those predicted in downward flowing region. These transverse waves form irregular lines that resemble some of the second grade surface pattern shown by So et. al [1]. These patterns survive until complete solidification of the film, and are generally attributed to the impact of pressure variations [1] generated by the turbulent eddy fields such as the one presented in Fig. 2. However the present study shows that even with a weakly perturbed static wiping process, waves are able to develop.

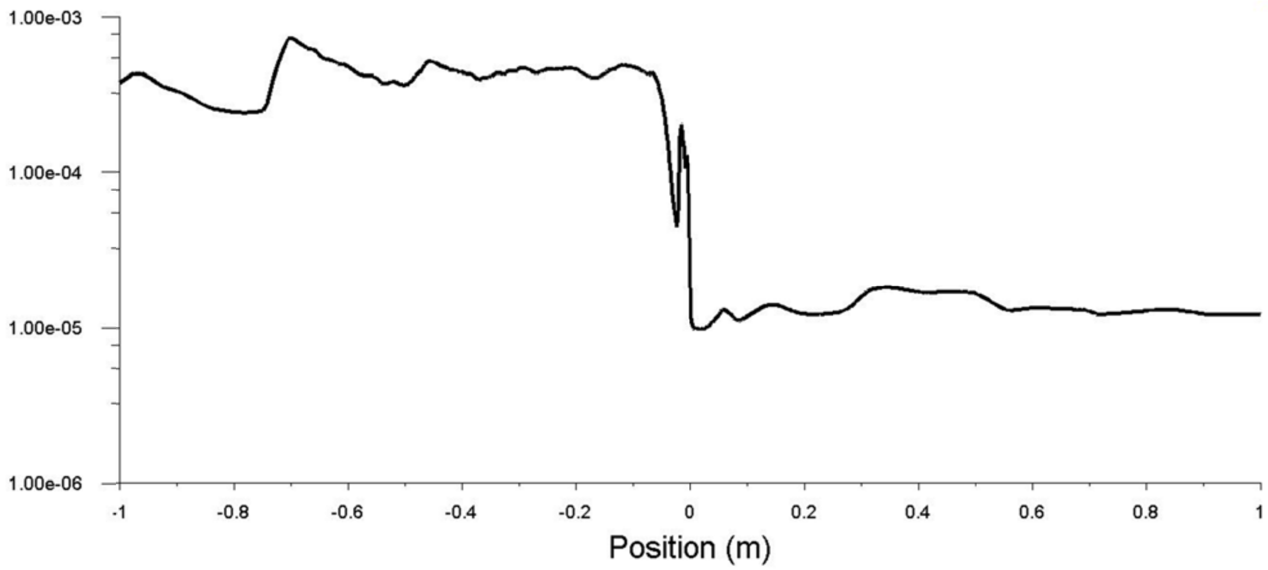

Fig.5. Typical instantaneous liquid zinc height (m) along the strip (impinging jet = position 0).

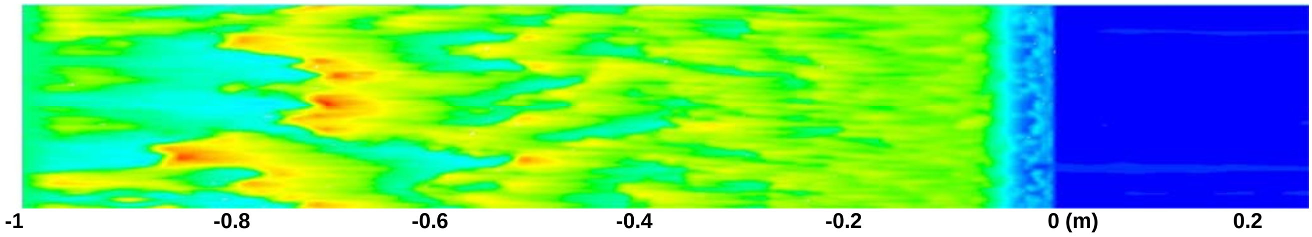

Fig. 6. Liquid zinc height (10 μm (blue) – 600 μm (red)) in the thick film region along the strip (impinging jet = position 0).

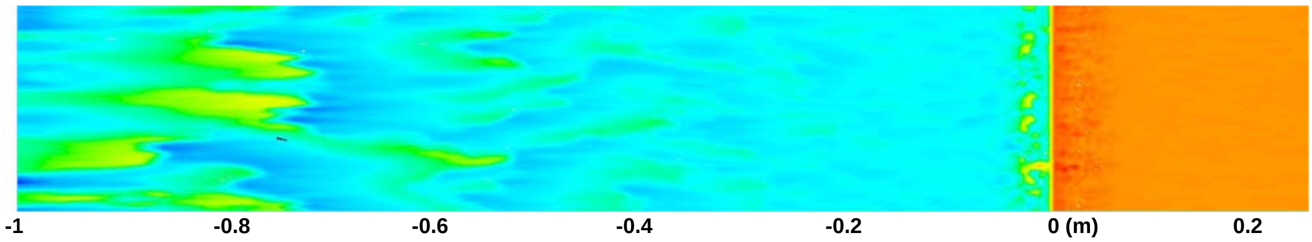

Fig. 7. Velocity of the gas/film interface (-0.75 m/s (blue) - +1.96 m/s(red)) in the thick film region along the strip (impinging jet = position 0).

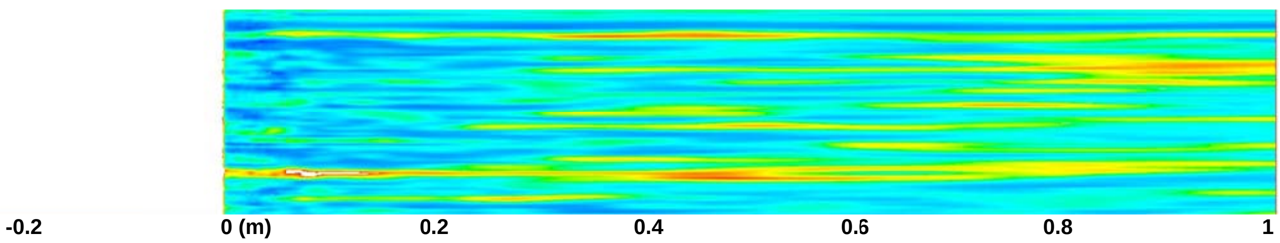

Fig. 8. Liquid zinc height (7 μm (blue) - 20 μm (red)) in the thin film region (after wiping) along the strip (impinging jet = position 0).

5. Conclusion

We have presented a novel approach based on the shallow layer approximation to simulate the gas wiping process of a liquid film flowing upward with a plate. The dynamic film is controlled by the combined action of the gravity, viscosity, inertia, surface tension, and the jet pressure and shear stress. Numerical disturbances were introduced in the average pressure force as well as in the inlet liquid film height to test the stability of the system.

The model successfully predicted the experimentally observed final film thickness. In addition, finger like waves develop in the liquid flow back to the bath. After gas wiping, the liquid film is thin and irregular. In the present work it was found that the wiping process is inherently unstable. The clarification of the mechanisms behind these instabilities needs further investigations.

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