Numerical Simulation of Gas-Jet Wiping in Steel Strip Galvanizing Process

Delphine LACANETTE, Stéphane VINCENT, Eric ARQUIS and Pascal GARDIN

Transferts, Ecoulements, Fluides, Énergétique (TREFLE), UMR 8508 Site ENSCPB—Université Bordeaux 1, 16 Avenue Pey-Berland, 33607 PESSAC Cedex, France. E-mail: lacanette@enscbp.fr, vincent@enscbp.fr, arquis@enscbp.fr.

1) ARCELOR Research, Voie Romaine, 57283 MAIZIERES Cedex. E-mail: pascal.gardin@irsid.arcelor.com

We have investigated the film thickness and thermal exchange occurring during the coating and cooling of a liquid film on a substrate. The aim of our study is to demonstrate the interest of Direct Numerical Simulation tools for Interfacial flows to understand, on the one hand, the mechanisms involved in the deposition of the film on the moving substrate, and on the other, to measure characteristic parameters of the process. The direct numerical simulation is presented here in two-dimensions based on the Navier-Stokes equations, generalized to free surface flows. They are approximated by VOF (Volume Of Fluid) methods. A Large Eddy Simulation (LES) model is used to take the turbulence into account. We attempt to define the governing parameters of the process and propose a description of the flow. The characteristic parameters of the wiping of the film and the associated thermal exchanges are presented in terms of wiping thickness, transfer coefficient, cooling rate and temperature gradient along the film.

KEY WORDS: turbulence; gas-jet wiping; film coating; direct numerical simulation (DNS); volume of fluid (VOF).

1. Introduction

Coating techniques are frequently used in many industrial processes such as paper manufacturing, wire coating and in the iron and steel industries. Depending on the applications considered, the film thickness must be controlled by mechanical (scraper), electromagnetic (if the fluid is appropriate), or hydrodynamic (gas jet wiping) operations. Here our study is dedicated to this last process. Few studies are found in the literature in spite of the wide utilization of this process. The scarcity of studies is due to the difficulty of conducting experiments with jets of such high Reynolds numbers and the high temperature of the environment.

Indeed, highly coupled physical phenomena occur in this problem. Viscosity and surface tension affect the shape and thickness of the film, turbulent flows of air interact with this liquid interface, and the jet produces cooling effects on the film. Based on recent advances in numerical modeling of free surface and interfacial flows, this work presents a numerical tool designed to give the iron and steel industries more information about the influence of the various parameters in this process. The aim of our study is to demonstrate that recent numerical technologies for interface tracking when coupled to Eulerian grid discretizations and incompressible multiphase flow models are relevant, on the one hand, for describing film coating and turbulent jet wiping, and on the other hand are a useful tool for engineers to estimate quantitative characteristic parameters of the process, such as the asymptotic thickness of the film or the constraint exerted by the jet (pressure, shear stress on the film).

In the following sections we first describe the numerical model, giving the governing equations, the approximation methods and the turbulence parameters. Second, both hydrodynamic and thermal results are compared to experimental ones. Concerning the aforementioned asymptotic thicknesses with or without wiping of the jet, a comparison with theoretical expressions from the literature is established. The interest here lies in the identification of the respective importance of the governing parameters of the process on the thickness of the film. A study of parameters related to the process parameters such as strip speed or the Reynolds number of the jet and related to the fluids is presented. Concerning the turbulence aspects, a preliminary study of the impingement of a non-isothermal turbulent jet on the upward moving film is presented. The film thickness after wiping, the temperature gradients in the film and the global thermal parameters, such as the cooling rate or the heat transfer coefficients, are measured. Finally, we present a discussion of these results.

2. Physical Description

In the process, a strip plate exits a liquid zinc bath at a velocity, \( V_p \), and consequently a film is created. The domain we consider is composed of a plate plunged into a bath of liquid metal (fluid 2) moving upward in air (fluid 1) and consequently creating an asymptotic film thickness, \( e_f \), as presented in Fig. 1. In order to limit the size of the computation, a ratio \( H/L \) is considered, \( H \) being the height and \( L \)
the width of the domain, while the nominal depth of the bath (fluid 2) is kept constant in time. A preliminary computation with a domain \(H/L = 1\) and without the restriction of constant bath depth has been carried out. The final thickness for both of these cases is similar. The constraint on the size of the computations can be avoided by using the ratio \(H/L = 100\) and all the results shown here have been obtained with this ratio in order to refine the interfacial zone. A sliding condition is imposed at the left of the domain, a zero flux condition on the right and top boundaries whereas a no-slip condition is chosen at the bottom. At a certain height \(h_{\text{jet}}\) chosen to avoid disturbing the bath (typically 0.35 m), a strongly dynamic, turbulent gas jet impinges on the film, the resulting stress and pressure leading to a recirculation of the liquid metal towards the bath and to a change in film thickness. The jet is simulated by a slit, placed on the right side of the computational domain, along which the velocity is supposed to be uniform, whereas Neumann conditions are adopted on the remainder of the boundary. After some distance, this thickness converges to an almost constant value.

The characteristic lengths of the flow are \(h_{\text{jet}}\), the asymptotic thickness of the film without the interaction of the jet, \(e_{\text{f}}\) the asymptotic thickness of the film after the gas-jet wiping and the characteristic velocity is \(V_{\ell}\), the strip speed. In relation to practical applications the Reynolds number based on the thickness \(R_{\text{e},h} = \rho hV/\mu\) of the fluid ranges from 750 to 2260 and the Froude number \(F_{\ell} = V^2/gh_{\text{f}}\) from 2000 to 5400. The ratios of densities, \(\rho_1/\rho_2\), and dynamic viscosities, \(\mu_1/\mu_2\), are fixed to the values of 5600 and 190 respectively. Concerning the jet, the Reynolds based on \(d\), the width of the nozzle, ranges from 3000 to 13000.

3. Numerical Modelling

3.1. Governing Equations

When using the expression Direct Numerical Simulation, we imply the explicit description by the grid of all the characteristic scales associated with the interface. The Direct Numerical Simulation (DNS) of flow in two dimensions is based on a formulation of the Navier–Stokes equations generalized to free-surface flows. The thermal exchanges are modeled by the energy equation (3) written in terms of temperature. We are interested in a two-phase, incompressible, non isothermal, and immiscible flow in a field \(\Omega\). In the Navier–Stokes and energy equations (1), (2), (3), \(\rho\) is the density, \(\mu\) is the dynamic viscosity, \(C_p\) is the specific heat, \(\lambda\) is the thermal conductivity, coefficients 1 and 2 are related to each fluid 1 and 2, \(g\) is the gravity vector, \(u\) is the velocity vector, \(T\) is the temperature, \(t\) the time, \(\rho\) the dynamic pressure, and \(\mathbf{F}_{\text{TS}}\) the source term representing the stress of surface tension. Surface tension is taken into account and influences strongly the wiping phenomenon. It is introduced into the model by a source term. In the advection equation (4) for the phase function \(C\), or color function, \(C\) is the local volume fraction. This equation is solved by Volume Of Fluid (VOF) methods which are used to describe the evolution of the free surface and simultaneously characterize the evolution of the fluids 1 and 2.

\[
\rho \left( \frac{\partial u}{\partial t} + (u \cdot \nabla)u \right) = -\rho g - \nabla p + ((\mu + \mu_t)(V u + \nabla u)) + \mathbf{F}_{\text{TS}}
\]

\[\nabla \cdot \mathbf{u} = 0\]

\[
\rho C_p \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)T = \nabla \cdot ((\lambda + \lambda_{\text{t}}) \nabla T)
\]

\[
\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = 0
\]

The DNS model (1)–(4) is able to simulate the rise of the laminar film without the jet \((\mu_{\text{t}} = 0\) and \(\lambda_{\text{t}} = 0\)). However, since all the scales of the turbulent flow are not taken into account by the DNS interfacial grid, the study of the turbulent jet wiping requires an explicit modeling of turbulence in order to limit the computational cost. To be consistent with the unsteady modeling of the free surface and the considered space scales, a RANS turbulence model is not suitable in our context. Thus large Eddy Simulation (LES) has been chosen in which a turbulent viscosity \(\mu_{\text{t}}\) (5) and a turbulent conductivity \(\lambda_{\text{t}}\) (6) are added in Eqs. (1), (3):

\[
\mu_{\text{t}} = \rho (C_s A)^2 \cdot 2(V u \otimes V u)
\]

\[
\lambda_{\text{t}} = \mu_{\text{t}} \cdot \text{Pr}_{\text{SM}} \quad \text{with} \quad \text{Pr}_{\text{SM}} = 0.3
\]

The value of the subgrid scale turbulent Prandtl number \(\text{Pr}_{\text{SM}}\) is based on the literature.

3.2. Numerical Methods

A finite volume spatial discretization of the conservation equations is performed on a fixed staggered Cartesian grid over the whole computational domain, with variable density and viscosity. The temporal discretization and the coupling between velocity and pressure are achieved using an augmented Lagrangian method. The advection terms in (1), (3) are evaluated by a hybrid scheme whereas a centered scheme is used for the other terms. The linear system is solved by an iterative Bi-Conjugate Gradient Stabilized technique. The advection equation (4) can be solved by several methods, the one we use here is a Volume Of Fluid–Total Variation Diminishing method (VOF–TVD). No interface reconstruction is required and the numerical diffusion of the color function \(C\) remains weak. The VOF-
TVD method has already been validated.11–13) Concerning the turbulence, the LES is based on a concept of scale separation in which the larger structures are solved (1)–(4) directly and the smaller ones are modeled (5), (6). From a numerical point of view, the scale separation is carried out on the local space scale through spatial filtering. Since the smaller scales are more homogeneous and less affected by the boundary conditions than the larger scales, the modeling is more acceptable in this case. The small-scale motions are modeled using a ‘subgrid model’ which attempts to describe turbulence as phenomena of interaction between scales of different lengths or the use of a spectral description of turbulence.

4. Numerical Results

In order to track both the motion of the interface and the large scale of turbulence, the mesh size and the time step must be adapted to these physical requirements while maintaining reasonable computational cost. The computational grid is 150×120, with mesh refinement at the interface of the film to adequately describe the variations. The film is drawn by at least 10 nodes along the x-axis and the jet by 10 nodes along the z-axis. The time step is typically about 10⁻² s, a value required by the use of the LES model. On a pentium 1.7 GHz, 14 h of CPU time are needed to reach the stabilized state, i.e. 50 000 iterations corresponding to a physical time of 0.5 s.

4.1. Study of the Film Development

At time zero, the plate starts to take liquid from the bath. After a certain lapse of time an equilibrium state is reached, in the sense of the convergence of the thickness of the film. An example of the numerical solution being stabilized, with respect to the film thickness, is presented in Fig. 2.

The experimental data available concern global parameters only (film thickness). Thus, the numerical tool has to be validated using these experimental data. Ellen and Tu1) performed a comparison of measured, theoretical, and computational coating masses of gravity-stripped hot dip liquid metal coatings which can be easily converted into film thicknesses. Their comparison is used in Fig. 3 to validate our computation. The evolution of the coating masses with respect to the strip speed is accurately predicted by the simulation tool. The analytical formula of the thickness of a film is given by Deryagin and Levi14) in the range of quite high Capillary numbers:

\[ h_i = \frac{2}{3} \sqrt{\frac{\mu U}{\rho g}} \] (7)

4.2. Study of the Impinging Jet

Before considering the full problem, the impingement of a plane jet on a flat and dry surface has been studied in order to validate the choice of the turbulence model for the case of jet stripping of liquid coating.

Two of the major parameters are validated against experimental data, the pressure distribution along the plate and the velocity distribution along the axis of the jet, as shown in Figs. 4 and 5. A good agreement is observed between numerical solution and reference data.

Concerning the pressure distribution along the plate shown in Fig. 4, the mean pressure \( P \) is non-dimensionalized by the maximum pressure at the impact \( P_s \). \( h_i \) is defined as \( x/b \), \( b \) being equal to \( x \) for \( P = P_s/2 \). The analytic formula giving the non-dimensional pressure as a function of \( h_i \) is taken from Hrycak.16)

\[ \frac{P}{P_s} = e^{0.693 h_i} \] (8)

4.3. Study of the Gas–Jet Wiping Process

4.3.1. Film Shape Analysis

We now consider the interaction between the liquid film and the turbulent jet. Both a high value of the Reynolds number (\( \text{Re} = 12700 \)) and the proximity of the jet to the film (ratio \( L/d = 10 \)) imply a strong influence on the free surface through the pressure and the shear stress. In order to illustrate the ability of the numerical tool to track local characteristics of the free surface flow, typical film motions are presented. The Figs. 6 and 7 show widely stretched pictures along the x-axis, the ratio of the visualization window
is respectively 35 and 212. Upstream of the impinging zone the surplus of liquid metal goes down along the film as shown in Fig. 6(a), in the impinging zone the jet deforms the interface in Fig. 6(b), and downstream, the film thickness is reduced and advected at the velocity of the plate in Fig. 6(c).

During the impingement, drops are rent from the film, a phenomenon which can last under some conditions. The deformation of the interface is shown in Fig. 7. The thickening of the film downstream of the impinging zone can be noted in Fig. 7(f).

An analytical formula (Eq. (9)) giving the thickness $e_t$ of a wiped film as a function of the physical parameters of the fluids, the maximum pressure gradient $\nabla P_{\text{max}}$ of the impinging jet and the maximum shear stress $\tilde{\tau}_{\text{max}}$ is derived from Ellen and Tu.1)

$$e_t = \frac{2}{3} \sqrt{\frac{\mu_0 V_{\text{strip}}}{\rho_0 g}} \frac{3 \tilde{\tau}_{\text{max}} + \sqrt{\tilde{\tau}_{\text{max}}^2 + 4(1 + \nabla \tilde{P}_{\text{max}})}}{4(1 + \nabla \tilde{P}_{\text{max}})}$$

$$\nabla \tilde{P}_{\text{max}} = \frac{0.357 K_v \rho_0 V_0^2 e}{\rho_0 g b d}$$

$$\tilde{\tau}_{\text{max}} = \frac{0.03 \rho_0 V_0^2 e}{d \sqrt{\mu_0 V_{\text{strip}} \rho_0 g}}$$
The analytical formula given above is compared to industrial data on galvanizing lines. For a ratio $d/e=10$, and a range of Reynolds numbers of the jet from 5 800 to 16 600, industrial data are compared to the theoretical formula in Fig. 8.

The industrial data correctly agree with those obtained with the analytical formula. This formula can therefore be used for the comparisons with our computational data.

The wiped film shows a stabilized thickness, in spite of the disturbances generated in the lower part: under these conditions, for a Re_{jet} of 12 720, the numerical stabilized thickness is reduced by 92% in comparison to the initial one. This thickness obviously depends on parameters such as the dynamics of the jet and the strip speed.

4.3.2. Parametrical Study of the Gas–Jet Wiping Process

In particular, several parameters governing the process of gas-jet wiping have been isolated: first, the strip speed which influences the final thickness, and second the main parameters defining the turbulence of the jet such as the mean outlet velocity or the nozzle to plate distance.

• Influence of the Strip Speed

Although the strip speed can be considered to be quite low in comparison to that of the jet, its influence is quite significant for typical strip speeds observed in industrial coating processes. Keeping all the parameters of the computation at the same values and increasing the strip speed, the final thickness increases as shown in Fig. 9 in the range of industrial values of strip speed.

• Reynolds Number of the Jet

The influence of the Reynolds number of the jet has been investigated in the range of Reynolds numbers from 3 180 to 12 720 and the corresponding results are reported in Fig. 10. The corresponding thicknesses are compared well with the theoretical ones from Ellen and Tu.

The computational values corroborate with the theoretical ones, showing a decrease of the thickness as the Reynolds number increases.

• Distance Nozzle to Plate

Keeping the size of the nozzle of the jet constant, for a Re_{pl} ranging from 30 to 52 and for a Re_{jet}=4 420, we have looked at the effect of changing the nozzle to plate distance. In Fig. 11 for a ratio smaller than 7–8, it can be seen that the thickness is not dependent on the nozzle to plate distance even though small discrepancies are observed since they are smaller than the mesh size. For ratios greater than 7–8 the thickness seems to show a linear increase. This could be related to the potential core of the jet. Intuitively, the thicknesses in the range of ratios smaller than 8 should
be proportional to the nozzle to jet distance in a smaller degree than those larger than 8. This new relation between the nozzle to plate distance and the thickness is of interest in the design of gas jet wiping processes. Furthermore, it could be interesting to work in the range of $L/d$ lower than 8 to produce thicknesses independent on the variations of $L$.

4.4. Thermal Effect of the Gas–Jet

While keeping the previous configuration we now solve the thermal problem by including a solution of the energy equation (3). With respect to the temperature range, the thermophysical characteristics of the liquid are assumed to be constant, whereas the gas is modeled as a perfect gas. The bath temperature is maintained at a hot uniform value (460°C), whereas the jet enters at a temperature of 50°C, this latter temperature being also initially that of the ambient air. When the jet impinges on the film, both gas jet wiping and cooling of the film are observed in Fig. 12. In this configuration, a detailed analysis of the mean temperature cartography in the wiped film reveals a decrease in temperature of 7°C at a distance of 45 cm above the jet impact point, corresponding to a relative cooling rate of 1.5% defined by $(T_f - T_0)/T_f$, with $T_f$ being the temperature of the film below the impact of the jet, and $T_0$ the temperature 45 cm above the jet impact. It can be observed in Fig. 13 that the decrease of the temperature along the film in the vertical direction is sharp. A corresponding convective heat transfer coefficient is estimated along the interface. Its distribution along the plate is presented in Fig. 14 and its maximum is about 1 000 W·m$^{-2}$·°C$^{-1}$, a value which seems to be realistic in forced convection in such conditions.

5. Conclusions

Direct Numerical Simulation allowed us to reach a stabi-
lized state of the free surface by simulating the unsteady rise of the film on the plate.

Concerning the effect of the turbulent gas–jet on the film, the jet’s efficiency in thinning and cooling the film is shown while keeping the profile of the wiped film stable. These results will be useful for industrial problems in coating and cooling processes, since our numerical tool allows the description and the control of the process, in order to improve it in terms of flow instabilities. A major interest of the numerical tool is also to have access to all the local fields and thus to be able to estimate the heat transfer coefficient for example, which is difficult to measure experimentally. Moreover, we have shown that in this fluid configuration, the jet is efficient for wiping and produces only a minor cooling effect. Finally, with a relatively low computational cost, parametric studies are easy to conduct with respect to geometrical and thermophysical properties of the problem in such a complex industrial problem.

Acknowledgements
The authors gratefully acknowledge ARCELOR Research for their financial support of this study. The authors also wish to thank the IDRIS and CINES for their computer support.

REFERENCES