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A numerical experiment on the interaction between a film and a turbulent jet

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Abstract

This work is focused on the study of the impingement of a turbulent plane jet on a moving film. A computational fluid dynamics code has been used to simulate the interaction between the turbulent plane jet and the moving film. Since the problem of coupling between turbulence and free surface flow is poorly understood and experiments in this problem are difficult to carry out, this new numerical tool has been designed to give insight into global and local parameters of the free surface flow. ***To cite this article: D. Lacanette et al., C. R. Mecanique 333 (2005).***

Résumé

Expérimentation numérique de l'interaction entre un film et un jet turbulent. Ce travail est consacré à l'étude de l'impact d'un jet plan turbulent sur un film liquide en mouvement. Un outil de simulation numérique en mécanique des fluides a été utilisé pour simuler l'interaction entre le jet plan turbulent et le film en mouvement. Le problème du couplage entre turbulence et surface libre étant mal connu d'une part, et l'expérimentation de ce cas étant difficile à réaliser d'autre part, ce nouvel outil a été conçu pour donner des grandeurs globales et locales de l'écoulement diphasique. ***Pour citer cet article : D. Lacanette et al., C. R. Mecanique 333 (2005).***

Keywords: Computational fluid mechanics; Interface; Turbulence; LES-VOF coupling

Mots-clés : Mécanique des fluides numérique ; Interface ; Turbulence ; Couplage LES-VOF

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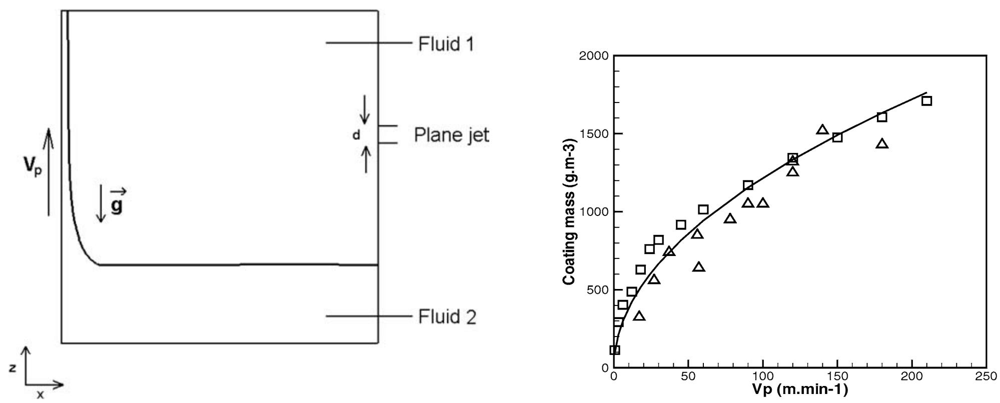
1. Introduction

Coating techniques are often difficult to characterize, especially techniques which include a turbulent jet used to provide a thin and regular thickness. In spite of their wide utilization in industrial processes, few references are found in the literature [1,2]. A strip plate exiting a liquid bath at a velocity V_p and consequently creating a film is considered. The computational domain is composed of a plate plunged into a bath of liquid moving upward in the air and therefore creating an asymptotic thickness. 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 the numerical modeling of free surface and interfacial flows [3–6], this Note presents a new numerical tool designed to provide more information about the influence of the various parameters on this process. The major parameters governing the whole process are very difficult to measure, the interest of the simulation here is to replace experimentation. When using the expression 'numerical experimentation' we understand the code as a means to characterize the velocity field and the position of the interface. The aim of this Note is to use the simulation as a tool to examine the local scale phenomena. The scientific originality of this study is the coupling between turbulence and a free surface.

2. Numerical model

The considered domain is represented in Fig. 1(a). 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, 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.

We are interested in a two-phase, incompressible, isothermal flow of immiscible fluids in a field Ω. The Navier–Stokes equations (1), (2) in their two phase formulation are considered, in which ρ is the density, μ is the dynamic



(a) (b)

Fig. 1. (a) Visualization of the computational domain; (b) comparison of measured, theoretical and computational coating masses of gravity-stripped liquid metal coatings (line: theoretical values from analytical formula [14], △: experimental data [13], □: present study).

Fig. 1. (a) Visualisation du domaine considéré ; (b) Comparaison des grammages mesurés, théoriques et simulés dans le cas d'un essorage gravitationnel par un métal liquide (trait : valeurs théoriques issues de la formule analytique [14], △ : données expérimentales [13], □ : cette étude).

viscosity, $\mathbf{g}$ is the gravity vector, $\mathbf{u}$ is the velocity vector, t the time, p the dynamic pressure, and $\mathbf{F}_{TS}$ 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 momentum equations as a source term [7]. A new advection equation, (3), for a phase function C, has been introduced in the model to describe the interface evolution.

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \rho\mathbf{g} - \nabla p + \nabla\cdot\big((\mu+\mu_T)(\nabla\mathbf{u} + \nabla^T\mathbf{u})\big) + \mathbf{F}_{TS} \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0 \tag{2}$$

$$\frac{\partial C}{\partial t} + \mathbf{u}\cdot\nabla C = 0 \tag{3}$$

The model (1)–(3) is able to simulate the rise of the laminar film without the jet ($\mu_T = 0$). However, since all the scales of the turbulent flow are not taken into account by the 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 Reynolds Averaged Navier Stokes (RANS) turbulence model is not suitable in our context. Thus Large Eddy Simulation (LES) [8] has been chosen in which a turbulent viscosity μ_T (4) is added in Eq. (1):

$$\mu_T = \rho(C_s\bar{\Delta})^2\cdot\sqrt{2(\nabla\mathbf{u}\otimes\nabla\mathbf{u})} \tag{4}$$

The LES is based on a concept of scale separation in which the larger structures are solved (1)–(3) directly and the smaller ones are modeled (4). From a numerical point of view, the scale separation is carried out on the local space scale through spatial filtering.

The conservation equations are discretized by finite volumes on a fixed staggered Cartesian grid. The time discretization and the coupling between velocity and pressure are achieved using an augmented Lagrangian method [9,10]. The advection terms in Eq. (1) are evaluated by a hybrid scheme [11] whereas a centered scheme is used for the other terms. The linear system is solved by an iterative Bi-Conjugate Gradient Stabilized technique [10]. A Total Variation Diminishing (TVD) [12] Volume Of Fluid (VOF) method [4] is used to approximate the evolution equation of the free surface (3). This technique is distinguished by no interface reconstruction and a weak numerical diffusion of the color function C which has already been validated in [10,12].

3. Physical validation

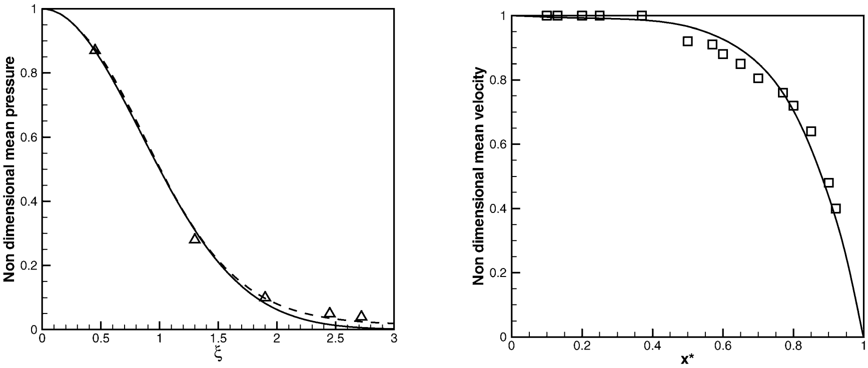
This part is dedicated to the validation of the numerical tool on experimental data. Only the original configuration of the interaction between the jet and the film is presented here, even if the case of gravity-stripped liquid metal coating is of particular interest. Its successful investigation is illustrated in Fig. 1(b).

3.1. Turbulent plane jet

Let U_0 be the inlet velocity and L the nozzle to plate distance. The Reynolds of the air jet is $\rho_a d U_0/\mu_a = 11\,000$ and $L/d = 10$. The impingement of a plane turbulent jet on a flat surface has been investigated. Non-dimensional values such as the mean pressure distribution at the wall or the mean velocity $\bar{u}$ along the jet axis are presented in Fig. 2. They are compared to experimental data from Ellen and Tu [1] for the mean pressure at the plate and from Maurel and Solliec [15] for the mean velocity along the jet axis. The distribution of the mean pressure along the plate is also compared to an analytical formula from Hrycak [16] given in the following expression:

$$\frac{P}{P_s} = \mathrm{e}^{0.693\xi^2} \tag{5}$$

The pressure P is here non-dimensionalized by the maximum pressure at the impact P_s. ξ is defined as z/b, b being equal to z for $P = P_s/2$ while $\bar{u}$ is non-dimensionalized by the inlet velocity U_0. x^* is defined as $(L-x)/L$.



(a) (b)

Fig. 2. Main parameters of the impingement of a plane jet on a flat surface: (a) distribution of the mean pressure along the plate (—: analytic formula [16], – – –: present study, △: experimental data [1]); (b) distribution of the mean velocity along the axis of the jet (—: present study, □: experimental data [15]).

Fig. 2. Principaux paramètres de l'impact d'un jet plan sur une surface plate : (a) distribution de la pression moyenne le long de la plaque (— : formule analytique [16], – – – : cette étude, △ : données expérimentales [1]) ; (b) distribution de la vitesse moyenne le long de l'axe du jet (— : cette étude, □ : données expérimentales [15]).

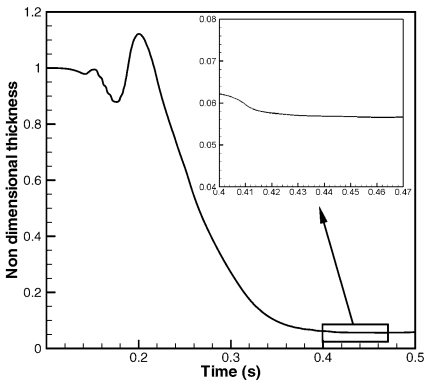


Fig. 3. Time evolution of the film thickness during the wiping at a fixed point downstream of the wiping area.

Fig. 3. Evolution temporelle de l'épaisseur du film pendant l'essorage en aval de la zone d'impact.

In this configuration, the main parameters governing the plane jet are validated on experimental and theoretical data.

3.2. *Gas-jet wiping of a liquid film*

Under some circumstances, the final coating thickness has to be decreased, this being achieved by introducing a turbulent gas-jet. The Reynolds of the liquid film is $\rho_l V_p e_f/\mu_l = 750$, that of the jet is 12 720, the capillary number is $\mu_l V_p/\sigma = 10^{-2}$ and the ratio $U_0/V_p = 100$. The typical film thickness e_f is 200 µm, $\mu_l/\mu_a = 190$ and $\rho_l/\rho_a = 5625$.

A pointer is introduced in the domain in the zone of the asymptotic thickness i.e. far away from the impinging zone. The evolution of this asymptotic thickness is then known during time and presented in Fig. 3. A zoom is shown in the zone of interest so that the asymptotic value can be read. All thicknesses have been non-dimensionalized by the thickness before the gas-jet wiping. The rate of wiping is directly read from the figure.

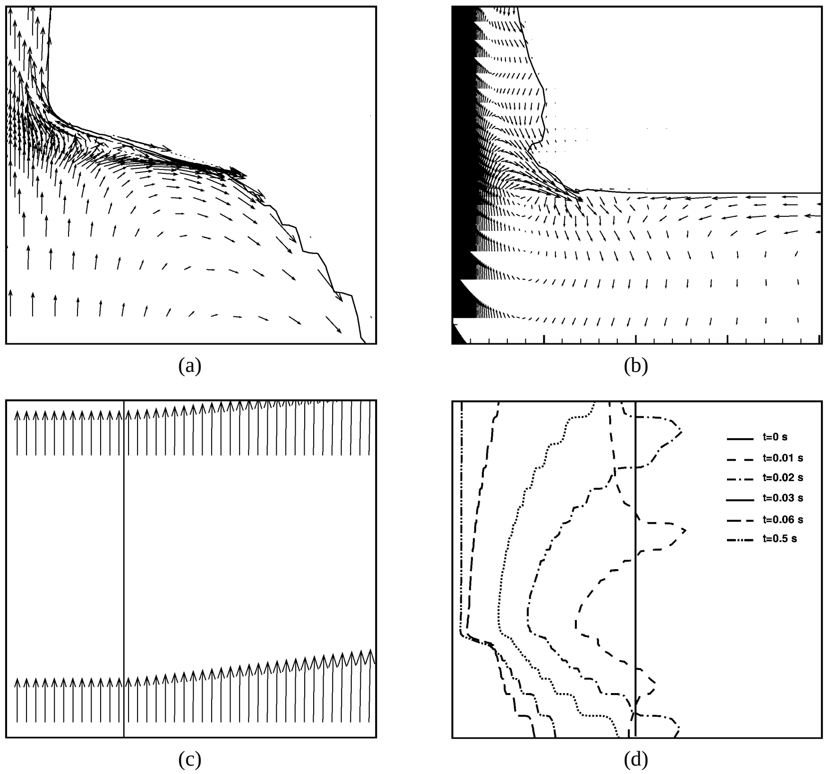


Fig. 4. Visualization of the deformation of the interface ($C = 0.5$): (a) the impinging zone with $z/x = 300$; (b) upstream of the impinging zone with $z/x = 50$; (c) downstream of the impinging zone with $z/x = 1160$; (d) position of the interface for 6 times with $z/x = 1250$.

Fig. 4. Visualisation de la déformation de l'interface ($C = 0{,}5$) : (a) la zone d'impact avec $z/x = 300$; (b) en amont de la zone d'impact avec $z/x = 50$; (c) en aval de la zone d'impact avec $z/x = 1160$; (d) position de l'interface pour 6 temps différents avec $z/x = 1250$.

Industrial data give a ratio of wiping under these specific conditions of 94.3% compared to the ratio of 93.7% for our present study. The thicknesses resulting from the gas-jet wiping is therefore validated nicely.

4. Local description of the film-jet interactions

Since the global parameters have been validated on experimental data, our numerical tool can be used to better understand the local description of the film-jet interactions. Under the constraint of the turbulent jet, the shape of the liquid film is modified. The impinging zone (Fig. 4(a)) is the place where the jet deforms the interface. The shear stress of the jet initiates the folding up of the liquid as it can be seen just below the impact where the velocity field goes down. This phenomenon lasts some time and upstream of the impinging zone (Fig. 4(b)) the surplus of liquid still goes down along the film. A movement of the liquid can be noticed in the bath near the base of the film. Downstream of the impinging zone (Fig. 4(c)) the film is entrained at a velocity almost constant along its section. In Fig. 4(d) are presented the positions of the interface during the wiping. Time 0 is the time reference, when the jet is introduced in the computation. First the film is altered under the shear stress of the jet. Second, the slit in the film increases due to the combined effects of the velocity of the plate and of the action of the jet. Finally, the shape of the film is stabilized at time 0.5 s.

Fig. 5(a) refers to the mean velocity of the jet in the domain. The maximum of the velocity is located at the impingement point. The fluctuations of the velocity tangent to the film are presented in Fig. 5(b). The zone where

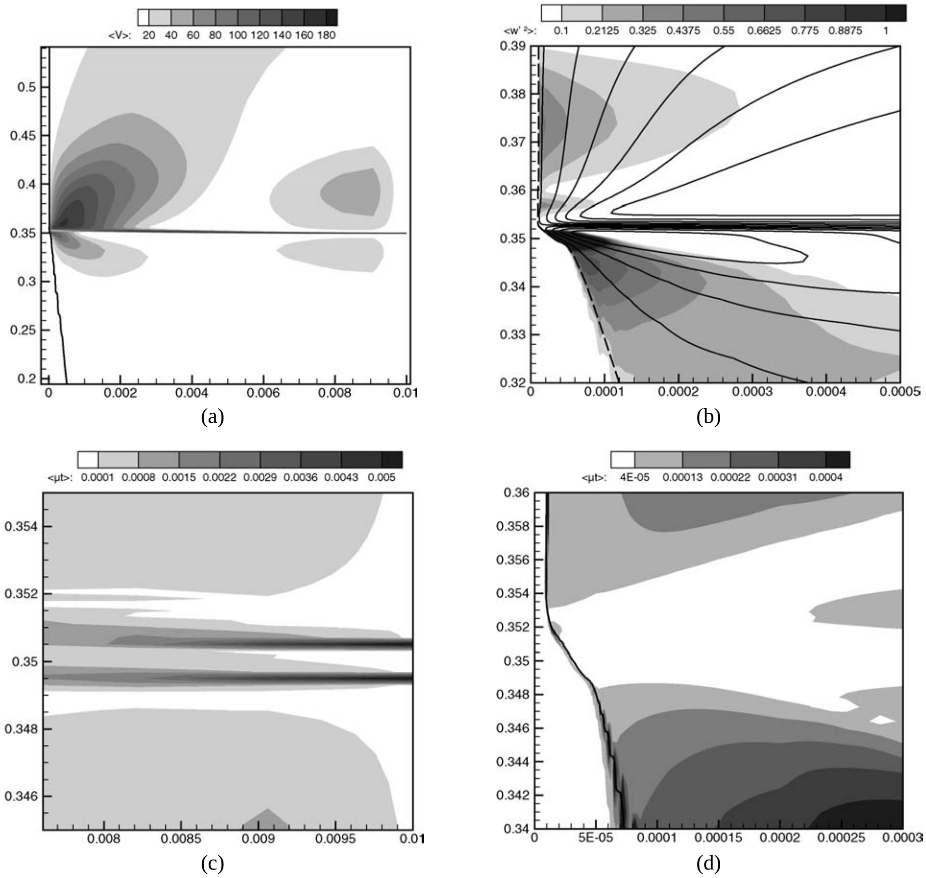


Fig. 5. Visualization of the gas-jet wiping: (a) mean velocity in $\mathrm{m\,s^{-1}}$ (—: interface); (b) fluctuations of the velocity tangent to the film in $\mathrm{m^2\,s^{-2}}$ (– – –: interface, —: mean velocity tangent to the film in $\mathrm{m\,s^{-1}}$): (c) mean eddy viscosity in Pa s – zoom at the outlet: (d) mean eddy viscosity in Pa s – zoom at the impingement (—: interface).

Fig. 5. Visualisation de l'essorage pneumatique : (a) vitesse moyenne en $\mathrm{m\,s^{-1}}$ (— : interface) ; (b) fluctuations de la vitesse tangentielle au film en $\mathrm{m^2\,s^{-2}}$ (– – – : interface, — : vitesse moyenne tangentielle au film en $\mathrm{m\,s^{-1}}$) ; (c) viscosité turbulente moyenne en Pa s – zoom sur l'injecteur ; (d) viscosité turbulente moyenne en Pa s – zoom à l'impact (— : interface).

the fluctuations are higher is located just below the impact of the jet in the air. The fluctuations are all in the air, no major fluctuation is located in the film. The repartition of the mean eddy viscosity is presented in Figs. 5(c) and 5(d). Its intensity is in the range $\mu < \mu_t < 100\mu$, which is classically found in LES simulations of single phase flows [8].

5. Conclusions

Numerical experiments of the gas-jet wiping have been dealt with in order to provide local description of interface and flow behaviors. After having validated the global numerical results on experimental data, the numerical tool has been used to better understand the physical comportment of the film under the constraint of the plane turbulent jet. Turbulence parameters such eddy viscosity or fluctuations have been measured and their repartition at the impingement of the jet on the film has been shown. The simulations displayed in this work are a first step in experimenting the interactions between turbulence and a free surface.

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References

[1] C.H. Ellen, C.V. Tu, An analysis of jet stripping of liquid coatings, J. Fluids Engrg. 106 (1984) 399–404.
[2] D. Lacanette, S. Vincent, E. Arquis, Numerical simulation of the development of a film and the effect of gas-jet wiping, in: 5th Euromech Fluid Mechanics Conference, Toulouse, France, August 2003.
[3] D. Juric, G. Tryggvason, Computation of boiling flows, Int. J. Mult. Flow 24 (3) (1998) 387–410.
[4] W.J. Rider, D.B. Kothe, Reconstructing volume tracking, J. Comput. Phys. 141 (1998) 112–152.
[5] R. Scardovelli, S. Zaleski, Direct Numerical Simulation of free-surface and interfacial flow, Annu. Rev. Fluid Mech. 31 (1999) 67.
[6] D. Enright, R. Fedkiw, J. Ferziger, L. Mitchell, A hybrid particle level-set method for improved interface capturing, J. Comput. Phys. 183 (2002) 83–116.
[7] J.U. Brackbill, B.D. Kothe, C. Zemach, A continuum method for modeling surface tension, J. Comput. Phys. 100 (1992) 335–354.
[8] P. Sagaut, Large Eddy Simulation for Incompressible Flows, Springer-Verlag, Berlin, 1998.
[9] M. Fortin, R. Glowinski, Méthode de Lagrangien augmenté, Application à la résolution numérique des problèmes aux limites, Collection méthodes mathématiques de l'informatique, Dunod, Paris, 1982.
[10] S. Vincent, J.-P. Caltagirone, A one-cell local multigrid method for solving unsteady incompressible multiphase flows, J. Comput. Phys. 163 (2000) 172–215.
[11] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere, New York, 1980.
[12] S. Vincent, J.-P. Caltagirone, Efficient solving method for unsteady incompressible interfacial flow problems, Int. J. Numer. Methods Fluids 30 (1999) 795–811.
[13] A. Nikoleizig, A. Kootz, T. Weber, M. Espenhahn, Stahl u. Eisen, 1978.
[14] B.V. Deryagin, S.M. Levi, Film Coating Theory, Focal Point Press, New York, 1964.
[15] S. Maurel, C. Solliec, A turbulent plane jet impinging nearby and far from a flat plate, Exp. Fluids 31 (2001) 687–696.
[16] P. Hrycak, Experimental Flow Characteristics of a Single Turbulent Jet Impinging on a Flat Plate, U.S. National Aeronautics and Space Administration, Washington, DC, TN-D-5690, 1970.