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Technique for delaying splashing in jet wiping process

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ABSTRACT

The current study presents an experimental investigation of a technique for delaying the occurrence of splashing in jet wiping process by means of a side jet. Gas jet wiping is a hydrodynamic method of controlling the film thickness applied on a substrate in coating processes. It consists of a turbulent slot jet impinging on a moving surface coated with a liquid film. The process is limited by splashing; a rather violent film instability which is characterized by the ejection of droplets from the runback flow and results in the detachment of the film from the substrate. In the present study an additional side jet is used close to the main wiping jet in order to stabilize the runback flow and avoid splashing. The mean film thickness after wiping is measured using a light absorption method and the results are compared for the single jet wiping and two jet configuration. It is shown that the use of the side jet allows for stronger wiping, resulting in lower values of the final film thickness which cannot be achieved with a single jet.

1. Introduction

Jet wiping is a hydrodynamic method for controlling the final film thickness in coating techniques, used in various industrial processes. Typical fields of application include hot-dip galvanizing of metal strips or wires and coating of photographic films. In the case of hot-dip galvanization, steel strips are coated with a thin film of zinc to improve their resistance to oxidation. The moving strips are dipped in a bath with molten zinc and dragged out being covered with a rather thick layer of the coating liquid (initial thickness h_0). The gas-jet wiping process uses a turbulent slot jet to wipe the coating film dragged by the moving substrate and control its final thickness. The wiping mechanism relies on the interaction between the gas jet and the liquid film taking place on the moving surface. The process reduces the thickness of the film applied on the moving substrate, whereas the excess liquid returns to the bath forming a runback flow as illustrated in Fig. 1. The film thickness after wiping, h_f, depends on the substrate velocity U, the nozzle pressure P_n, the nozzle to substrate standoff distance Z, the nozzle slot width d, as well as the liquid properties. The process has been the subject of previous studies [1–7], and some analytical models have been proposed for the film thickness distribution at the wiping region. The pressure gradient and shear stress distributions from the gas jet have been identified as the governing parameters. Moreover, numerical studies mainly using the Volume-of-Fluid model for multiphase flow simulations have been carried out to predict the final film thickness and wiping behavior [8,9].

The jet wiping process is limited by a rather violent film instability called splashing. The instability is characterized by the ejection of droplets from the runback flow and results in an explosion of the film, at which point the runback flow detaches completely from the substrate (Fig. 2). The splashing phenomenon degrades the final coating quality as the process becomes unstable and the main wiping parameters (pressure gradient and shear stress at the impingement) are negatively affected. This instability occurs when the substrate velocity and the jet velocity increase, so it limits the production rate. The phenomenon has been investigated in previous studies [5,10–12] and a first attempt to delay the occurrence of splashing is made by tilting the wiping nozzle [11,12].

In the present study a new technique to delay the occurrence of splashing is investigated. An additional side jet is used close to the main wiping jet in order to stabilize the runback flow and avoid the splashing. In this way stronger wiping can be applied, resulting to lower values of the final film thickness which cannot be achieved with a single jet. The aim of this paper is to present a first experimental investigation of the technique, examining the limit conditions where splashing occurs with and without the side jet.

2. Splashing phenomenon

The splashing mechanism has been approached by Yoneda [5,13] through Hinze's model [14], which has been developed for the breakup of liquid film sheared by turbulent gas flow. A

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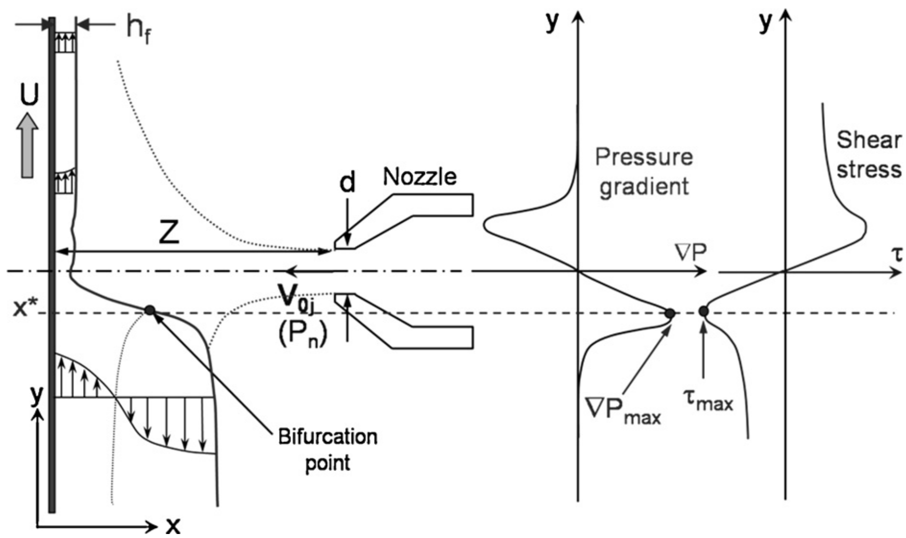

Fig. 1. Schematic of jet wiping process presenting the interaction between the slot jet and the liquid film. The film thickness is reduced and the excess liquid returns to the bath forming a runback flow. The main parameters of wiping are the pressure gradient and shear stress from the jet.

phenomenological approach has been proposed by Buchlin [7], postulating that splashing occurs when the shear effect produced by the downward gas wall jet overcomes the stabilizing effect of the surface tension (modeled as $\sigma/2h_0$). Expressing the shear stress term t_{wj} in terms of the typical dynamic pressure of the wall jet and evaluating the ratio of dominating forces controlling the splashing mechanism leads to the effective jet Weber number [12] given in Eq. (1).

$$We = \frac{\rho_g V_{wj}^2 h_0}{\sigma} \tag{1}$$

The critical We^* above which splashing occurs is correlated with the critical film Reynolds number, based on the strip velocity U and the final thickness h_f as shown in Eq. (2).

$$Re = \frac{\rho_l U h_0}{\mu_l} \tag{2}$$

The wall jet velocity can be modeled taking also into account the nozzle tilt angle α as show in Eq. (3).

$$V_{wj} = \frac{V_{0j}}{Z/d}\sqrt{(1+\sin\alpha)} \tag{3}$$

An empirical model is proposed [11,12] for prediction of the phenomenon, correlating the critical We^* and Re^* at which splashing occurs, as shown in Eq. (4).

$$We^* = e^{(A\alpha+B)} Re^{*-n} \tag{4}$$

The value of coefficients A and B as well as the exponent n depends on the nozzle design, with $0.018 \le A \le 0.066$, $5.5 \le B \le 7.9$ and $1.44 \le n \le 1.91$. As it is shown in Fig. 3, the empirical correlation represents a limit above which splashing occurs. It has been shown that tilting the jet nozzle downwards can displace this splashing limit to higher We^* for constant Re^*.

3. Experimental method

The test facility which is used for the wiping experiments is presented in Fig. 4. It includes a transparent cylinder made of Plexiglas with radius $R = 0.225$ m, dipping into a bath of dyed dipropylene glycol. The nozzle to cylinder standoff distance Z is adjustable. The final liquid film thickness h_f is determined using the light absorption technique [15]. A diffused light source is used inside the transparent cylinder and a high-speed camera is placed 1/8 of the cylinder rotation downstream wiping, recording images of the cylinder covered with the liquid layer. The light is partly absorbed by the liquid film

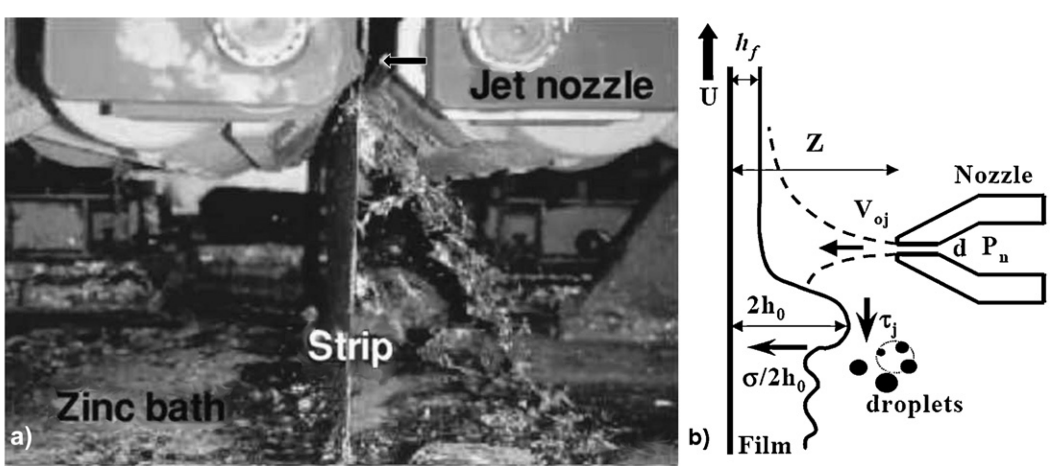

Fig. 2. The splashing phenomenon. (a) Splashing in industrial production line, (b) schematic shown the formation of droplets from the runback flow when the shearing effect from the gas flow overcomes the stabilizing effect of the surface tension.