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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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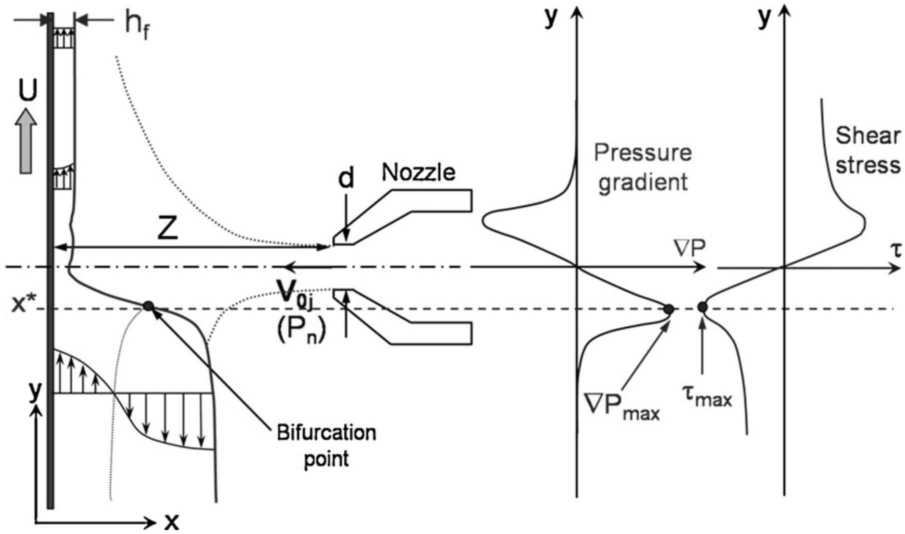

Fig. 1. Schematic of jet wiping process presenting the interaction between the slot jet and the liquid film. The film thickness is reduced and the excess liquid returns to the bath forming a runback flow. The main parameters of wiping are the pressure gradient and shear stress from the jet.

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

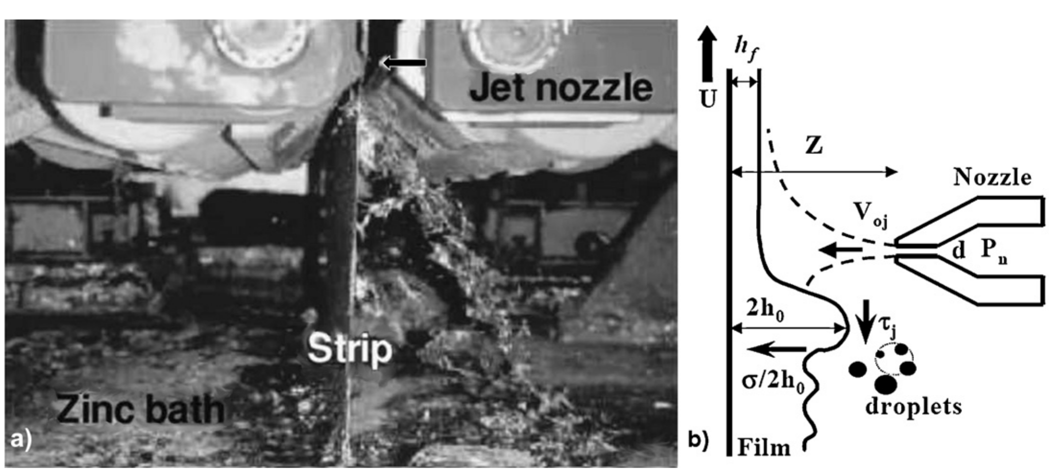

Fig. 2. The splashing phenomenon. (a) Splashing in industrial production line, (b) schematic shown the formation of droplets from the runback flow when the shearing effect from the gas flow overcomes the stabilizing effect of the surface tension.

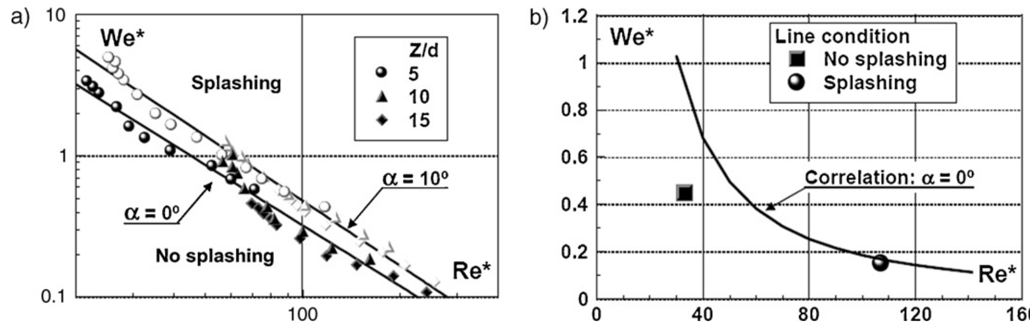

Fig. 3. Splashing correlations. (a) Splashing curves presenting the correlation between We^* and Re^* for two different nozzle tilt angles. The data presented here are obtained using the same experimental setup as described in the present study, but using a single jet for wiping and tilting the nozzle at different angles. (b) Validation of the empirical correlation obtained experimentally for the conditions of the true industrial production line. The points presented on the plot are examples of wiping cases in a true industrial galvanizing line. Good agreement is shown between the predicted limit of splashing and the observed conditions for which it occurs in the industrial environment.

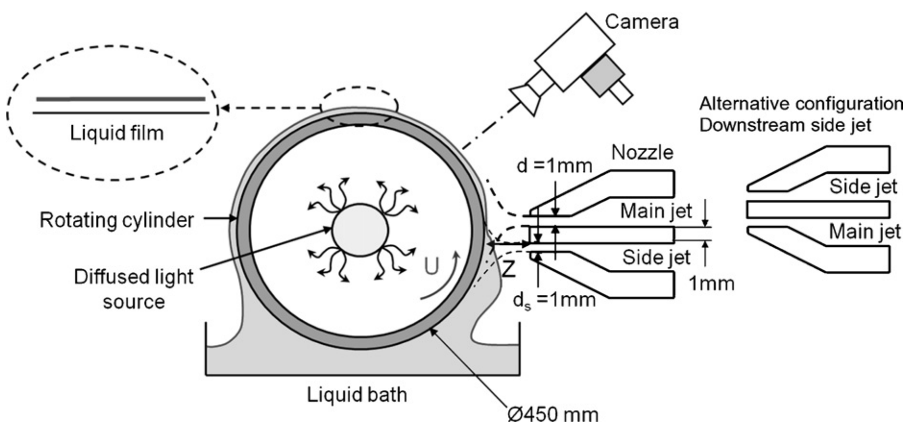

Fig. 4. Schematic of the experimental facility using the light absorption technique. The light from the diffused source inside the cylinder is partially absorbed by the liquid film. The film thickness is measured from images of the film, correlating the level of gray with the local film thickness. The position of the side jet is also presented. An alternative configuration is possible placing the side jet downstream the main jet, by inverting the nozzle.

and the technique associates directly the brightness of the greyscale image to the film thickness.

The nozzle is supplied with pressurized air from a 40 bar line through a settling reservoir under 15 bar. The pressure is measured in the settling chamber of the nozzle with a Validyne transducer. Measurements of mean film thickness are made for different nozzle pressures, which correspond to different exit velocities of the jet.

The wiping process is limited by splashing, which is observed visually as first droplets are ejected from the runback flow until the whole runback flow detaches from the substrate. In this state the wiping mechanism is ruined and possibly the ejected liquid droplets block the nozzle opening, at which point the process is stopped. The limit conditions at which measurements can be taken are considered as the limits of jet wiping before splashing.

To delay the occurrence of splashing, a side jet is used close to the main jet. In the current study the side jet is placed parallel to the main jet at a distance of 1 mm, having an opening of 1 mm. Measurements of the mean film thickness are made keeping the main jet at the reference conditions ($P_n = 600$ Pa) and increasing the side jet nozzle pressure in steps of 150 Pa. For the configuration without the side jet, the main jet nozzle pressure increases in steps of 150 Pa. The liquid used in the experiments is dipropylene glycol (density: $\rho = 1023\,\mathrm{kg\,m^{-3}}$, viscosity: $\mu = 0.105$ Pa s, surface tension: $\sigma = 0.032\,\mathrm{N\,m^{-1}}$).

4. Results

Due to the difficulty of the comparison between the results obtained using a single jet and a combination of a main jet with a side jet, the total energy of wiping E is introduced. This represents the energy per unit time (or power, in Watts) that is supplied to the nozzle in form of compressed air. It is computed as: $E = Q{\cdot}P_n$, where Q is the total volume flow rate of air provided to the nozzle and P_n is the nozzle pressure. Therefore higher nozzle pressures indicate higher wiping energy and stronger wiping. Using the total wiping energy, different jet configurations with different efficiency at wiping can be compared.

The final mean film thickness results are presented in Fig. 5, normalized with the film thickness of a reference case with a nozzle

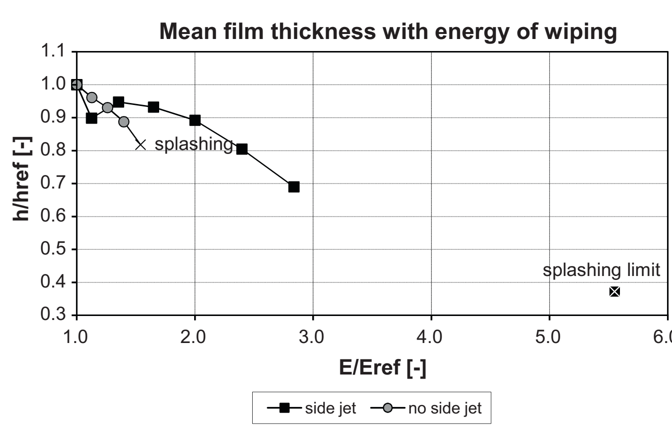

Fig. 5. Results of normalized mean film thickness versus the energy of wiping for the cases with and without a side jet. Splashing limit conditions are depicted using a weak side jet with a strong main jet (splashing limit).

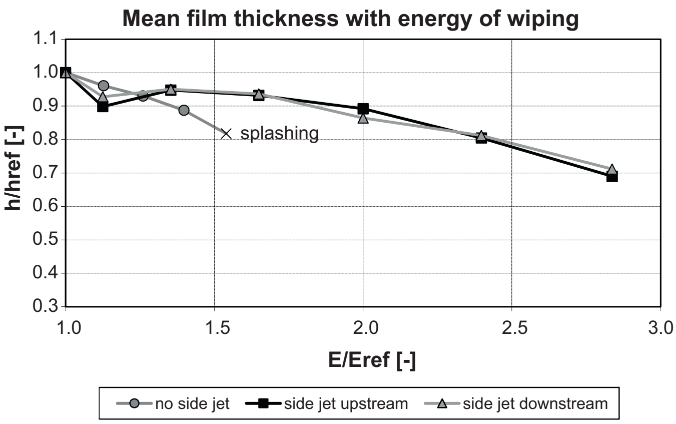

Fig. 6. Results of normalized mean final film thickness with energy of wiping for the configurations with upstream and downstream placement of the side jet. The case of wiping with a single jet is used as a reference for the comparison, with the splashing limit indicated.

pressure $P_n = 600$ Pa, standoff distance $Z = 10$ mm, jet slot opening $d = 1$ mm, strip velocity $U = 0.34\,\mathrm{m\,s^{-1}}$ which gives a mean film thickness $h_{ref} = 380 \times 10^{-6}$ m and wiping energy $E_{ref} = 9.5$ W. The standoff distance Z, jet slot opening d, strip velocity U and the liquid properties are kept constant while the nozzle pressure is changed as indicated in Section 3.

The effect of the placement of the secondary jet is investigated by changing the position of the side and putting it downstream the wiping region (above the main jet). The results are compared with the previous case in Fig. 6, keeping the same reference conditions.

5. Discussion

For the case of wiping without the side jet, splashing occurs rather early in this short standoff distance configuration and the lowest film thickness that can be reached is limited significantly. In this case it cannot be lower than 80% of the reference value. Using the side jet, stronger wiping jets can be used, reaching much smaller film thickness, lower than 70% of the reference value in this configuration. Moreover, the limit of splashing for the case with the side jet is shown in Fig. 5, presenting the limit conditions that can be reached when using a rather weak side jet (300 Pa) with a strong main jet (1800 Pa). This configuration seems to suppress the instability of the runback flow that leads to splashing and allows to go to very high wiping energies, resulting in strong wiping with final thickness of about 37% of the reference case.

The effect of the placement of the secondary jet in this symmetric parallel configuration is investigated by simply placing the side jet downstream instead of upstream the main jet. The results for the final film thickness after wiping are shown in Fig. 6. As it is expected for this configuration the change has small effect on the wiping. It appears that in this case the jet is not tilted downwards like when tilting the nozzle, but it is the gas flow field over the runback flow that is affected. Possibly the unsteady wiping that appears close to splashing conditions is stabilized with the help of the side jet, avoiding the splashing. This permits to reach much smaller film thicknesses, not possible when using a single jet. It is noted that when the splashing limit conditions are surpassed by using the side jet, when this is deactivated splashing occurs again. This indicates that the continuous operation of the side jet is needed for avoiding splashing in the examined conditions.

6. Conclusions

In the present study a first experimental investigation is presented about a technique to delay the occurrence of splashing in the jet wiping process. By use of a side jet close to the main wiping jet much stronger wiping can be applied, resulting in smaller film thickness before splashing occurs. This technique to delay splashing in the jet wiping process can be of high industrial interest as it can be used to reach conditions that are not possible with a single jet. In the investigated conditions it is shown that much lower film thicknesses can be reached with the use of the side jet, not possible when using a single wiping jet. The study can be extended to different configurations and wiping parameters, as well as a further investigation of the mechanism that results in this effect of delaying the splashing can help to clarify the physical phenomena that take place in this interaction.

Appendix A. Nomenclature

In the present study a first experimental investigation is presented about a technique to delay the occurrence of splashing in the jet wiping process. By use of a side jet close to the main wiping jet much stronger wiping can be applied, resulting in smaller film thickness before splashing occurs. This technique to delay splashing in the jet wiping process can be of high industrial interest as it can be used to reach conditions that are not possible with a single jet. In the investigated conditions it is shown that much lower film thicknesses can be reached with the use of the side jet, not possible when using a single wiping jet. The study can be extended to different configurations and wiping parameters, as well as a further investigation of the mechanism that results in this effect of delaying the splashing can help to clarify the physical phenomena that take place in this interaction.

Roman letters

A	splashing correlation coefficient (−)
B	splashing correlation coefficient (−)
d	nozzle slot width (m)
E	total wiping energy per unit time supplied to the nozzle (W)
h	local film thickness (m)
h_f	film thickness after wiping (m)
h_{ref}	film thickness after wiping for the reference case used for normalization (m)
n	splashing correlation coefficient
P	static pressure at jet impingement (Pa)
P_n	nozzle exit dynamic pressure (Pa)
Q	total gas volumetric flow rate ($\mathrm{m^3\,s^{-1}}$)
R	cylinder radius (m)
Re	film Reynolds number, $\rho U h_f/\mu$ (−)
U	substrate velocity ($\mathrm{m\,s^{-1}}$)
V_{0j}	jet exit velocity ($\mathrm{m\,s^{-1}}$)
V_{wj}	characteristic wall jet velocity ($\mathrm{m\,s^{-1}}$)
We	jet Weber number, $\rho_g V_{wj}^2 h_0/\sigma$ (−)
x	spatial coordinate in the direction normal to the substrate (m)
y	spatial coordinate in the moving substrate direction (m)
Z	nozzle to substrate distance (m)

Greek letters

α	nozzle tilt angle (°)
μ	dynamic viscosity (Pa s)
ρ	density ($\mathrm{kg\,m^{-3}}$)
σ	surface tension ($\mathrm{N\,m^{-1}}$)
τ	shear stress due to impinging jet (Pa)

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Subscripts/superscripts

g	gas
j	jet
l	liquid
max	maximum
ref	reference case used for normalizing
wj	wall jet
0	without wiping
*	critical for splashing

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