Experimental investigations of the liquid-film instabilities forming on a wire under the action of a die

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A B S T R A C T

The liquid film remaining on a wire withdrawn from a liquid bath and forced through an annular die is experimentally investigated on a dedicated facility. An optical laser-based technique recently introduced to study liquid-film instabilities on small-radius cylinders allows the measurement of the mean final thickness and wave characteristics. Experimental results are compared to analytical predictions obtained with simple models specifically derived for this configuration and based on liquid-film properties (density, viscosity and surface tension) and operating parameters (wire speed and die dimensions). The experimental measurement of surface-perturbation features (wave amplitude, wavelength and amplification factor) as a function of the operating parameters reveals the presence of a single wavelength for low values of the withdrawing velocity and a progressive wave disappearance for high speeds, in accordance with theoretical predictions.

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1. Introduction

Many industrial applications are based on the deposition of a thin liquid-film on a solid surface so as to form, after drying, a coating layer. Examples include the fabrication of optical fibers, paper and photographic film manufacturing, finishing of steel strips, wire coating. Here we focus on the last process which, more generally, aims at covering a small-radius cylinder with a thin layer of another material, initially liquid, in order to protect or paint textile or optical fibers, electric wires, etc. (Tadmor and Gogos, 1979). In its simplest form, wire coating consists in withdrawing a wire from a liquid bath and letting it dry without undergoing any other kind of treatment. This is known as dip coating. The mean final thickness \( h_f \) depends on the wire radius \( R \), fluid density \( \rho \), surface tension \( \sigma \), dynamic viscosity \( \mu \), and wire velocity \( U \). For a given fluid and fixed \( R \), the final thickness \( h_f \) can be controlled only by changing \( U \) which, due to high-productivity industrial requirements, should be as large as possible. High withdrawing speeds, however, result in a large coating thickness that might not be acceptable. In order to combine high productivity and precisely controlled film thickness, more complex coating techniques such as die coating have been devised. In die coating (see Fig. 1), special dies are employed to mechanically remove, via direct physical contact between the device and the liquid film, the undesired extra liquid from the wire. For an exhaustive review on this process the reader is referred to Mitsoulis (1986b). Clearly, in certain practical cases (e.g. those involving very high temperatures) the physical contact between the die and the coating poses serious problems, which can be overcome by resorting to other techniques based on the hydrodynamic action of a blast of air that wipes off the extra liquid. These methods are commonly referred to as jet finishing, jet stripping, or gas jet wiping (Zuccher, 2008).

In die coating the mean final thickness can be predicted rather simply by assuming a fully developed flow within the die, constant fluid properties, and negligible effects of surface tension and viscous heating. In their first studies, Paek and Schroeder (1979, 1981) analyzed the flow in a conical nozzle and assumed an exponential form for the free surface of the liquid leaving the die. Torza (1976) modeled the coating process as the withdrawal of a cylinder from a bath of fluid. Panoliaskos et al. (1985) used a simple analysis and assessed the effects of surface tension forces and viscous heating, and compared their predictions with experimental data finding good agreement. Other studies (Sakaguchi and Kimura, 1985; Tiu, 1986; Koaiizawa et al., 1995) confirmed that a simple algebraic expression based on liquid properties and geometrical parameters can correctly predict the mean final thickness. The first numerical investigations were performed by Wagner and Mitsoulis (1985) and Mitsoulis (1986a), who simulated the flow of polymers through wire-coating dies for both Newtonian and non-Newtonian fluids using a general-purpose finite element code. Also pressurized coating cups (France and Dunn, 1976; Chida et al., 1982; Paek and Schroeder, 1984) are commonly employed for optical-fiber coating but are not considered here.

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As opposed to the relatively large amount of literature concerning the prediction of the mean final thickness in problems similar to die coating, the study of fluctuations occurring in such a process has been the subject of little attention. If these perturbations are stable but feature large amplitudes or, in the worst-case scenario, are unstable with increasing-in-time/space amplitudes, the final coating can be severely compromised. In these cases, the industrial product is unacceptable either because typical values of the coating characteristics become unknown and, thus, uncontrolled (e.g., the heat-transfer coefficient, which is important in chemical reactions, may vary depending on the local coating thickness) or because the final finish may not be aesthetically good enough. Frequently, the instability limits the production rate and, thus, a mechanical device is employed to fix the final thickness. Its mean final thickness depends on both operating parameters (liquid properties) and die geometry (Note that the geometrical dimensions are not respected in the figure).

Fig. 1. Die coating process. A thin liquid layer is formed on the surface of a wire withdrawn from a liquid bath. Its mean final thickness would increase with increasing withdrawing velocity and, thus, a mechanical device is employed to fix the final independently of . The mean final thickness depends on both operating parameters (liquid properties) and die geometry (Note that the geometrical dimensions are not respected in the figure).
process, this work aims at providing, for such a process, some experimental measurements of the wavelength, wave speed, wave amplitude and amplification factor as a function of the operating parameters.

2. Experimental set-up and measurement technique

Experimental results were obtained using the GALFIN facility originally developed and constructed at the von Kármán Institute (VKI) to carry out measurements during the wire coating process. The wire is typically 8 m long and 2 mm in diameter and forms a closed loop. Its tension is ensured by a mechanical stretching device and a set of pulleys, whereas a motor connected to one of them moves the wire at a constant speed owing to friction. After the wire has gone through the liquid bath (as in Fig. 1) and the coating characteristics have been detected, it is cleaned by a doctor blade so as to recover the liquid (that goes back to the bath) and to avoid slippery conditions between the driving pulley and the wire, which could compromise the wire speed and therefore the measurement. The liquid typically employed for the tests is silicon oil, with the possibility to use different values of viscosity, density and surface tension. The values used for these experiments are reported in Table 1. A complete description of the facility can be found in Zuccher (1999).

A laser-sheet based non-intrusive experimental technique that could satisfy the requirements of both good spatial resolution and high sampling frequency was employed (see Zuccher (2005)) to study the instabilities of the liquid film occurring in die coating. As sketched in Fig. 2, a laser source produces a laser sheet 5 mm wide, which is collected by a receiver placed in front of the source at about 300 mm with the wire positioned in between. The measurement is easily obtained because the light detected by the receiver is linearly proportional (with a negative slope) to the diameter and amplification factor as a function of the operating parameters. The liquid typically employed for the tests is silicon oil, with the possibility to use different values of viscosity, density and surface tension. The values used for these experiments are reported in Table 1. A complete description of the facility can be found in Zuccher (1999).

The possibility to extract information on wave characteristics through this technique relies on the assumption of axisymmetric waves. A technique for the detection of non-axisymmetric waves would require multiple probes acting in the same plane perpendicular to the wire but in different azimuthal positions. Due to the complexity of such a system, investigations are here limited to one azimuthal position, assuming axisymmetric waves as done in several theories (see, e.g., Lin and Liu (1975)). The voltage from the laser-sheet probe is converted into the total diameter, which includes both the wire and the coating. In order to retrieve the liquid-film thickness \( h(t) \) it is necessary to know the mean wire diameter \( d \), which is obtained by averaging the diameter as a function of time measured during a dry run in which the total wire length is scanned for a sufficient number of times. The mean value of the final thickness \( h_f \) is eventually computed by averaging \( h(t) \).

The details on how to retrieve wave characteristics using the laser-sheet probe and the appropriate post-processing procedure can be found in Zuccher (2005). The phase speed is measured by utilizing, during the same test, two probes as in Fig. 2 and positioned at a distance \( D \) from each other. The time delay \( \Delta t \) needed for a particular surface peak to travel from the first probe to the second one is found by performing the cross-correlation between these signals. Having measured the distance \( D \) between the two laser sheets (see Fig. 2), the absolute phase speed is computed as \( c_t = D/\Delta t \). The wavelength of the perturbation is extracted by employing the Fast Fourier Transform (FFT) of the signal \( h(t) \). The amplitude \( A \) is defined as half of the difference between the maximum and the minimum of the signal filtered within the band of interest (only one wavelength is detected in the present experiment – for the general case of multiple wavelengths see Zuccher (2005)). The amplification factor is computed by considering two amplitude measurements \( A_1 \) and \( A_2 \) at different distances from the die. In fact, in theoretical works the form of the perturbation is typically \( A = A_0 \exp(i(x - ct)) \) (see, e.g., Lin and Liu (1975)), where \( A \) is the amplitude at a certain

![Fig. 2. Sketch of the experimental set-up and laser-probe detection system. The laser-sheet produced by the laser source is detected by the receiver. The wire, covered by the liquid-film and positioned in between, interrupts part of the laser, allowing a very precise measurement based on the output signal from the receiver. If two identical probes are employed it is possible to measure the wave velocity and the wave amplitude at two different locations from the die (\( D \) is the distance between the probes, \( L \) is the distance of the bottom probe from the die).](image-url)
point $x$ in space (along the wire) and $t$ in time, $c = c_r + ic_i$ is the complex wave speed, and the coordinates $x$ and $t$ are measured with respect to the reference location where the amplitude is $A_0$. Therefore, from $A = A_0 \exp(i(x - ct))$, the experimental growth rate is immediately computed as $c_i = (1/\Delta t) \ln(A_2/A_1) = (c_r/D) \ln(A_2/A_1)$. When comparing theory to experiments, it should be kept in mind that the expression for $c_i$ given above is correct provided that the evolution is in its linear stage (as it is assumed in the theory).

The error analysis shows that the uncertainty associated to the mean final thickness, which is related to the uncertainty of the coefficients in the calibration curve and to the uncertainty of the acquisition board, is on the order of 8 $\mu$m, close to the spatial resolution of the probe. Considering that the expected value of the mean final thickness is about 400 $\mu$m, the relative uncertainty of $h_t$ is about 1.6%. The uncertainty related to the wavelength is in the order of 0.0004 m, whereas the uncertainty of the wave amplitude is in the same order of magnitude as for the mean final thickness, i.e. 8 $\mu$m.

3. Results

Before presenting the experimental results, we recall very briefly a simple model that predicts the final thickness in die coating, as it will be used to compare experiments to theory. Assuming that (i) the axial velocity component is much larger than the radial one which is, thus, negligible, (ii) the flow is axisymmetric, (iii) the flow within the die is fully developed, (iv) the liquid film is stationary and has constant properties and (v) the effects of surface tension and viscous heating are negligible; then the mean final thickness $h_f$ can be expressed as (see, e.g., Panoliaskos et al. (1985), Sakaguchi and Kimura (1985) and Koaiizawa et al. (1995))

$$h_f = \left( \frac{k^2 - 1}{2 \ln k} \right)^{1/2} - k, \quad \text{with} \quad k = \frac{R}{R_d},$$

where $R_d$ is the internal die radius. Clearly, in (1), only the ratio $k$ between the wire radius and the internal radius of the die plays a role, i.e. the model for the final thickness relies only on the geometry and is independent of fluid properties and withdrawing speed. However, with reference to Fig. 3, the expression of $h_f$ can be further complicated by assuming a more general geometry of the die.

Fig. 4 reports the mean final thickness $h_f$ normalized with the wire radius as a function of the capillary number $Ca = \mu U/\sigma$ for different configurations ($L$ is the distance of the bottom probe from the die and $D$ is the distance between the two probes, as in Fig. 2). The theoretical prediction provided by (1) is reported on the same plot to show the very good agreement between theory and experiments. Since the wire radius is $R = 1$ mm, the values on the vertical axis of the plot are the actual thickness in millimeters. It should be noted that the theoretical model predicts a constant value because all fluid properties and wire velocity are disregarded in deriving it, whereas a slight dependence on $U$ is observed in the experiments. Error bars are not reported because repeated measurements provided differences which cannot be appreciated on the plot and therefore would not add information. This was expected because
of the very small uncertainty predicted by the error analysis (see last paragraph of Section 2).

The experimental wave velocity $c_r$, obtained as described in §2 and normalized with $r/l$ so that $c_r l / r$ can be viewed as a “wave capillary number”, is shown in Fig. 5 together with the theoretical predictions by Lin and Liu (1975). The measured and predicted values match remarkably well. This is probably due to the fact that the mean final thickness is very small and therefore the wave velocity is quite close to the wire velocity.

Fig. 6 shows the wavelength $\lambda/\ell_c$ normalized with the capillary length $\ell_c = \sqrt{2 \sigma g \rho \ell}$ as a function of the capillary number.

The quantitative description of the stable or unstable nature of the liquid film is provided by the measured amplification factor $c_i$, reported in Fig. 9. The fact that it is negative is in accordance with all previous figures.

The experimental results reported in this section could have a remarkable impact in industrial applications. In fact, it is found that the waves, when present, are stable and therefore their amplitude keeps decreasing as the wire is dragged away from the die. The wave amplitude, which slightly decreases with the capillary number, is a very small percentage of the film thickness and, thus, these waves do not compromise the final product. This is the main

![Power spectrum](https://via.placeholder.com/150)

Fig. 6. Wave length $\lambda/\ell$, normalized with the capillary length $\ell_c = \sqrt{2 \sigma g \rho \ell}$ as a function of the capillary number.

![Power spectrum](https://via.placeholder.com/150)

Fig. 7. Progressive wave disappearance for increasing capillary number. (a) $Ca = 1.59$, (b) $Ca = 2.54$, (c) $Ca = 3.57$ and (d) $Ca = 3.77$. 
It is found that the mean final thickness of the liquid film is almost constant with the pulling speed and matches the theoretical value provided by a very simple model (Panoliaskos et al., 1985) that includes only geometrical parameters and neglects liquid-film properties and withdrawing speed. The measured wave velocity fits very well the theoretical curve predicted by Lin and Liu (1975). Only one wave is detected and its wavelength is almost constant with the pulling speed, in accordance with the theoretical prediction of Homsy and Geyling (1977). The wave amplitude progressively decreases with the capillary number and, above a certain value of the latter, the peak in the power spectrum becomes too low to be distinguished from the noise, causing a complete disappearance of waves. This confirms furthermore the theoretical conclusions of Homsy and Geyling (1977), who showed that the growth constant decreases with increasing wire speed.

References

Hong Kong, pp. 4–5.

4. Concluding remarks

This study presents some experimental investigations carried out to characterize the liquid film left on a wire after it has been withdrawn from a liquid bath and has undergone the action of an annular die intended to reduce its final thickness. The understanding of this configuration is of particular interest for industrial applications such as the die-coating process.