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

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ABSTRACT

The liquid film remaining on a wire withdrawn from a liquid bath and forced through an annular die is experimentally investigated on a dedicated facility.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.

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 ρ, surface tension σ, dynamic viscosity μ, 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; Koaizawa 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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Nomenclature

A	wave amplitude
Ca	capillary number ($Ca = \frac{\mu U}{\sigma}$)
c	complex wave speed ($c = c_r + ic_i$)
c_r	wave speed
c_i	amplification factor
D	vertical distance between two laser probes
h	liquid-film thickness
i	$\sqrt{-1}$
k	ratio between wire radius and internal die radius $\left(k = \frac{R}{R_d}\right)$
L	vertical distance between the bottom probe and the die
l_c	capillary length $\left(l_c = \sqrt{\frac{2\sigma}{\rho g}}\right)$
R	wire radius
R_d	internal die radius
r	radial coordinate
U	wire (withdrawing) velocity
x	axial coordinate
Greek symbols	
α	wavenumber $\left(\alpha = \frac{2\pi}{\lambda}\right)$
λ	wavelength
μ	liquid-film (dynamic) viscosity
ρ	liquid-film density
σ	liquid-film surface tension
Subscript	
f	final (thickness)
0	wire

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 predictive theory confirmed by experimental evidence is of considerable practical significance. To the author's knowledge, the only work concerning die-coating instabilities is that of Jiang et al. (2005), who developed a classical linear perturbation analysis and numerically investigated the dependence of the coating perturbations on the operating and geometric parameters.

A considerable number of studies have focused on the more general case of instabilities occurring in the liquid film falling on a vertical cylinder. The works of Lin and Liu (1975) and Krantz and Zollars (1976) are commonly recognized as the fundamental studies in this area. However, the earlier works by Tomotika (1935), who studied the instability of a cylindrical thread of a viscous liquid surrounded by another viscous liquid, and by Goren (1962), who considered the instability of an annular coating of liquid on a wire, set the basis for further developments (see, e.g., Mashayek and Ashgriz (1995)). Atherthon and Homsy (1976) derived the governing equations for the instability by employing an asymptotic (long-wave) analysis; Homsy and Geyling (1977) investigated the film instabilities occurring on a cylinder in rapid coating, while Shlang and Sivashinsky (1982) considered the weakly nonlinear stability of a film flowing down a cylinder using the strong surface tension approximation. The problem has also been tackled numerically by Solorio and Sen (1987), who solved the linear equations without any further limiting assumption. Rosenau and Oron (1989) derived an equation for the evolution of a disturbed-film interface flowing down an infinite vertical cylindrical column. Quéré (1990) described annular films flowing and thinning along vertical fibers, observing the Rayleigh instability in thick coatings and no instabilities in thin films. Kliakhandelr et al. (2001) examined the dynamics of a thick layer of viscous liquid flowing down a thin vertical fiber in both linear and nonlinear regimes and, recently, Hamadichea and Abou-Shadyb (2006) studied the instability during the specific process of optical-fiber coating. The nonlinear waves developing in thin films falling down on vertical wires and tubes were also studied (Trifonov, 1992; Frenkel, 1992; Hung et al., 1996; Cheng et al., 2001).

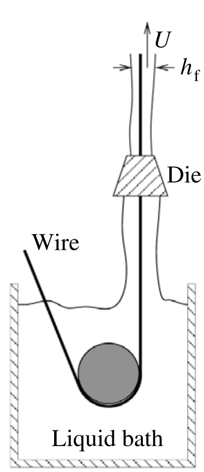

Fig. 1. Die coating process. A thin liquid layer is formed on the surface of a wire withdrawn from a liquid bath. Its mean final thickness h_f would increase with increasing withdrawing velocity U and, thus, a mechanical device is employed to fix h_f independently of U. The mean final thickness depends on both operating parameters (liquid properties) and die geometry (Note that the geometrical dimensions are not respected in the figure).

Experimental results concerning wire-coating instabilities, or at least thin-liquid-layer instabilities on vertical cylinders or tubes, are more rare in literature than those theoretical or numerical. Kapitza and Kapitza (1949) investigated the film of water or alcohol on a glass vertical cylinder and measured coating thickness, wave amplitude, phase velocity and wavelength. Goren (1962), in the same work previously mentioned for the theoretical development, carried out experiments by painting thin layers of honey onto fine wires and using a microscope to study the instability. His measurements of the wavelength agreed with his theory in the limit of negligible inertia.

Different measurement techniques (Hewitt, 1978; Alekseenko et al., 1994; Nozhat, 1997; Shedd and Newell, 1998; Mouza et al., 2000; Stelter et al., 2000; Shedd and Newell, 2004) have been employed over the years for the study of the thin liquid film on vertical cylinders or tubes. Recently, Zuccher (2005) introduced a laser-based measurement technique that allows the detection of both mean final thickness and perturbations of the liquid film.

Due to the lack of data regarding configurations useful for the understanding of the instabilities occurring during the die-coating 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 of the wire covered by the coating film. This probe allows a sampling frequency up to 3 kHz with a 5 μm spatial resolution. Moreover, the possible problem of a wire moving in the horizontal plane is completely overcome because the total light received by the detector does not depend on the position of the wire, which is therefore free to oscillate within the 5 mm span. A remarkable advantage of such a technique is that the wave speed can be retrieved by using two probes set at a known distance from each other, as shown in Fig. 2, and by performing the cross-correlation between the two signals. Moreover, the knowledge of the wave amplitude at two different distances from the die allows the direct measurement of the amplification factor.

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 $h(t)$.

Table 1
Typical liquid properties and operating parameters used in the experiments

Description	Symbol	Values	Dimensions
Wire velocity	U	0.28–1.15	m/s
Liquid density	ρ	951	kg/m^3
Liquid viscosity	μ	0.114	kg/(m s)
Liquid surface tension	σ	0.02	kg/s^2
Wire radius	R	0.001	m
Die internal radius	R_d	0.002	m

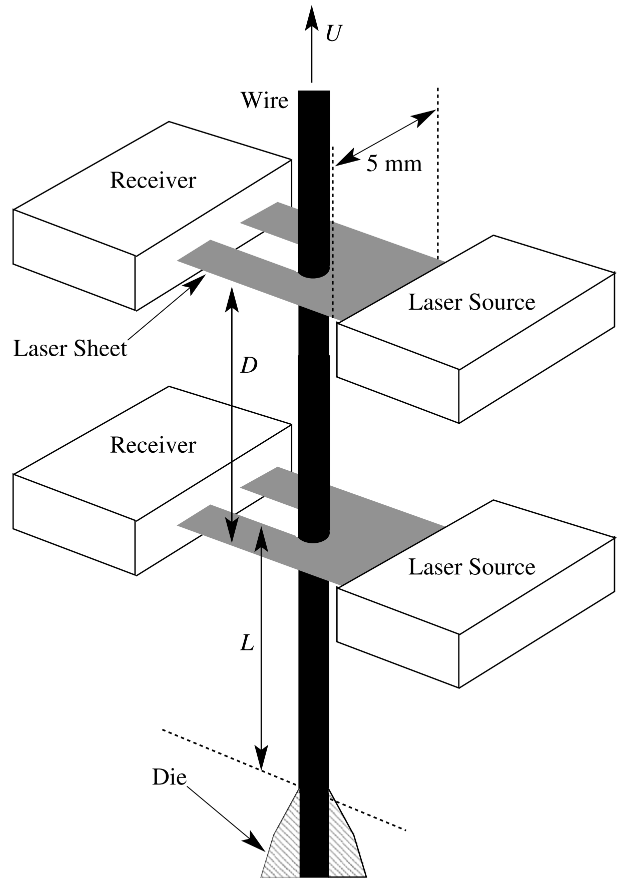

Fig. 2. Sketch of the experimental set-up and laser-probe detection system. The laser-sheet produced by the laser source is detected by the receiver. The wire, covered by the liquid-film and positioned in between, interrupts part of the laser, allowing a very precise measurement based on the output signal 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).

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 Δt 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 $c_r = D/\Delta t$. 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 wave (half peak-to-peak amplitude) and is computed as $A = \text{std}(h)\sqrt{2}$, where std($h$) is the standard deviation 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 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 μm, close to the spatial resolution of the probe. Considering that the expected value of the mean final thickness is about 400 μm, the relative uncertainly of h_f 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 μm.

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 Koaizawa et al. (1995))

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

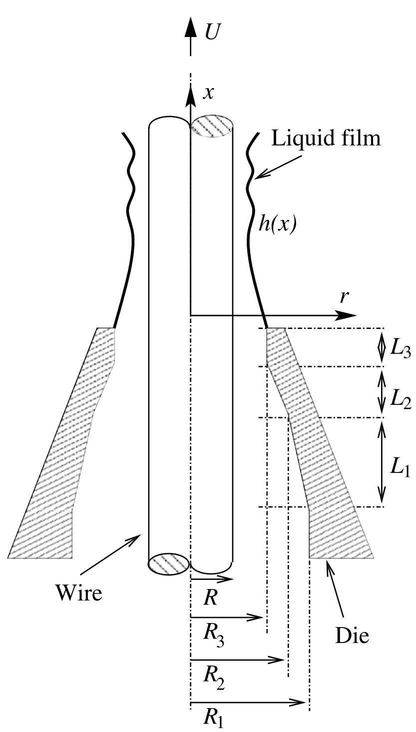

Fig. 3. Schematic diagram of a general die. The geometry is axial-symmetric and the die might have different internal shapes (geometrical dimensions are not respected in the figure).

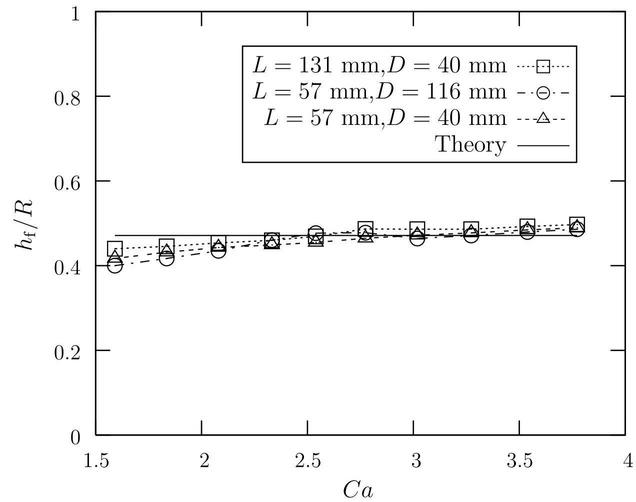

Fig. 4. Mean final thickness h_f/R normalized with the wire radius as a function of the capillary number, comparison between experiments and theory.

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 R 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

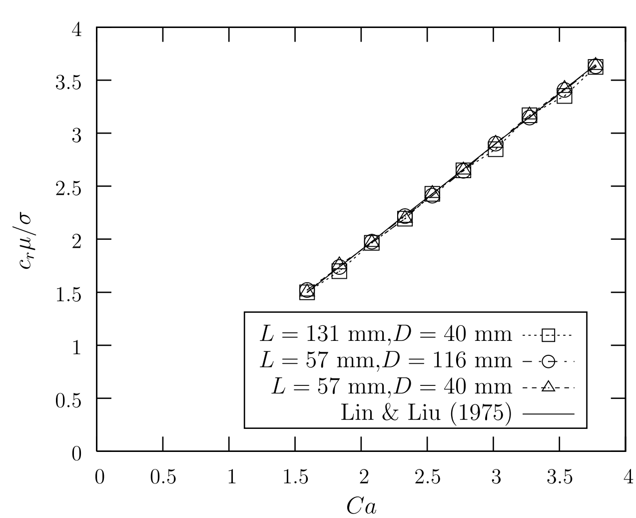

Fig. 5. Normalized wave velocity $c_r\mu/\sigma$ as a function of the capillary number, comparison between experiments and theory.

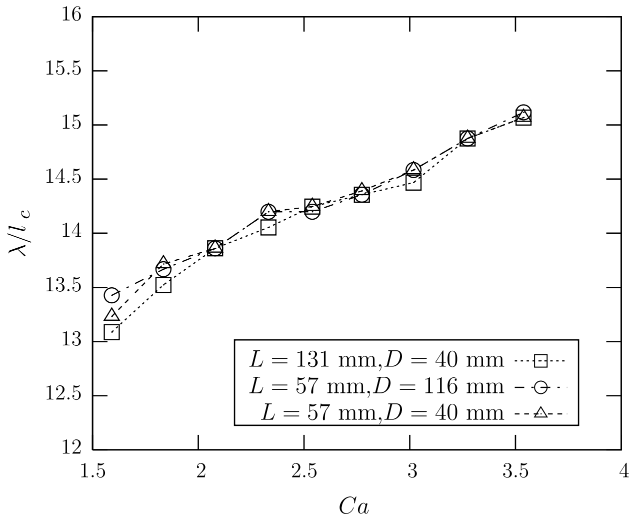

Fig. 6. Wave length λ/l_c normalized with the capillary length $l_c = \sqrt{\frac{2\sigma}{\rho g}}$ as a function of the capillary number.

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 σ/μ so that $c_r\mu/\sigma$ 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 λ normalized with the capillary length l_c ($\sqrt{2\sigma/\rho g} \approx 2.07$ mm). Results refer to different distances L from the die and different distances D between the laser probes and reveal a very slight increase of λ/l_c with the capillary number, in the order of about 5%. This is in accordance with Homsy and Geyling (1977), who observed that the wavelength of maximum growth remains approximatively constant with the wire speed. Contrary to Figs. 4 and 5, here the last experimental point is at $Ca = 3.57$ because for larger speeds the wavelength is no more detectable. This phenomenon of "wave disappearance" is clearly presented in Fig. 7, which reports the power spectra of h as a function of the wavelength for increasing values of the capillary number. At $Ca = 1.59$ (Fig. 7a), a very sharp and clear peak is localized at $\lambda = 27.8$ mm; at $Ca = 2.54$ (Fig. 7b) the peak moves to $\lambda = 29.4$ mm but its power is reduced of about 50% with respect to the previous case. For $Ca = 3.54$ (Fig. 7c) the wavelength $\lambda = 31.1$ mm features a very small peak, which can still be distinguished from the noise, whereas at $Ca = 3.77$ one might guess that the peak is around $\lambda = 35$ mm, but since this is not clearly distinguishable from the background noise such a point has been excluded from Fig. 6.

The use of two laser probes for retrieving the experimental phase speed allows also to understand whether the liquid film is stable or not by comparing the wave amplitude at two different distances from the die. Results are plotted in Fig. 8. At both distances from the die the relative wave amplitude (A/h_f) is practically the same (there is a difference in the numbers, but this is not visible in the plot). Moreover, it should be noticed that the wave amplitude is a very small percentage of the film thickness, as desired in the industrial process of die coating.

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 the finding from 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

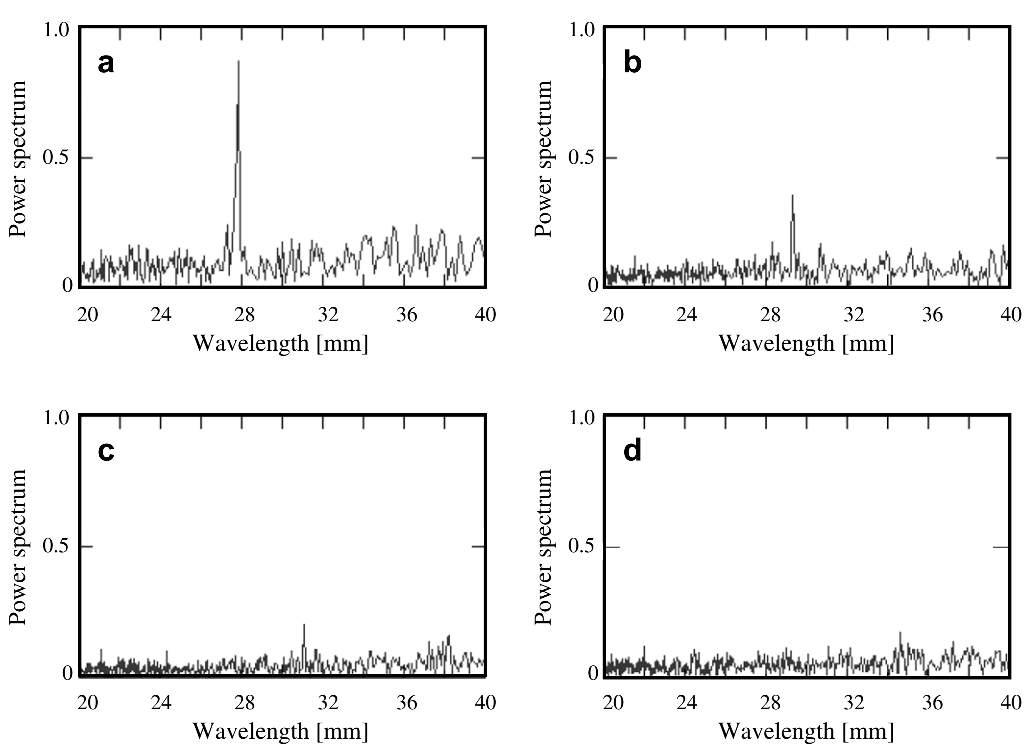

Fig. 7. Progressive wave disappearance for increasing capillary number. (a) $Ca = 1.59$, (b) $Ca = 2.57$, (c) $Ca = 3.57$ and (d) $Ca = 3.77$.

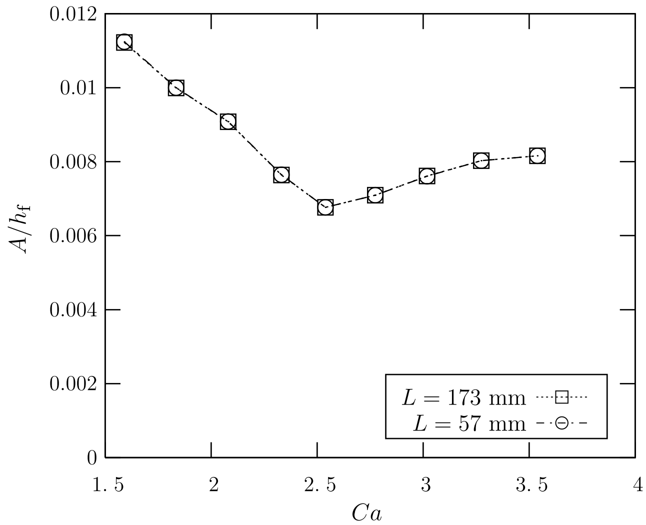

Fig. 8. Normalized amplitude A/h_f as a function of the capillary number at two different distances from the die.

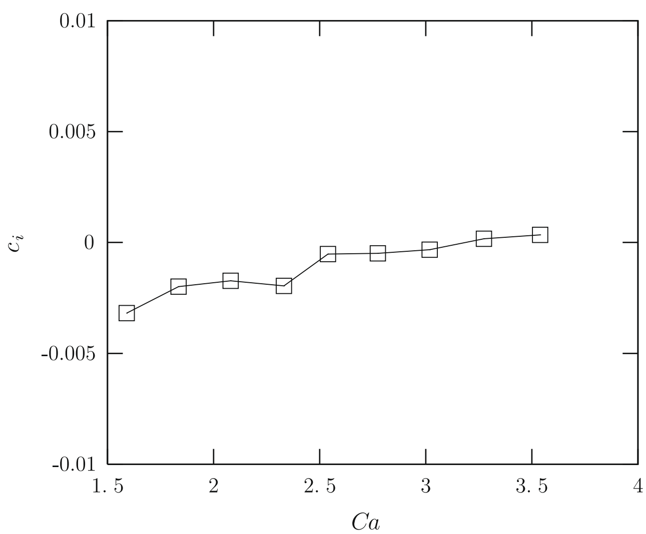

Fig. 9. Amplification factor c_i as a function of the capillary number.

concern within industry. Moreover, the wave amplitude is consistently reduced by increasing the wire speed (capillary number) up to a cut-off value beyond which no waves can be detected. The fact that the film becomes more stable with increasing speed, whereas the wavelength of maximum growth does not change remarkably, provides evidence to support the claim of Homsy and Geyling (1977), who showed in Fig. 2 of their original work that at a fixed film thickness and varying pulling speed the amplification factor decreases with increasing speed and that the wavelength of maximum growth remains approximatively constant.

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.

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.

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