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RESEARCH ARTICLE

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A novel measurement technique for the study of wire coating instabilities

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Abstract A new non-intrusive investigation technique developed especially for the study of liquid film instabilities occurring in the wire coating process is presented. A laser-sheet-based probe assures high spatial resolution and high frequency response, along with robustness to wire movements and vibrations. Moreover, the calibration is easy and fast, since the calibration curve is linear. The post-processing procedure allows the detection and measurement of the most important wave characteristics, such as wavelength, wave amplitude, wave velocity, and amplification (damping) factor. Results obtained with this technique are compared with existing theories, showing good agreement. More than one wave is detected and it is found that short waves dominate at low entrainment speeds, whereas long waves dominate for high speeds, with a smooth transition from the former behavior to the latter. The trend of the amplification factor follows that predicted by the theory. Due to its simple implementation and automatic data analysis, this technique seems to be very promising, not only for research purposes, but also for industrial applications. Among those, the most straightforward would be in the control of the final surface properties during the wire coating process, in order to ensure the desired characteristics.

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1 Introduction

Wire coating is an industrial process which aims at covering a wire, or, more generally, a small-radius cylinder, with a thin layer of another material. The wire can reduce to a fiber in the limit of a very small radius, leading to a very specific area, known as the "fiber coating". For a recent review on the latter subject, the reader is referred to Quéré (1999).

The interest in studying the process of wire coating is due to the wide range of industrial applications in which it can be found. Various coating processes have been employed to create an insulator layer on a wire, to protect or to paint textile fibers and to protect optical fibers (Tadmor and Gogos 1979). A new and technologically cutting-edge field is the high-temperature superconductor (HTSC) bi-component wire fabrication. Bi-component, in this particular case, means that a normal metal wire is covered with HTSC, carrying along different advantages, such as (1) a parallel conductor (the normal metal) to be used in case of loss of superconductivity in the HTSC and (2) a heat sink (the normal metal itself) that helps to withstand local overheating of the wire, and subsequent loss of superconductivity (for more details on this technology, see Jin et al. (1987), Sekine et al. (1988), and Yamada et al. (1987)).

One of the easiest ways to accomplish wire coating is to deposit a thin liquid film on the wire by withdrawing it from a liquid bath and then to let it dry (see Fig. 1 for a sketch). This technique, otherwise known as dip coating, is the oldest and the simplest. The wire is drawn out from a liquid bath and it is dried without undergoing any other kind of treatment. The mean final thickness h_0 depends on the wire radius r_0, the fluid density ρ, surface tension σ, dynamic viscosity μ, and on the wire velocity V. The desired final thickness h_0 is achieved by controlling V, assuming that the liquid cannot be changed because the coating material is fixed. If high productivity is required, as in every industrial process, the withdrawal

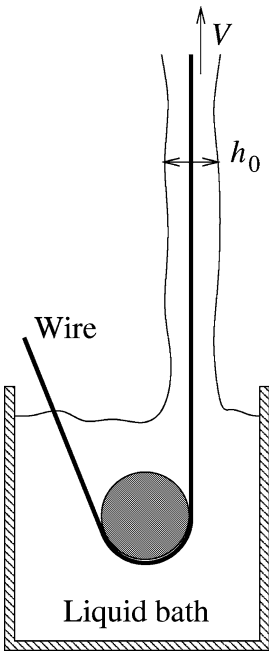

Fig. 1 Wire coating process. The wire is withdrawn from a liquid bath so that a thin liquid layer is formed on its surface. The mean final thickness h_0 depends on the wire radius and the fluid properties. In some cases, instabilities can develop within the film, leading to an undesired product. (Note that the geometrical dimensions are not respected in the figure)

speed can be increased. This, however, results in an increase of the coating thickness as well, since the latter is directly proportional to the wire velocity. In order to combine high productivity and precisely controlled film thickness, it is necessary to introduce further complications, such as in die coating and annular jet wiping coating.

These two other techniques differ from dip coating because additional devices are used to control the final liquid thickness h_0 by acting on the liquid film after it has been withdrawn. In die coating, the final thickness is reduced to the desired value by using a mechanical device, the die, whereas in annular jet wiping, an annular jet acts like a knife, ensuring the target value of the final thickness.

Since, in die coating, the coated wire is extruded, in many cases, this technique cannot be applied because of the direct physical contact between the liquid and the die. Annular jet wiping is the best alternative in these situations. When a die or a jet are used to control the final thickness, h_0 is a function of the geometry of the die or the characteristics of the jet, along with the wire radius r_0 and the fluid properties (ρ, σ, μ).

In the wire coating process, a thin, continuous, uniform in thickness, and smooth layer of liquid is expected. However, it is sometimes difficult to achieve because of flow instabilities. They represent a considerable problem. If waves are present in the liquid layer before drying, the final coating will result in an undesired product, either because typical values of the coating characteristics can change (e.g., the heat transfer coefficient – important in chemical reactions) or the final finish may not be good enough. Of course, this is true only when the wave amplitude, referred to the coating mean thickness, is not negligible.

Frequently, the instability sets a limit on the production rate or dictates the selection of the liquid in precision coating. A predictive theory of film instability confirmed by experimental evidence is, therefore, of considerable practical significance.

In the theoretical study of wire coating stability, the wire is replaced by a small cylinder, and a linearization and perturbation approach is usually developed in order to simplify the problem.

The works of Lin and Liu (1975) and Krantz and Zollars (1976) are considered to be the fundamental studies in this area, as far as the linear stability theory is concerned. However, an earlier work by Goren (1962) considered the instability of an annular coating of liquid on a wire or on the inside of a small tube, and showed that disturbances of a certain wavelength can grow more rapidly than others. He not only developed the theory, but he also performed experiments. Homsy and Geyling (1977) investigated the film instabilities occurring on a cylinder in rapid coating. More recently, Shlang and Sivashinsky (1982) considered the 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 for the fluid falling down a cylinder, without any other limiting assumption. Rosenau and Oron (1989) derived an amplitude equation which describes the evolution of a disturbed film interface flowing down an infinite vertical cylindrical column. Trifonov (1992) investigated the nonlinear waves developing in thin films falling down on vertical wires and tubes using an integral method. Yarin et al. (1993) obtained the evolution of the capillary instability of a thin liquid layer on a cylinder for both isothermal and non-isothermal conditions. Studies on the hydrodynamic instability of a fluid layer flowing down a rotating cylinder have also been carried out (Dávalos-Orozco and Ruiz-Chavarría 1993).

From the experimental viewpoint, besides the mean final thickness, the most important characteristics that need to be measured in order to identify the stable or unstable behavior of the fluid on the vertical cylinder (wire) are wave velocity, wavelength, wave amplitude, and amplification factor. All these features represent the main results expected for a comparison with theoretical predictions.

Experimental results on wire coating instabilities, or at least, thin-liquid-layer instabilities on vertical cylinders or tubes, are more rare in the literature than theoretical or numerical studies. Kapitza and Kapitza (1949) investigated the film of water or alcohol on a glass vertical cylinder (250 mm long and 30 mm in diameter), measuring the coating thickness, wave amplitude, phase velocity, and wavelength. The observed regular steady

waves were classified by the authors as ''periodical'' and ''single''. These results were used by Lin and Liu (1975) for comparison with their theory. Goren (1962), besides developing the theory previously mentioned, 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. More recently, de Bruyn (1997) experimentally investigated the surface-tension- and gravity-driven instabilities of a thin layer of fluid on a horizontal cylinder. He found agreement of wavelength and growth rate with theoretical predictions in both small-radius (surface-tension-driven instability) and large-radius (Rayleigh–Taylor instability) cases.

As far as possible measuring techniques are concerned, Alekseenko et al. (1994) stated that, due to the complexity of the film surface wave structure, there are no measuring techniques currently available to completely satisfy all the specified requirements. Hewitt (1978) and Alekseenko et al. (1994) outlined the main techniques used in liquid-film thickness measurements, such as the film conductance and film capacitance method, the needle contact method, the light absorption method, the fluorescence method, the γ-ray and X-ray absorption methods, etc. Recently, Mouza et al. (2000) developed a photometric technique for film thickness measurements based on the absorption of light passing through a layer of dyed liquid. Nozhat (1997) applied a laser interferometry technique to measure the thickness of the liquid flowing on the inner surface of a glass tube. An advantage of this method is that it shows the shape of the thin film on the inner surface of the vertical tube at a point in a horizontal cross section. Stelter et al. (2000) presented an optical method of elongational rheometry suitable for the characterization of the behavior of viscoelastic polymer solutions in elongational flows. The liquid thread is illuminated by a diode laser such that the shadow of the thread projected onto the photodetector reduces the optical light power received proportionally to the thread diameter.

The aim of the present paper is to prove the suitability of a new non-intrusive experimental technique for the study of liquid film instabilities typical of the wire coating process.

2 Choice of measurement technique

In order to chose the appropriate investigation technique capable of detecting the wave characteristics and the growth/decay rate, several approaches have been considered besides those already in use and presented in the cited literature.

The driving idea was a technique that was simple to use, robust, cheap, easy to calibrate, and, preferably, that does not necessarily need frequent calibration. These constraints were mainly dictated by the possibility to export the technique to industrial applications, where the monitoring of coating surface characteristics is an issue. The focus was, from the very beginning, on optical techniques, since other methods (film conductance, film capacitance, light absorption and fluorescence, γ-ray and X-ray absorption) are much more complex.

The first idea was a CCD video camera and digital image processing (DIP), but it was abandoned because of various reasons. These include the large amount of singular pictures needed, low maximum reachable frequency (25 Hz), very difficult calibration, ''pillow'' effect if the camera is not exactly perpendicular to the wire, impossibility to observe a complete wave in only one image (due to resolution requirements).

The second idea was a probe based on two intersecting laser beams, which scan the area under investigation, where the wire is placed. Since the wire is set between the laser sources and the receivers, by knowing the scanning frequency and the time during which the laser beams are interrupted, the total width (wire plus coating) can be easily obtained. The main drawback of such a device is the acquisition frequency, 3 Hz, which is too low to follow the small waves typical of these kinds of experiments.

Because of these reasons, it was necessary to think of a new probe which could satisfy the requirements of both good spatial resolution and high sampling frequency. The latter limit is set by the need for tracking the surface waves in a wide range of wavelengths. Moreover, a fast calibration and a procedure as free as possible from optical misalignments (like those typical of CCD cameras) was particularly sought.

A new laser-sheet-based non-intrusive experimental technique was thus introduced and its sketch is reported in Fig. 2. A laser source produces a laser sheet 5 mm wide. A receiver is placed in front of the source at a distance of about 300 mm and the wire is positioned in

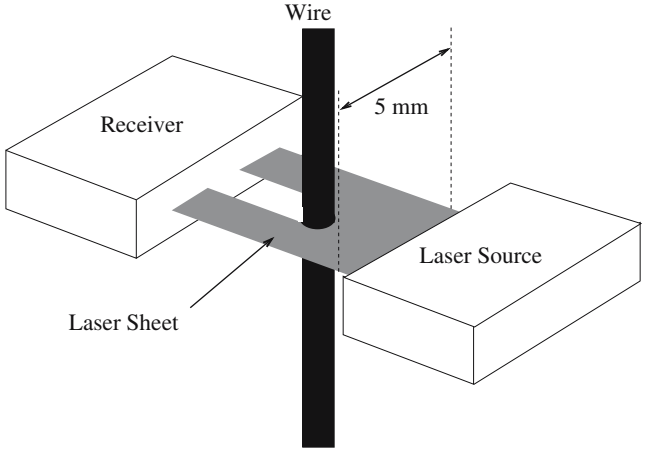

Fig. 2 Sketch of the laser probe. The laser sheet produced by the laser source is detected by the receiver. The wire, positioned in between, interrupts part of the laser, allowing a very precise measurement based on the output signal from the receiver. The light received, in fact, is proportional (with a negative slope) to the total wire diameter, where ''total'' means physical wire diameter plus liquid film

between. The light collected by the receiver is linearly proportional (with a negative slope of the curve) to the diameter of the wire: if the diameter increases, the signal from the receiver decreases because less light is sensed.

This probe is an extremely suited investigation tool when dealing with liquid–film instabilities because its sampling frequency can reach 3 kHz, with a 5-μm spatial resolution.

Moreover, the problem of a moving wire in the horizontal plane is completely overcome with this technique. The total light received, in fact, does not depend on the position of the wire, which is free to oscillate within the 5-mm span. Of course, this holds as long as the wire is fully immersed in the laser sheet and its thickness (the wire diameter plus the coating) is smaller than the laser-sheet width (5 mm). If these requirements are not satisfied, the measurement is useless and completely wrong.

When using this measurement technique, particular attention should be paid to the optical elements, which are necessary in order to ensure a laser sheet that is perfectly parallel and has no divergence. Due to the hard operating environment, the lens of the laser source and receiver can easily get dirty if oil droplets fall on them, with consequent optical deformation and output-signal reduction.

The possibility to extract information about the wave through this technique relies on the assumption that waves are axisymmetric. A technique for the detection of nonaxisymmetric 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 limited here to one azimuthal position, assuming, therefore, axisymmetric waves, as in several theories previously mentioned.

Finally, a remarkable advantage of such a technique is that the wave speed can be retrieved by using two probes set at a known distance and by performing a cross-correlation between the two signals.

3 Wave characteristics

From the laser-sheet probe, a voltage as a function of time is first obtained and converted through the calibration curve into the total diameter, which includes both the wire and the coating. The liquid-film thickness $h(t)$ is thus obtained by subtracting the mean wire diameter d from the total diameter.

The time series $h(t)$ so obtained is the starting point of the post-processing procedure presented in this section. If the phase speed c_r (one possible choice of the wave velocity) can be measured by utilizing two laser-sheet probes, the signal is immediately transformed as a function of space. If the phase speed can not be measured, because only one probe is available, its value can be computed through the theory (Lin and Liu 1975), which has been proved to be very reliable. This procedure is correct if the phase speed c_r is constant, i.e., the system is non-dispersive. Lin and Liu (1975) indeed showed that this is true for axisymmetric waves in films on cylinders. The signal as a function of space $h(x)$ is then processed in order to retrieve the general wavelength λ_k (more than one wave can be detected; for this reason, the subscript k is introduced), the wave amplitude A_k corresponding to the kth wave, and the amplification/decay factor G.

The data are processed according to following steps:

1. Calculation of the mean final thickness h_0 from the signal as a function of time $h(t)$.
2. Evaluation of the phase speed c_r from the experiments via cross-correlation between two signals obtained at two different locations for the same test.
3. Fast Fourier transform (FFT) of the signal and computation of the spectrum as a function of the wavelength, using c_r to transform frequencies in wavelengths.
4. Detection of the wavelengths of interest λ_k from the spectrum.
5. Band-pass filtering of the signal such that it contains only the wavelength λ_k detected at step (4).
6. Evaluation of the wave amplitude of the signal obtained at point (5). Since it contains only the part associated with the wavelength λ_k, A_k is retrieved.
7. Evaluation of the amplification factor G (only if two probes are used).

3.1 Mean final thickness

The voltage from the laser-sheet probe is converted into the total diameter. Since the latter includes both the wire and the coating, in order to obtain the liquid-film thickness $h(t)$, it is necessary to know the mean wire diameter d. This is accomplished by averaging the diameter as a function of time measured during a dry run. One needs to make sure that the total wire length is scanned for a number of times, so that a good average value can be computed. The mean wire diameter is then subtracted and the coating thickness is obtained as a function of time. The mean value h_0 is retrieved simply by averaging $h(t)$.

3.2 Phase speed

The phase speed is directly measured once two waveforms at two different stations are available. By performing a cross-correlation between the two signals, the time delay needed for a particular surface peak to go from the first probe to the second probe is found. Knowing the distance between the two measurement points D, the absolute phase speed is easily obtained:

$$c_r = \frac{D}{\Delta t}.$$

This procedure is possible only if two identical probes are available and, rigorously speaking, is valid only for nondispersive systems, where the phase speed is constant. As previously underlined, Lin and Liu (1975) showed that this is true for axisymmetric waves.

In Fig. 3, a sketch of the setup with two probes is reported. The two variable parameters are D, the distance between them, and L, the distance of the bottom probe from the liquid bath.

An example of the way in which the phase speed is retrieved is shown in Figs. 4 and 5. Two signals recorded at two different stations are plotted in Fig. 4. The general wave-form is clearly very similar in the two cases, but the signals look shifted by a delay Δt. This delay accounts for the (upward) translational velocity due to the wire, the phase speed, and the effect of gravity. Figure 5 displays the two signals after one of them has been shifted with respect to the other by the time delay provided by the cross-correlation.

The visual inspection of such a plot reveals also that the system, even if it is dispersive, behaves as a nondispersive one, with all wavelengths traveling at the same (constant) phase speed. In a strongly dispersive system, the two signals would not have been so close to each other after the time shifting, but would have been characterized by slightly different shapes. This observation allows us to consider the phase speed to be constant.

3.3 Wavelength

The fast Fourier transform (FFT) is performed on the signal as a function of time, and then the spectrum is reported from a function of frequency to a function of wavelength. This is easily done, since the phase speed is now known, and each wavelength is simply c_r divided by the frequency.

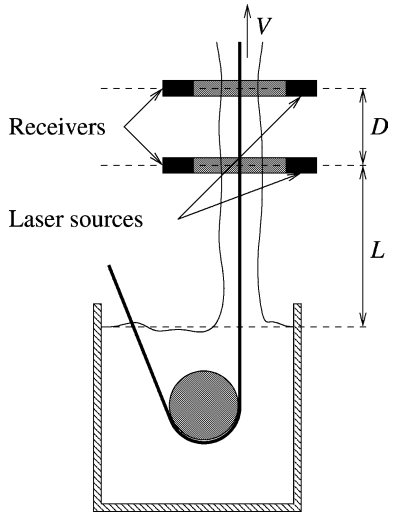

Fig. 3 Position of two laser probes with respect to the experimental apparatus. D is the distance between the probes and L is the distance of the bottom probe from either the liquid bath or the die (in die coating)

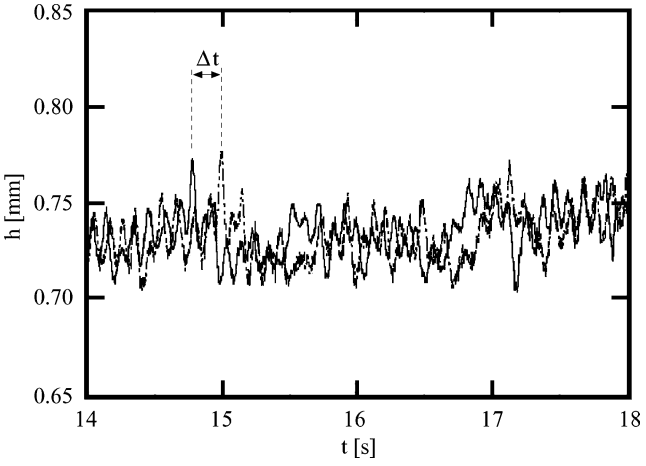

Fig. 4 Two signals measured at two different points. One signal is recorded at a distance L from the liquid bath and the other at a distance D from the first signal. The two signals are very much alike, but shifted by a delay, due to the fact that the wave is driven upwards by the wire

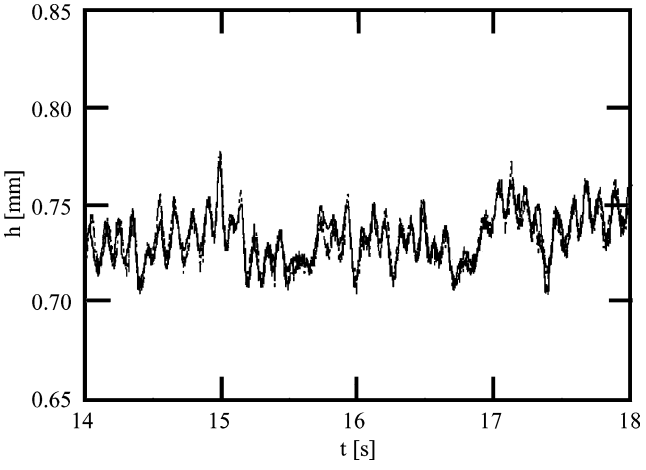

Fig. 5 Two signals measured at two different points after shifting. By comparing this figure with Fig. 4, one can realize that the two signals are highly correlated if shifted by Δt

An example of a typical spectrum is shown in Fig. 6. In one signal, there is usually more than a single peak and the wavelengths detected are usually not simple harmonics. If one is interested in computing the relative importance of each of them with respect to the whole signal, the ratio between the integral of the spectrum around the peak and the integral of the entire spectrum can provide a good measure.

3.4 Wave amplitude

For each of the previous observed wavelengths, the corresponding amplitude is computed by reconstructing a new signal that contains only the wavelengths in the

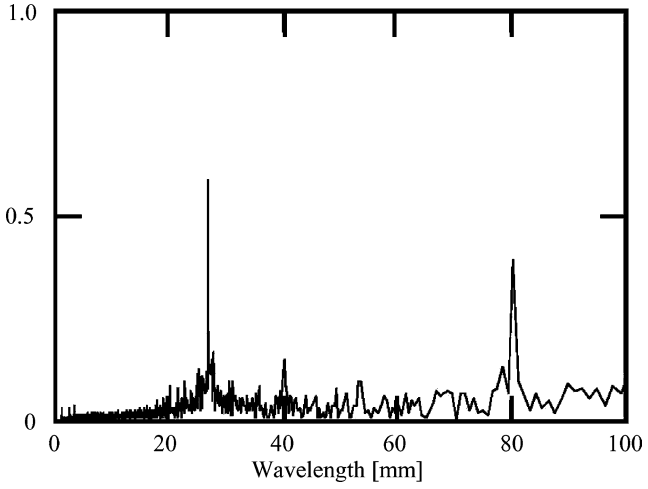

Fig. 6 Power spectrum of the signal as a function of space. More than one single wavelength is usually detected

range of interest. This is done by employing a band-pass filter, which corresponds to multiplying the original spectrum by a unitary shape function different from zero only in the band range and by applying an inverse FFT.

Figure 7 shows the comparison between a typical signal before and after filtering. Two effects are clearly visible. One is associated with low frequencies, detectable in the original signal and removed in the filtered one. Low frequencies are responsible for slow variations of the signal, and, therefore, they are related to large changes in its amplitude. On the other hand, the band-pass filter also removes higher frequencies, which can be associated with either very small wavelengths or electronic noise. These wavelengths, however, do not contribute considerably to the signal amplitude.

Once the filtered signal is obtained, the amplitude A (defined as the difference between the maximum and the minimum of the wave) is given by:

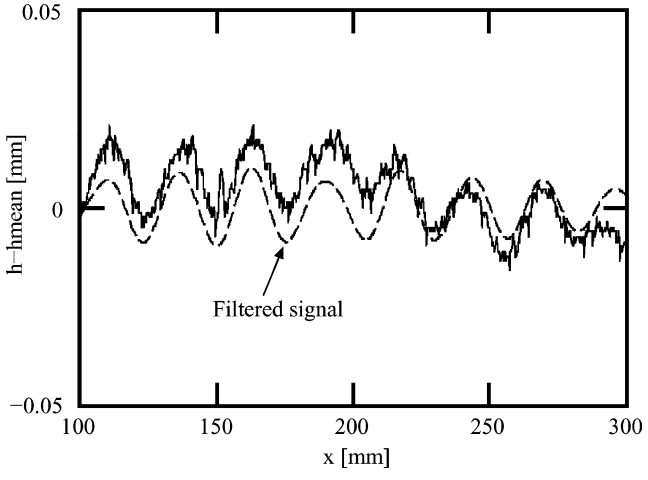

Fig. 7 Example of the band-pass filtering procedure. Notice that both low and high wavelengths are removed, the former being more responsible of the signal amplitude than the latter

$$A = \mathrm{std}(h)2\sqrt{2}$$

where std(h) is the standard deviation of the filtered signal.

3.5 Amplification factor

A straightforward answer regarding the stable or unstable behavior of the liquid film is given by the direct measure of the quantity G, defined as:

$$G = \ln\left(\frac{A_2}{A_1}\right),$$

where A_2 and A_1 are the wave amplitudes measured respectively at the top and at the bottom station. G is the growth or decay rate of a detected surface wave and is of extreme interest in the study of liquid film instabilities.

In order to compare the measured amplification factor with the theoretical one, we recall that the form of the wave solution is (Lin and Liu 1975):

$$A = A_0 \exp\left(\mathrm{i}(x - ct)\right),$$

where A is the amplitude at a certain point x in space (along the wire) and t in time, $c = c_r + \mathrm{i}\, c_i$ is the complex wave speed, and the coordinates x and t are measured with respect to the reference where the amplitude is A_0. By considering two measurements of the amplitude A_1 and A_2 at different distances from the liquid bath, and replacing the time Δt needed for a peak to travel from the former to the latter with $\Delta t = D/c_r$, where c_r is the wave speed experimentally measured using two probes (Fig. 3) and D is the distance between them, one obtains immediately a measure of the growth rate:

$$c_i = \frac{c_r}{D}\ln\left(\frac{A_2}{A_1}\right). \quad (1)$$

4 Experimental results and discussion

The results presented in the this work were performed using the already existing GALFIN facility, which was originally developed and constructed at the von Kármán Institute (VKI), Belgium, to carry out measurements on wire coating. 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. One of the latter is connected to a motor that moves the wire at a constant speed, relying on the friction between the two surfaces. 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).

In Fig. 8, the mean final thickness h_0, normalized with the radius of the wire r_0, is shown as a function of the Capillary number $Ca = \mu V/\sigma$. The results refer to the case of dip coating and are compared with the theory developed at VKI in the past (Parellada 1997). Two different distances L from the liquid bath are considered, 180 mm and 350 mm, for ten different Capillary numbers. Since the radius r_0 is 1 mm, from Fig. 8, the thickness in millimeters is directly available. When the velocity increases, the mean final thickness, consequently, increases. Experimental results seem to be in good agreement with the VKI theory, with an error on the order of less than 5% in the worst case scenario. Figure 8 contains the information that the average value h_0 is indeed the "final" thickness, as it does not change as a function of the distance from the liquid bath L.

In Fig. 9, the experimental phase speed c_r, normalized with σ/μ, is reported as a function of the Capillary number for five different test configurations and compared with the theory by Lin and Liu (1975). The tests have been performed by changing the distance from the liquid bath L from 290 mm to 450 mm, and the distance between the two probes D from 40 mm to 190 mm. From Fig. 9, it is clear that, in all the experiments, the value of the phase speed increases for increasing wire velocity, following a behavior close to that of a straight line from the origin of the axes. For small Capillary numbers, this is more evident and experiments agree well with the theory, whereas for higher values, there is a deviation from the theoretical line, with observed values smaller than theoretical ones. The maximum difference is within 10%. The fact that, at fixed Capillary numbers, the experimental phase speed is always the same independently of the distance from the bath or between the two probes confirms the repeatability of the experiments and is an a posteriori check that supports the assumption of a constant phase speed c_r.

In Fig. 10, the wavelengths detected at each Capillary number are shown normalized with the Capillary length $l_c = \sqrt{2\sigma/\rho g} = 2.1$ mm. Bubbles are centered in the measured wavelength and their size is proportional to the contribution of that particular wavelength to the spectrum. This contribution is computed by evaluating the ratio between the area under the peak in the power spectrum and the area below the whole spectrum. From the theory (Lin and Liu 1975), it is known that a critical value α_c of the wavenumber α exists, so that, if the wavenumber is smaller than α_c, the flow is unstable independently of the Reynolds number Re based on h_0

Table 1 Typical wire velocity range and liquid properties used in the experiments

Description	Symbol	Values	Unit
Wire velocity	V	0.1–0.4	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 diameter	d	0.002	m

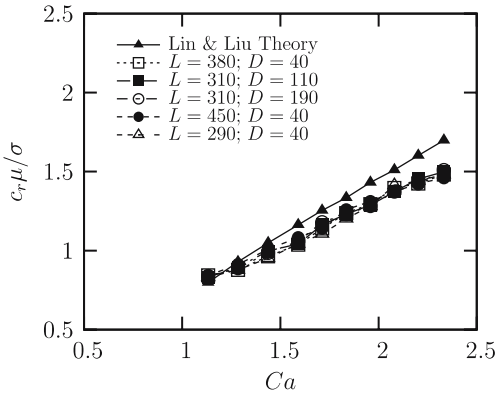

Fig. 9 Phase speed c_r as a function of the Capillary number Ca. L and D are in mm and are defined as in Fig. 3

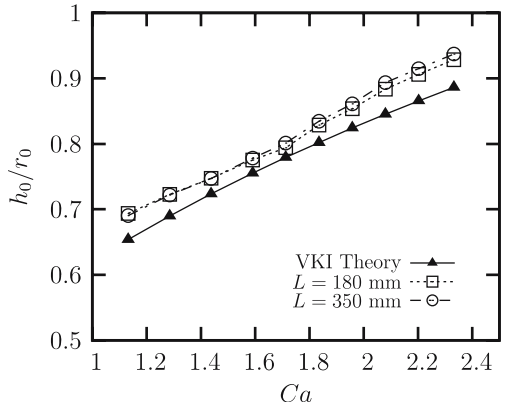

Fig. 8 Normalized mean final thickness h_0/r_0 as a function of the Capillary number Ca

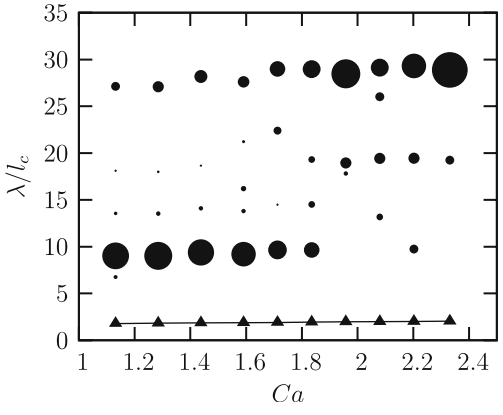

Fig. 10 Wavelength λ/l_c normalized with the Capillary length $l_c = \sqrt{2\sigma/\rho g} = 2.1$ mm as a function of the Capillary number Ca

and the flow velocity at the outer edge of the film. In other words, if the disturbance wavelength λ is greater than the critical wavelength $\lambda_c = 2\pi h_0/\alpha_c$, then the flow is unstable. Values of λ_c computed using the phase speed measured in the experiments are reported in Fig. 10 with a solid line and symbols. It can be observed that, for low Capillary numbers (up to $Ca = 1.8$), the instability is dominated by short waves, with typical wavelengths of 20 mm ($\lambda/l_c \approx 9$). At greater Capillary numbers, long waves dominate, even if peaks at short wavelengths are still observed. By repeating the same plot as in Fig. 10 for different distances from the liquid bath L, it is found that the typical wavelengths are independent of L.

Amplitudes measured at $L = 180$ mm and $L = 350$ mm from the liquid bath have been reported in Fig. 11, and normalized with respect to r_0. The curves show that the amplitude decreases when the velocity of the wire is increased. This information is important because if the uniformity of the coating is a constraint, small amplitudes are sought after. By comparing amplitudes at different distances from the bath, one can easily conclude that the flow is unstable at low Capillary numbers, as the amplitude at the higher probe (further from the liquid bath) is greater than the amplitude at the lower probe (closer to the liquid bath). On the other hand, the flow becomes more stable for larger Capillary numbers.

A better way to understand the stable or unstable nature of the flow is to compute the amplification factor according to Eq. 1 and obtained from the measurements of the amplitude A reported in Fig. 11. This is done in Fig. 12, where theoretical predictions and experimental results are shown. For increasing Capillary number, the amplification factor decreases, meaning that the flow goes towards a less unstable state. The agreement between theory and experiments is quite good, and the trend is clearly captured.

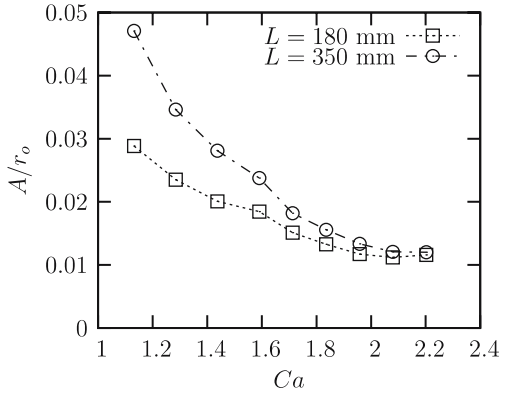

Fig. 11 Wave amplitude A/r_0 for different distances from the liquid bath as a function of the Capillary number Ca

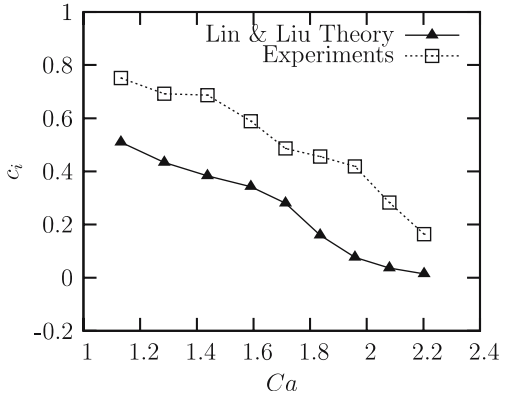

Fig. 12 Amplification factor c_i as a function of the Capillary number Ca

5 Conclusions

A new measurement technique is introduced to study surface waves occurring in the wire coating process. Phase speed, wavelength, wave amplitude, and amplification factor are measured by employing two identical probes featuring a 5-mm-wide laser sheet. The calibration curve of the sensors is linear and quite stable, and the data post-processing necessary to retrieve the wave quantities is completely automated, offering several advantages in both research and industrial applications.

Experimental results and existing theories compare with good agreement, confirming the validity of this experimental method. It is found that short waves dominate at low Capillary numbers (Ca), whereas long waves dominate for higher ranges of Ca. Agreement between theory and experiments is observed also in the phase speed, which turns out to be constant and behaves as predicted by Lin and Liu (1975). The trend of the amplification factor is captured as well.

The present technique overcomes the numerous problems related to data post-processing arising when cameras and video cameras are used, and provides high spatial resolution and high sampling frequency. Moreover, the measurement is not affected by wire movements, thanks to the fact that the laser detectors measure the total laser radiation independently of the wire position. All these features make the present technique particularly suited for detailed investigations in the area of liquid film instabilities on wires and cylinders.

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