Liquid film instabilities in die coating process

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Abstract

Liquid film instability in die coating process is experimentally investigated on a dedicated test facility. The signal from a new laser sheet non-intrusive probe, is processed to determine mean final thickness, wave velocity, wavelength, and wave amplitude. Only one characteristic wavelength is observed for low wire velocities while a progressive wave disappearance occurs for high velocity. Dies with defects are also tested finding waves only if the defect is comparable to the final coating thickness.

1. Introduction

The coating of wires with a liquid film is encountered in many industrial processes. The control the final thickness is performed using different techniques such as free dip coating [1][2], annular jet wiping [1][3] and die coating [4]. The die consists of a small orifice through which the coated wire is extruded: the final coating thickness h_0 is function of the geometry of the orifice, of the wire radius and of the fluid properties. During this process, however, it is sometimes difficult to achieve a smooth and uniform layer of liquid because of flow instabilities. This effect is obviously undesired since the coating characteristics can change (heat transfer coefficient), or because of esthetical reasons. Frequently the instability sets a limit on the production rate or in the selection of the liquid, so that a better understanding of film instability is of considerable practical significance.

2. Experimental set-up

Experiments are performed using GALFIN facility, shown in figure 1, designed to study different wire coating techniques. A complete description of the facility can be found in [3]. The wire passes through a liquid bath (1) and a metering device (2), a die or an annular-jet knife, controls the final film thickness. Two laser sheet probes (3) with varying vertical position allow measurements at different distances L from the liquid bath or from the die, an ejector (4) avoids run-back flow occurring when the coated wire touches the first pulley after the bath, an evacuating tube (5) connects the ejector to a filter to recover the liquid and finally a blade (6) cleans the wire after the measurements. The liquid used is silicon oil with density ranging from 900 to 970 kg/m^3, viscosity from 0.01 to 0.5 Pa.s and surface tension of 0.02 Pa.m. The wire tested has a radius r_o equal to 1 mm.

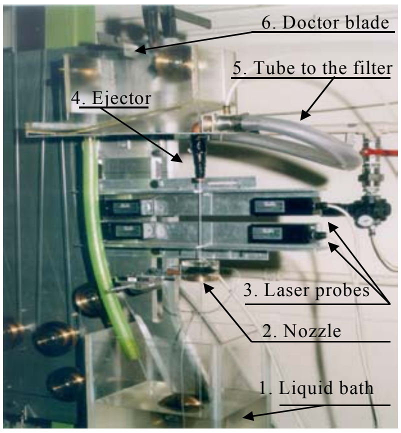

Figure 1: GALFIN facility

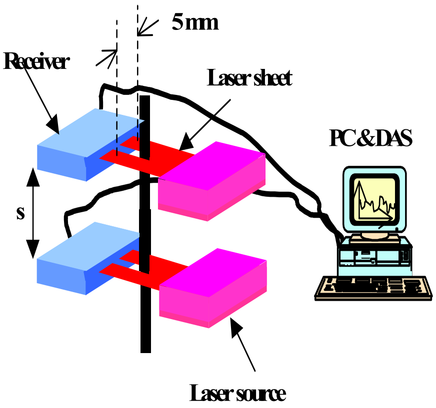

Figure 2: Measurement chain

3. Measurement technique & data processing

In order to capture free-surface waves in a wide range of wavelengths with high spatial resolution and high sampling frequency, a new optical probe is introduced. The principle relies on the obstruction by the wire of a narrow laser sheet 1 mm thick and 5 mm wide produced by a collimated laser source as sketched in figure 2. An opto-electronic detector behind the wire provides an output signal linearly proportional (with a negative slope) to the diameter of the coated wire. Such a probe is characterised by a sampling frequency of 3 kHz and a spatial resolution smaller than 5 μm. The mean coating thickness h_o is calculated from the time-dependent signal $h(t)$, and the wave velocity c_o is determined via cross-correlation of the signals from two identical probes set at a certain known distance s. Knowing the wave velocity, the signal is transformed as a function of space and the FFT leads to the spectrum in terms of wavelength ($\lambda = c_o/f$). For each detected peak, the corresponding wavelength is isolated, its energy content calculated and the signal reconstructed to evaluate the monochromatic wave amplitude A_λ corresponding to that particular wavelength λ.

4. Die without defects: results

In figure 3 the experimental and theoretical mean final thickness h_0 made dimensionless with the wire radius r_0 versus the wire capillary number *Ca* is shown. Tests are performed changing the distance from the liquid bath *L* (57 mm and 131 mm) and the distance *s* between the two probes (40 mm and 116 mm). The measured mean final thickness h_0/r_0 slightly increases with *Ca*, even if the theory predicts a constant value. A possible explanation is that the model is very simple and does not take into account the effect of viscosity and surface tension, which could be actually non negligible. Another explanation relays on the assumption of a die completely filled by the liquid, which is not true at low wire velocities, while for increasing velocities this model assumption is more satisfied. In any case, experiments show a good agreement with the theory. Figure 4 reports the evolution of the ensemble wave velocity expressed in terms of wave capillary number Ca_w versus the wire capillary number *Ca* for experiments and theory by Lin and Liu [5]. The scale starts from zero in order to see the slope of the curve. The surprisingly conclusion is that the measured and predicted values are in an extremely good agreement. This is probably due to the fact that the mean final thickness is very small implying the wave velocity to be not so different from the wire velocity. The two last Capillary number results are in dashed line because the presence of waves is not completely certain being very difficult to understand it from the spectra. This does not represent a problem, because when no waves are observed, the velocity measured is simply the velocity of the liquid film at the interface (which is very close to the wire velocity). In figure 5 the

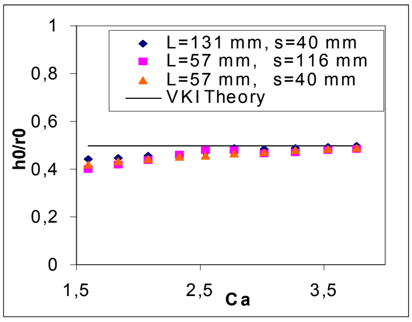

Figure 3: mean final thickness h_0/r_0

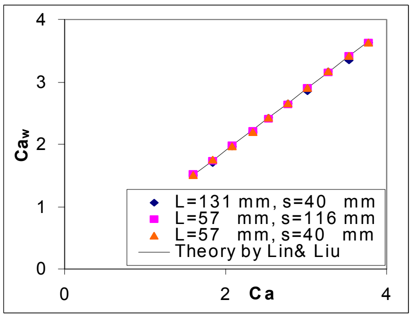

Figure 4: wave capillary number

relative wavelength λ/l_c (normalised by the capillary length l_c) is plotted versus the *Ca*, for different distances from the die *L* and for different

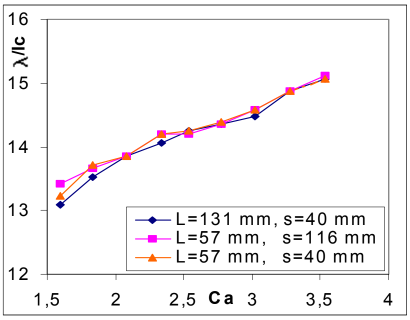

Figure 5: wavelength λ/l_c

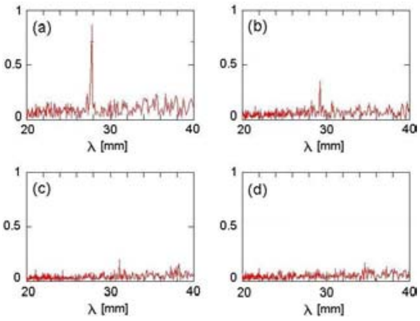

Figure 6: wave disappearance

distances between the probes *s*. Only one wavelength is detected and the relative amplitude increases for increasing *Ca*. For $Ca>3.54$ the peaks detectable from the power spectra become more and more smaller, showing a "wave disappearance" phenomenon. This is clearly presented in figure 6: at Ca=1.59, figure 6-a, a very sharp and clear peak is localised at $\lambda=27.8$ mm; increasing the wire velocity up to Ca=2.54, figure 6-b, 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, figure 6-c, the wavelength $\lambda=31.1$ mm has a very small peak, which can still be distinguished from the noise, while in the last test, at Ca=3.77, figure 6-d, only noise is found. It seems therefore that the phenomenon is dominated by a progressive damping when the wire velocity increases. In figure 7 the wave amplitude *A* divided by the mean final thickness is reported. The first remark is that not appreciable difference is found in the amplitude varying the distance from the die *L*: this probably means that the coating is very close to the neutral stability since no amplification neither damping is observed. An interesting feature is that the amplitude, at both distances *L*, decreases when the velocity is increased, but for *Ca* greater than 2.5 a slight increasing can be appreciated (above $Ca=2.5$, however, it is difficult to distinguish peaks from the noise in the spectra). What is reported in figure 7 is quite comfortable since it shows that when the velocity is increased the relative amplitude of the wave tends to decrease: a remarking result from the industrial point of view. In order to check if the wave is amplified or damped, the experimental amplification factor is computed $c_i=\ln(A_1/A_2)c_0/s$ and compared with the theoretical value predicted by Lin & Liu theory [5]. From figure 8 it is clear that the one from experiments is very small (it comes from the logarithm of a ratio very close to unity - A_1 and A_2 are almost the same) and around zero. Low values of *Ca* show a slight damping, while a weak amplification characterises high *Ca*. In any case these values are almost zero and a positive or negative sign probably has a small impact because even a slight amplification can be damped by the dissipation naturally present in the system. The predicted theoretical values are always positive in contrast with experimental results. However, the theory is linear and the physical system dissipative so that unpredictable non-linear phenomena or a small dissipation could provoke the flow stabilisation.

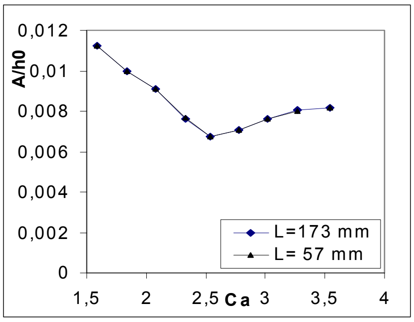

Figure 7: amplitude A/h_0

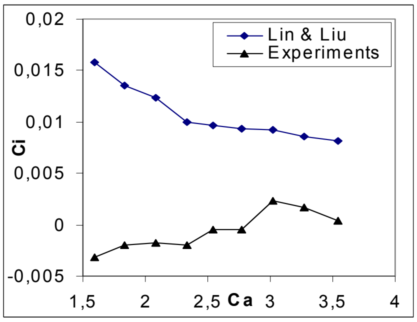

Figure 8: amplification factor

5. Die with defects: results

Tests regarding die with defects are performed with the main die-axis in the horizontal direction. The sketch of the die is reported in figure 9 and the changeable part, the one with defects, is shown in figure 10. Defects are produced using two parts shifted one with respect to the other along the axis of the die or in the plane normal to the axis so that they do not match exactly. Another possibility is to use a internal hole elongated in one direction, as the one reported in figure 10, so that h_0 is expected to be higher in one direction

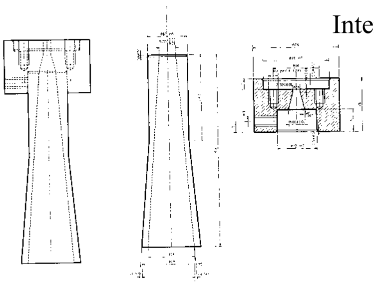

Figure 9: complete device

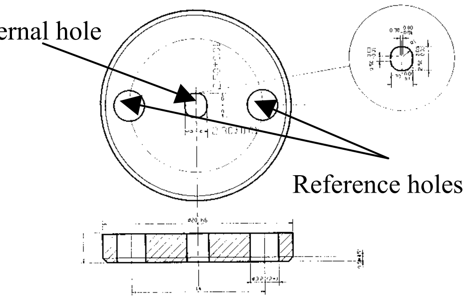

Figure 10: changeable part

and asymmetric effects should rise. No waves are detected but the case presented in figure 10, with the reference holes horizontally aligned. In this configuration h_0=0.163 mm and λ=33 mm. On the contrary, with the reference holes vertically aligned, no waves are found. The reason is probably in a gravity effect: the thickness is greater than in all the other cases and this destabilises the flow. From the other tests performed, the main conclusion is that if the geometrical defect is small compared to the final coating thickness, no waves on the free surface can be observed.

6. Conclusions

Experiments for the study of die coating instability are performed. The measured wave velocity perfectly fits the theoretical curve from Lin & Liu [5]. Only one wave is found and the wavelength increases as the Capillary number rises. For high wire velocity, a progressive wave disappearance is observed: the peak in the power spectrum decreases, without the possibility to be distinguished from the noise. The relative wave amplitude is almost constant with the Capillary number and with space, indicating a neutrally stable flow. The measured amplification factor confirms this observation: it is very small and close to zero, so that even a weak dissipation can make the flow stable anyway. Tests using die with defects reveal that no waves are found if the latter are small compared to the final coating thickness.

7. References

1. Buchlin, J.-M. and Zuccher, S. Liquid film instability of wire coating, in *Advances in Coating and Drying of Thin Films*, Proceedings of 3rd European Coating Symposium, University of Erlangen-Nürnberg (1999)
2. Tallmadge, J.A. and Gutfinger, C. Entrainment of liquid films-drainage, withdrawal and removal, *Industrial & Engineering Chemistry*, **59**, 19-34 (1967)
3. Parellada, C.; Anthoine, J. and Buchlin. J-M. Theoretical and experimental investigation of annular jet wiping, *Fluid Mechanics of Coating Processes-ECS-97 Proceeding,* Editor Bourgin. P, 204-211, Strasbourg (1997)
4. Buchlin, J-M,; Arnalsteen, M. and Teuwissen, G. " Modelling of wire die coating" *Advances in Coating and Drying of Thin liquid Films*, Proceedings of 3rd European Coating Symposium, University of Erlangen-Nürnberg (1999)
5. Lin S. P. and Liu W. C., *Instability of Film Coating of Wires and Tubes*, AIChE J., **21**, No. 4, 775-782 (1975)