ADVANCES IN THE STUDY OF DYNAMIC WETTING IN COATING FLOWS
Experiments with air and other gases under reduced pressures

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Introduction

Dynamic wetting or the process by which a gas on a solid surface is displaced by a liquid is central to coating flows and is most easily reproduced in the simple dip coating experiment in which we observe that, as the substrate speed is increased, the dynamic contact angle θ_D increases steadily until, at a critical speed, it approaches a maximum value of 180° at which point the displaced air is entrained between the solid and the displacing liquid and *dynamic wetting failure* can be said to occur. This wetting failure manifests itself by the sudden breaking of the dynamic wetting line into a saw tooth pattern with air being entrained at the trailing vertices. Understanding this phenomenon has preoccupied many scientists, including Scriven. The subject is still buoyant and a complete theory is yet to be accepted universally. Providing key data becomes thus crucial and this is precisely the objective of this paper.

Unlike other researchers, Scriven considered events which occurred before dynamic wetting failure was reached. In his words "the issue is not *whether* air entrains, but how much!"[1]. Central to this proposition is the role of the air which is carried as a thin film towards the liquid. According to Scriven, as the web speed is increased, this air film grows thick and thicker until it destabilizes and breaks down, causing the air entrainment. And that has been the inspiration for our work. Therefore, rather than manipulating the properties of the liquid, which has been the subject of numerous studies, all leading to similar observations that the viscosity of the fluid plays a critical part [2], we have concentrated on <u>manipulating the properties of the air</u>. For the same reasons and following Scriven's argument that air carried along rough webs can escape easier in the "valleys" between the "mountains" [3], we also

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[1] Unpublished. ISCST shall not be responsible for statements or opinions contained in papers or printed in its publications.

manipulated the substrate roughness to tease out indirectly the role of air in its entrainment. This paper presents this work [4-5] and new experiments we performed with gases at various pressures using an improved technique for imaging and recording dynamic wetting. The conclusions we draw confirm Scriven's incisive predictions.

Experimental Method

A dip coater has been installed within a vacuum chamber and comprises unwind and rewind modules for transporting polyester (smooth) or paper (rough) tapes down through the free surface of silicone oil held within a Perspex tank. The chamber is initially evacuated for about 1 hour to allow the fluid to be thoroughly degassed. Air, carbon dioxide or helium is then drawn back in and the pressure controlled for any given experiment. The web is illuminated along one edge by a sheet of white light at grazing incidence formed by masking down a beam from a 150 W reflector lamp using a slit (see Figures 1 & 2). An opaque 50 mm wide white tape was selected for this work to ensure that observations on the onset of entrainment and the associated "vvv" shaped gas pockets were confined to one surface of the tape. As the tape plunges through the free surface, it initially remains detached from the fluid because of the intervening gas, thereby decoupling light from being scattered into the receiving optics from the white tape surface. The resultant "vvv" thus appear dark against a white background (see Figure 3) and enable the inclination angles of the advancing dynamic contact line at the sides of the "vvv" to be determined. Figure 1 shows the set up for recording large "vvv" using a Macro-Switar 1:1.4 50mm focal length lens coupled to camera 1. In the set up of Figure 2, the field of view is reduced from 50 mm to 3.2 mm by replacing the lens with an INFINITY zoom lens. In this case, the optics were focused to image effects very close to one edge. Dynamic contact angles were determined by imaging the meniscus INFINITY zoom lens aligned with the plane of the tape and coupled to camera 2 - Figure 1. A general view of the onset of entrainment was recorded in both set-ups using camera 3. The

Fig.1

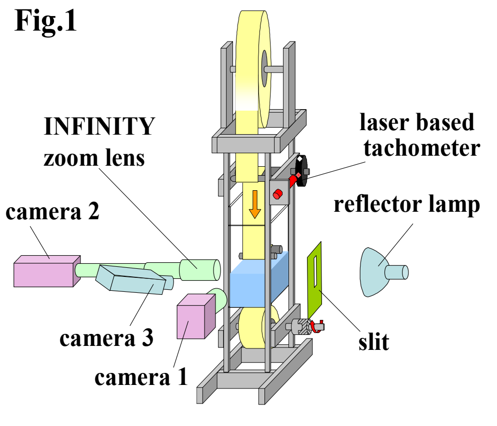
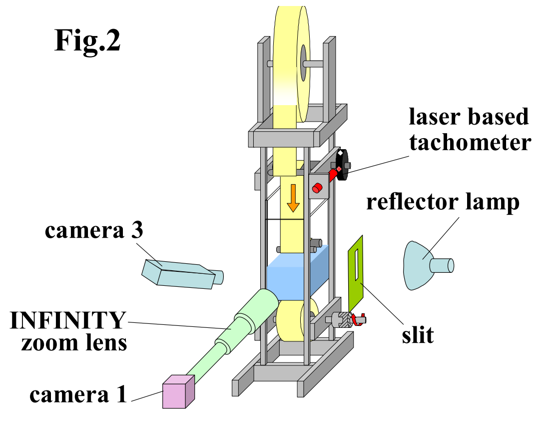


Fig.2



images from all cameras were combined onto a single frame using a multiplexer and recorded as a video sequence as speed was ramped up at a constant acceleration of 14 cm/s^2 to a maximum of typically 80 cm/s and then back down again at 8 cm/s^2. OPTIMAS software was used for determining the "vvv" height and inclination angles.

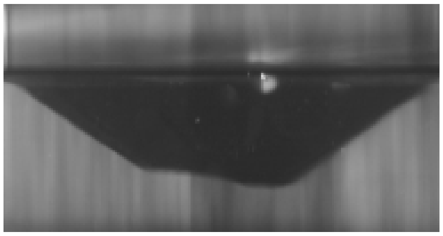


Figure 3: Image of a "V"

Results and Discussion

It is relatively easy to measure the speed of the onset of entrainment for pressures close to atmospheric as the associated bubbles are large enough to be seen on the images. The corresponding "vvv" are such that it is possible to determine the inclination angles reasonably precisely as found by Blake et al. (1979) [6]. Figure 4 shows good agreement with their results using glycerine of viscosity 85.3 mPa.s and a polyester web having similar surface properties to that used in our work. As pressure is reduced, however, released bubbles become increasingly small and associated "vvv" similarly reduce in size and the assessment of the inclination angle becomes increasingly more difficult. It was moreover observed that as pressure reduced, the onset of bubbles either coincided with or followed shortly after the meniscus broke to form a stream of bubbles down either edge of the web. It was therefore considered expedient to note the point of "edge break" as indicative of general entrainment – for when it was no longer possible to see very small bubbles against the white background presented by the tape. It was also noted that inclination angles at "vvv" near one edge as visualised in set-up (Figure 2) matched those found generally elsewhere under the same conditions and hence it was considered justified to take these angles where "vvv" well in from the edges were too small to be resolved by the optics. As shown in Figure 5, "vvv" at low pressures increase rapidly in size beyond a critical web speed and undergo hysteresis as the speed decreases again to zero. Figure 6 shows that when this is taken into account, the relationship $\cos \theta = U_{max}/U$ found by Blake & Ruschak (1979) [6] appears to still apply albeit the data are much more scattered due to the difficulties in obtaining measurements under these extreme conditions. As pressure is reduced, the entrainment speed increases slowly at first and then more rapidly on approaching a few mbar. The entrainment speed for helium at atmospheric pressure, while roughly equating to that for air and carbon dioxide, is seen from Figure 7 to climb more rapidly than for carbon dioxide and air as pressure is reduced. The entrainment speed for carbon dioxide, while remaining close to that for air, is seen to climb less slowly than for air. The viscosity of the three gases and the relative viscosity of air to that of helium and also of air to carbon dioxide as calculated from data obtained by Andrews and Harris (1995)

[7] are presented in Figures 8 & 9 for comparison as leading to a possible explanation for the results – these data being applicable to where the gas is confined between surfaces separated by small gaps of the order of 20µm.

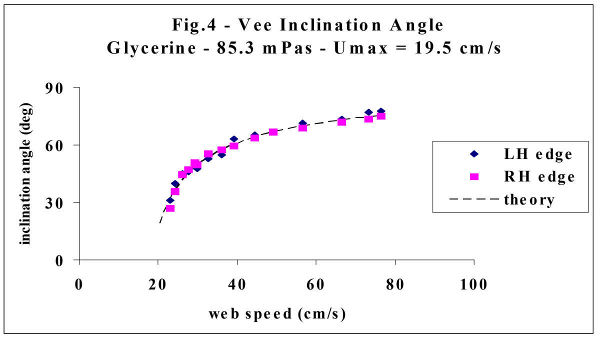


Fig.4 - Vee Inclination Angle
Glycerine - 85.3 mPas - Umax = 19.5 cm/s

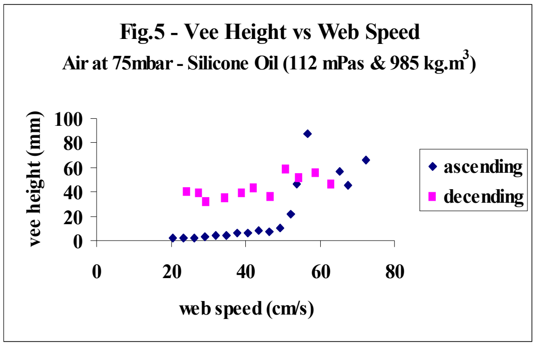


Fig.5 - Vee Height vs Web Speed
Air at 75mbar - Silicone Oil (112 mPas & 985 kg.m^3)

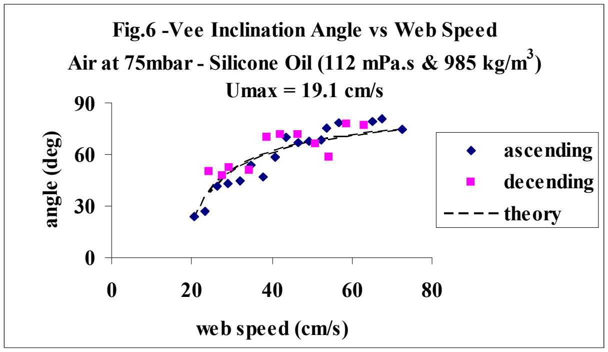


Fig.6 -Vee Inclination Angle vs Web Speed
Air at 75mbar - Silicone Oil (112 mPa.s & 985 kg/m^3)
Umax = 19.1 cm/s

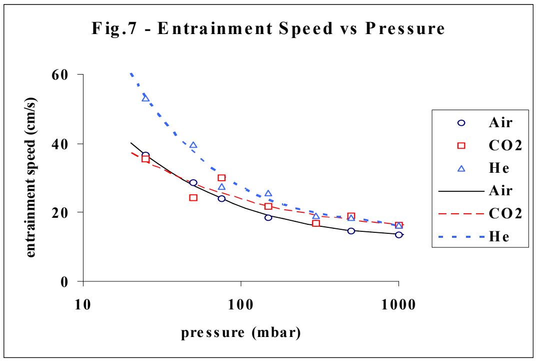


Fig.7 - Entrainment Speed vs Pressure

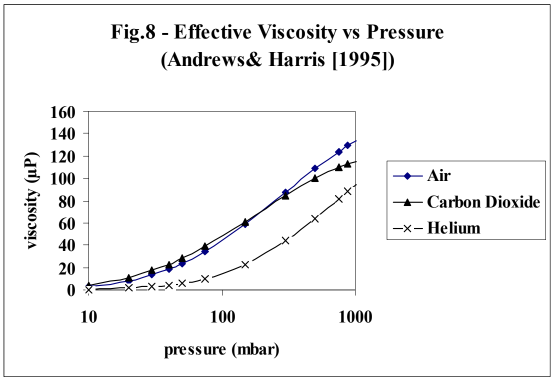


Fig.8 - Effective Viscosity vs Pressure
(Andrews& Harris [1995])

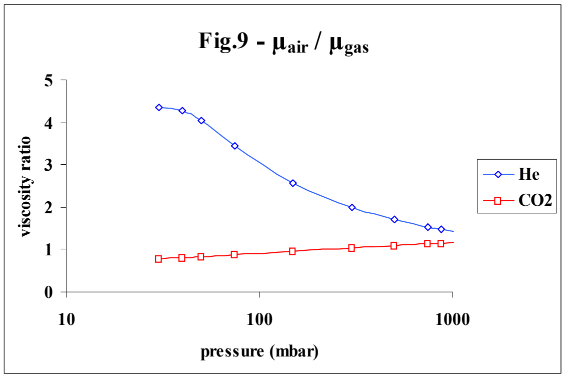


Fig.9 - μ_{air} / μ_{gas}

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