

Using high-speed cinematography to obtain visual evidence on air entrainment in low-speed roll coating

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ABSTRACT *High-speed cinematography can be used to obtain visual information on the sequence of events leading to air entrainment in the application of thin surface films such as coating colors and sizing. This visualization technique exploits differences in the refractive index at phase boundaries and relies on proper lighting arrangements. The limitations of high-speed cinematography are determined by illumination requirements, which increase greatly with the speed at which the coating is applied. At least two mechanisms of air entrainment were discerned at coating speeds just above the critical velocity. Our experimental observations support Scriven's proposed mechanism hypothesizing the collapse of the air film.*

KEYWORDS

Air entrainment
Analysis
Cameras
Coating
Fluid dynamics
Photography

In coating and sizing processes, liquid displaces air at a common interfacial line known as the "wetting" or "dynamic contact" line. Beyond a critical wetting speed, this contact line destabilizes, and air becomes entrained in the coating. If air is entrained in the coating as it is applied, the finished surface of the paper will be defective. Air entrainment is particularly important in manufacturing because it leads to undesirable processing effects such as "skipping" and impairs the overall efficiency of the operation (1-4).

Obtaining visual evidence is one of the most satisfactory ways of resolving doubts and gaining both qualitative and quantitative information. Most studies on entrainment have focused on measuring the air entrainment speed, however, because it is difficult to obtain visual data on air entrainment in coating processes. A method for observing the target area must first be designed with the proper magnification, illumination, and contrast.

In our efforts to render these fluid flow phenomena into recorded images, we employed high-speed cinematography along with the proper lighting to exploit differences in the refractive index at phase boundaries. Because coating colors are opaque, it is especially difficult to directly observe their entrainment behavior as they are being applied. They do not readily allow for the observation of flow without special techniques such as flash X-ray photography. Consequently, we conducted a more fundamental study with glycerin, a transparent, Newtonian liquid.

Background

Dynamic contact line

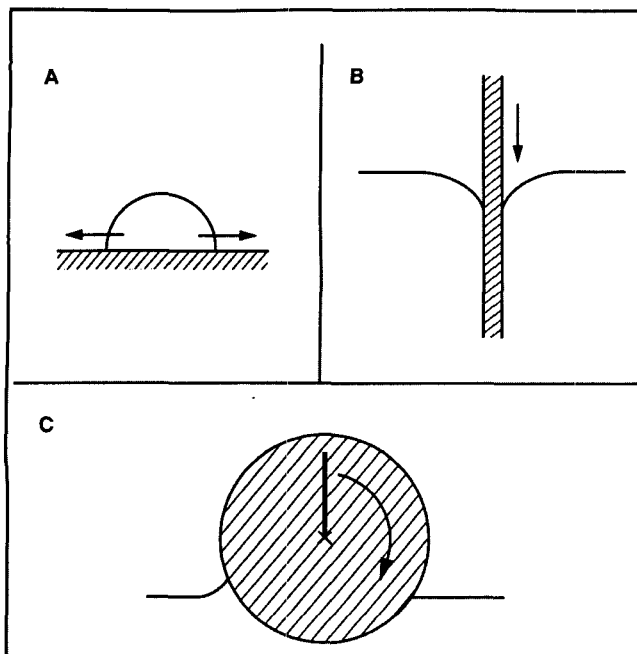
The dynamic contact line is a three-phase intersection, where two or more of the phases are in motion in the Eulerian sense. The dynamic contact line problem is not particular to the paper industry, and some of the configurations are shown in Fig. 1 (5). Figure 1B could be thought of as

paper entering the pond on a horizontal-squeeze roll size press. The configuration we studied is depicted in Fig. 1C and is analogous to the backing roll in a short-dwell coater. The location of the dynamic contact line with a short-dwell head in Fig. 2 reemphasizes the difficulty in conducting flow visualization studies with full-scale equipment. Flow visualization may be defined as the visual determination of fluid flow fields.

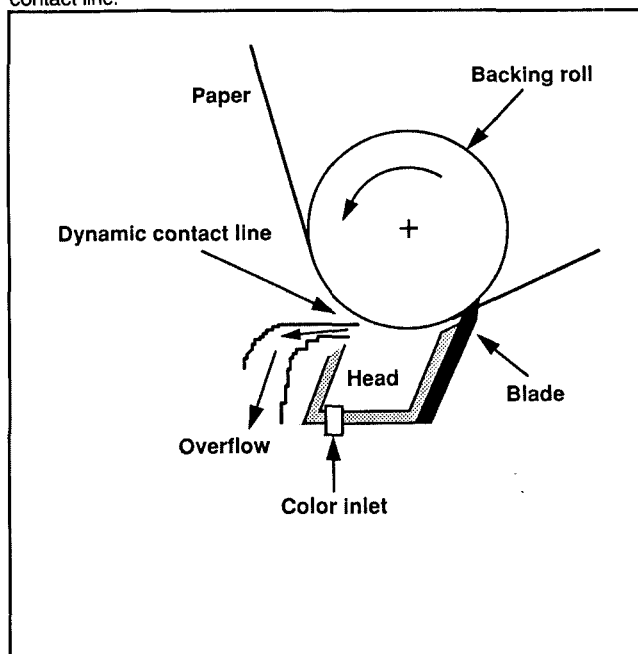
Other researchers (1, 6-16) have noted that the dynamic contact line passes from a straight line into a jagged or "sawtooth" configuration above a critical velocity. This critical velocity is influenced mainly by the viscosity of the fluid phase. It is the instability of the dynamic contact line in the sawtooth configuration that leads to air becoming entrained. The dynamic contact line in the short dwell head is assumed to form the same "sawtooth" configuration, but this phenomenon has not been recorded.

No experimentation to our knowl-

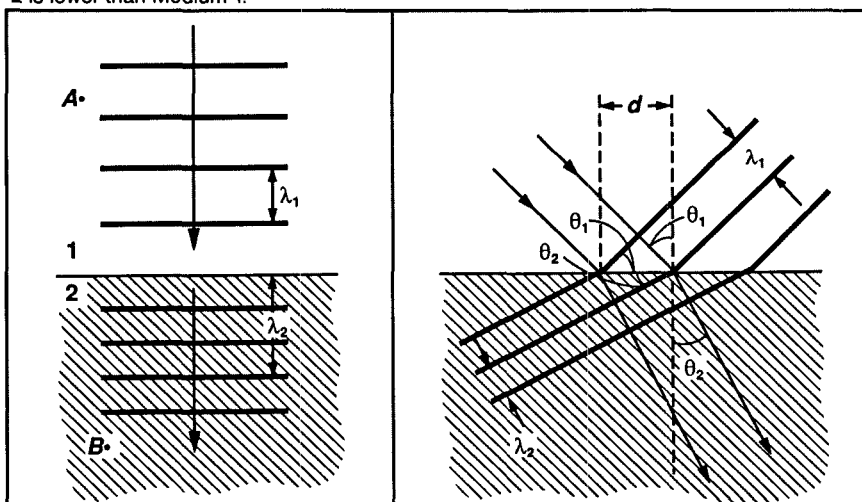
1. A: The spreading of a drop of liquid on a flat surface. B: The submerging of a tape or sheet in a bath of liquid. C: The rotation of a cylinder partially submerged into a bath of liquid.



2. The short dwell coating head with the location of the dynamic contact line at the intersection of paper, color, and air. The size of the coating head has been enlarged to show the details of the dynamic contact line.



3. Refraction, due to light passing through different media. The index of refraction in Medium 2 is lower than Medium 1.



I. Refractive indices

	Absolute index, n
Air*	1.003
Glycerin	
100% by wt.	1.47
88% by wt.	1.45
Plexiglas	1.49

*At standard temperature and pressure.

edge has visually captured the events leading up to and including air entrainment with either clear, Newtonian fluids, or opaque coatings. Quantitative results (1, 6-16) and industrial research coupled with insight as to the mechanism of air entrainment could lead to a breakthrough in designing the next generation of ultra-high-speed coating equipment.

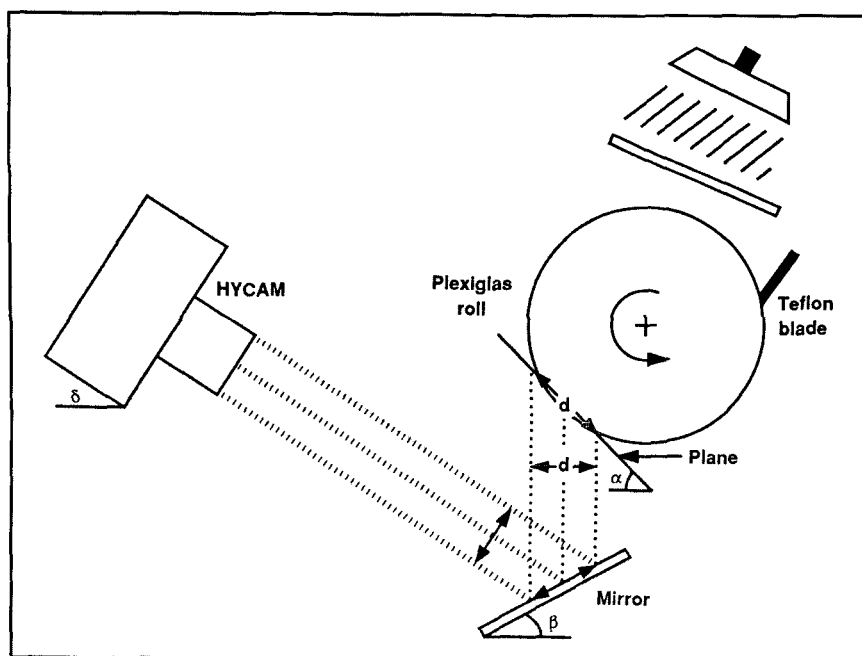
Basic principles of light and refraction

The techniques used in observing air entrainment involve some basic principles of light refraction. Light could be viewed as a wave that obeys the universal principle of wave propagation. To simplify the discussion here, we will approximate the ray theory of light.

The ray theory is applicable when the size of the light beam and the obstacles it interacts with are much

greater than the wavelength of light (17). When a beam of light passes from one medium to another and the speed of light is different in the second medium, the light beam is refracted. That is, the wave fronts are uniquely spaced, with this spacing dependent on the speed of light in the material. Fermat's principle of least time states that when a beam of light passes into a material with a different refractive index, the beam of light will follow the path requiring the shortest traveling time.

4. Experimental setup used for observing flow



These two physical laws are illustrated in Fig. 3. The absolute refractive index, n_a , is defined as the ratio of the speed of light in a vacuum, c , over the speed of light in the medium, v_i , and is given by

$$n_a = \frac{\sin \theta}{\sin \theta_i} = \frac{c}{v_i} \quad (1)$$

where θ and θ_i are the corresponding vacuum and medium ray angle with respect to the normal.

The relative index of refraction, n , is the ratio of the two absolute indices of refraction, n , and n_2 , given by

$$n = \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad (2)$$

A limiting case in which $\theta_2 = 90^\circ$ and thus $\sin \theta_2 = 1$ represents what is known as "total internal reflectance" and can be employed to form image outlines at the transition between materials. Total internal reflection can occur when a beam of light travels from a high refractive index to a lower index, which is the same as saying that the velocity in the second material is greater than in the first. The angle of incidence at which this occurs is the critical angle of incidence, θ_c .

For any angle $\theta > \theta_c$, total internal reflection develops.

This critical angle, θ_c , can be calculated by

$$\sin \theta_c = \frac{n_2}{n_1} \quad (3)$$

where $n_1 > n_2$. Alternatively, the critical angle can be determined through trial and error by slowly changing the angle of incidence until a darker area of total reflection results. The principle of total internal reflectance can be exploited in multiphase systems at phase boundaries, provided that the light beam travels from a high refractive index phase to a low one. A simple adjustment of lighting will give optimum contrast at phase boundaries.

The refractive indexes for glycerin, Plexiglas (methyl methacrylate), and air are given in Table I.

Background on high-speed cinematography

In our studies, we have used a HYCAM®, which is a high-speed 16-mm camera designed for the acquisition of photographic data pertaining to high-speed or short-lived events. It uses the rotary prism and continuous film flow principles of operation. It is capable of filming at up to 11,000 frames per second (fps) with a full-frame optical

head and up to 44,000 fps with a quarter-frame head.

The HYCAM is limited by its geometric aperture of $f/3.2$. A built-in crystal generator known as the timing light generator driven at selectable frequencies of 100, 1000, and 5000 Hz marks the in-board film edge. The timing light generator signal has an accuracy of 0.01% and thus provides high precision in determining elapsed time between events.

Standard video and high-shutter-speed video (both 30 fps) were used unsuccessfully because of insufficient resolution and speed. With these, however, the ability to review experimental data immediately is a definite advantage.

The definition usually adopted for high-speed photography is pictures taken at an exposure time of less than 1000 microseconds, or at a repetition rate greater than 250 pictures per second (18). The cost-to-benefit ratio and long-term usage requirements between electronic and mechanical high-speed systems must be considered judiciously before committing to any one system. An excellent review article by Sweatt *et al.* (19) compares state-of-the-art mechanical and electronic systems.

A high level of illumination is required with high-speed photography, and foot-candle requirements increase rapidly as filming speeds increase. The tungsten-halogen lamp is one of the most common incandescent lamps for diffuse lighting in photography. The input energy is converted to visible light with a color temperature of 3600 K; however, 80% of the input energy is transformed into heat (infrared) at the lamp (20). If concentrated light is required for a small area, the tungsten-halogen lamp may melt or damage the experiment if it is not protected.

Procedure

As mentioned, proper magnification, illumination, and contrast are required to obtain good results. We decided that the best setup would include using a mirror and a Kiron $f/4.5$, 70-210-mm zoom lens, which allowed for filming approximately 6 ft away from the subject.

Distances were marked on the applicator roll's surface to determine

the experimental apparatus behind a white linen diffuser shade. The diffuser shade helped to eliminate glare. Figure 4 presents the details of the experimental setup.

Sufficient light was available for filming at 240 fps and an aperture of $f/4.5$ when using Eastman Kodak 4-X Reversal 16-mm film (400 ASA, B&W, 7277). Color film is also available but has a slightly lower resolution. On viewing developed films, we felt that the framing rate provided good detail between events, although higher velocities on the applicator roll would require faster framing rates and more light. The maximum lean roll speed is 26.7 m/min.

Refraction provided excellent contrast between phases. Total internal refraction occurred at the Plexiglas-air interface within an air pocket of the "sawtooth" configuration. Whenever air entrainment was occurring, a dark area appeared in the positive final print with the reversal process.

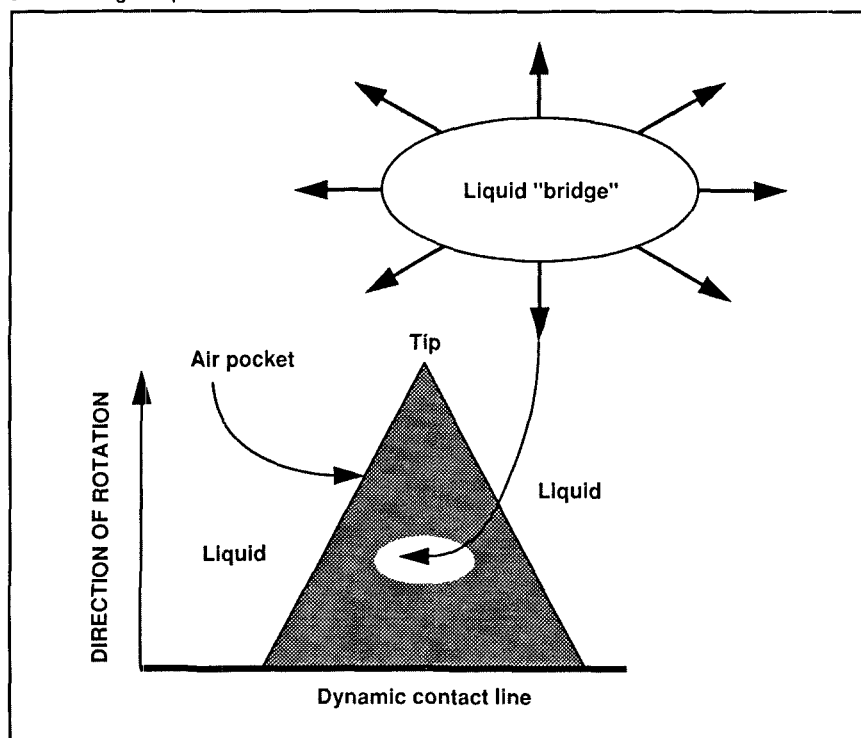
The transfer to video was made on a Rank Cintel machine via digital tape to super VHS. The video is a negative of the positive 16-mm film. A significant advantage of this dubbing process is that a frame-by-frame time code can be electronically "etched" onto the video image, allowing for accurate identification of a particular segment of the film. The video signal is sent to an image analyzer that quickly measures the dimension on a single frame.

Observations

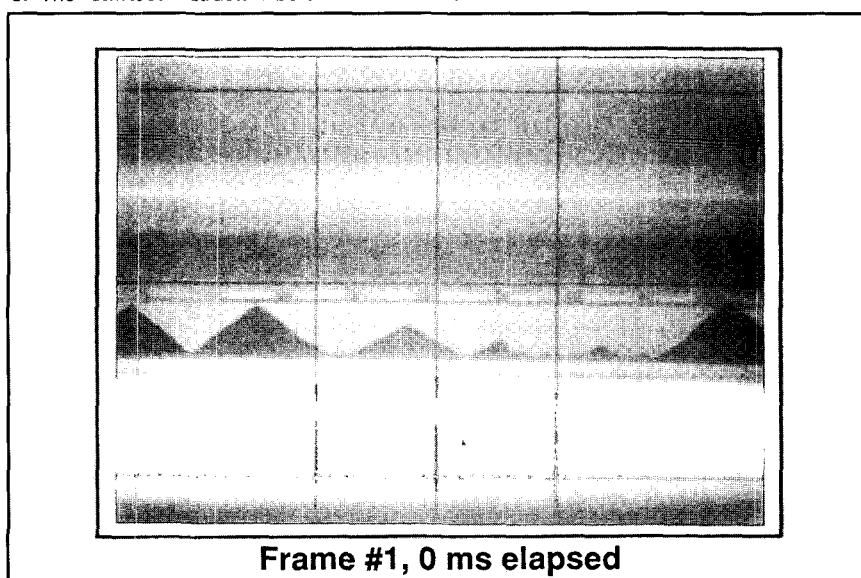
The photos in the series presented here are not as clear as the films under direct observation or the video shown in slow motion. These photos are 35-mm positive reproductions of the 16-mm frames presented in time sequence, showing the collapse of an air pocket toward the left side of each frame.

The distance markers on the roll surface are 1 cm apart, and the cross-hair dimensions can be derived from these. Through successively viewing and reviewing the videotapes, we were able to discern some possible mechanisms through which air entrainment was occurring. The fast frame rate, on the fringe of high-speed photography, coupled with the proper light arrangement, gave excellent contrast and detail.

5. The mechanism of radial outward growth of a liquid bridge in the air pocket. The arrows on the "bridge" represent the direction of advance.



6. The "sawtooth" structure before air entrainment



Discussion

Equipment limitations

Our objective was to gain insight into air entrainment in coating systems, using a fairly simple configuration. The high-speed camera and lighting arrangements can be used only in systems that allow light to penetrate.

Let us suppose that a short-dwell-time applicator was available that

would allow us to see through the coating head at industrial speeds. Let us also assume that the air entrainment rate is proportional to the linear coating speed and that lighting requirements are directly proportional for the same exposure. This is only an approximation, and actual requirements may be higher.

If the applicator entrains air at a machine speed of 1500 m/min, which

7. The "bridging" by the liquid at the edges of the air pocket appears at the left side as these photos are viewed in sequence.

8. In Frames 53-55, the air pocket is isolated and can only be entrained as a bubble, as shown in Frames 56, 58, and 81.

9. Frames 141, 201, and 241 show the re-emergence of the sawtooth structure that eventually will entrain air again.

sawtooth dimensions and to calculate the accurate linear roll speed from the timing light generator marks on the film. Four 1000-W tungsten-halogen lamps were positioned directly over is about 60 times faster than our highest experimental speed (26.7 m/min), we would require about 240 kW of illumination to film at 14,400 fps with direct illumination. High-speed strobes and pulsed laser sources would be needed, as opposed to sources of direct illumination, to prevent the equipment from being melted.

Mechanisms of air entrainment

Over 24,000 frames of film were taken and viewed to determine if some sort of mechanism or series of events caused the air pocket to break up and entrain air with the simple apparatus used. We observed two distinct and separate mechanisms to varying degrees in the collected films.

The first mechanism (not shown in photos) begins with the air pocket growing to a critical size and a liquid "bridge" penetrating the air pocket in the main body of the air pocket, as shown in Fig. 5. The main body is defined as being on or near the geometric center of the triangular-shaped air pocket. The bridge then grows radially outward, displacing air until it meets the air-liquid boundary at the edge of the triangular air pocket. This action produces a trapped gas area at the former tip of the triangular air pocket, which coalesces into a bubble and is carried by the bulk flow of the fluid as gaseous air.

The second mechanism starts at the base edges of the air pocket as liquid "bridges," growing radially inward toward the center of the air pocket. Once the advancing liquid fronts meet, the air pocket above is effectively isolated and thus can only enter into the liquid. This mechanism is illustrated in Figs. 6-9 taken from the 16-mm film.

Only certain quadrants of the pictures are meant to illustrate a specific case of initiation, propagation, entrainment, and reemergence of a particular flow structure. If the photo is divided vertically by the cross hairs on the picture, the middle two quadrants from line to line are each 16.3 mm wide. This gives an idea of the structure dimensions.

Frame 1 in Fig. 6 is meant to

illustrate the "sawtooth" structure before air entrainment. In Fig. 7, on the left side of each photo in Frames 43-51 is shown the "bridging" by the liquid at the edges of the air pocket. Total internal reflection ceases where the glycerin has "bridged" through the air pocket because it has a unique critical angle of refraction. In Fig. 8, Frames 53-55, the air pocket at the tip is isolated and can only be entrained as a bubble into the liquid, as shown in Frames 56, 58, and 81. In Fig. 9, Frames 141, 201, and 241 show the re-emergence of the sawtooth structure that eventually will entrain air again.

The approximate thickness of this air pocket can be calculated from the bubble diameter. The calculation indicates that the air pocket is about 5-20 μm , which is in agreement with predictions made by Scriven (2).

Conclusions

Mechanical photography proved to be

a good method of conducting this experiment in the laboratory. It allowed us to identify two mechanisms of air entrainment that support Scriven's hypotheses (2). A better understanding of the speed limitations imposed by the occurrence of air entrainment may lead to better designs of thin-film application equipment. □

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