Conducting fluid dynamics experiments with vertically falling soap films

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This article gives a detailed description of an apparatus in which flowing soap films are used to perform two dimensional fluid dynamics experiments. We have previously reported scientific findings made with the apparatus, but never carefully described the technique, or its full potential. A brief introduction is given on the nature of soap films as fluids and then all the details necessary for creating robust flowing films are listed. Typical parameters for the system are: flow speeds from 0.5 to 4 m/s, film thickness between 1 and 10 μm, and typical film sizes are 3 m tall and 10 cm wide although films of 20 m tall and 4 m wide have also been made. A vacuum apparatus is also described in which the air drag on the film can be reduced by a factor of 5–10. Finally, a large number of techniques for measuring flow and thickness are outlined and referenced. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1379956]

I. INTRODUCTION

Soap films are perhaps the closest physical approximation to the concept of a true two dimensional (2D) fluid. They offer the possibility of performing real experiments that are otherwise confined to the realm of theory or simulation. Soap films have already observed long standing predictions such as Kraichnan's inverse energy and forward enstrophy cascades,[1] and there are many other topics which can still be explored. A soap film is perhaps the ultimate stratified fluid and can also be used to study the interaction between fluid layers. The fluid dynamics of free surface flows and the importance of surfaces in rheology can also be addressed in new ways with soap films.

It has been recognized for over a decade that soap films can be used to shed light on these situations (and we are not introducing soap films to the small family of existing quasi-2D experiments). We are, however, introducing a new experimental apparatus which greatly advances the possibilities of soap films in fluid dynamics. Compared to the experiments of the 1980's we have approximately logged a tenfold increase in fluid velocity, a tenfold increase in film lifetime, a tenfold decrease in air friction, and a one hundredfold increase in system size. This article will give a review of what we have learned from working with fast flowing soap films over the past five years.

Although soap films are an appealing candidate system for studying 2D flow phenomena, there are still questions as to whether it is appropriately described as 2D incompressible Navier–Stokes flow. Thickness variations in the film may suggest otherwise,[2] and air drag on the film surface[3] can also affect the governing equations. To help answer these, and other questions in the future, this article describes a large number of techniques for measuring film velocity and thickness, as well as methods for altering the air drag on the moving film surface.

A. What are soap films?

Soap films have intrigued many, including some great historical figures such as Newton and Gibbs, and much has been published about them. Excellent overviews by Isenberg[4] and by Mysels *et al.*[5] are recommended as starting points for further study of the thermodynamic and hydrodynamic stability of soap films. An excellent short introduction to the stability of soap films, and using films for fluid dynamics experiments, was written by Couder *et al.*[6]

The standard view of a soap membrane is a micrometer thick sheet of water covered on either side by surfactant (soap) molecules. Without the surfactant the liquid sheet would be unstable and break up into droplets. Surfactants endow the film with an elasticity, or restoring force, against any local thinning that could lead to rupture. The basic picture of a cross section of a soap film attached to rigid supports has been sketched in Fig. 1. For a soluble surfactant such as soap, molecules can reside both on the surface and inside the interstitial fluid sheet. Dissolved molecules can either be isolated or clustered into micelles, and can replenish the surface when the film is stretched slowly. The interstitial fluid layer can be as thin as 100 Å, which is the thermodynamically stable state. The colorful soap films with which are familiar from childhood are actually metastable and will eventually reach the 100 Å state, which is a colorless Common Black film.

The thinning process can take many minutes and involves squeezing the interstitial fluid from between the two surfactant layers.[5] Our 2D fluid dynamics experiments are generally carried out over much shorter times, and spontaneous film thinning is not a concern. We have never carried out

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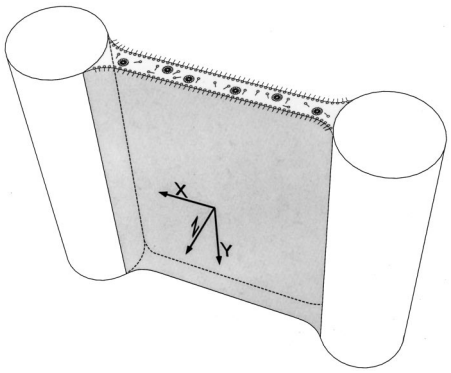

FIG. 1. Cross sectional diagram of a soap film spanning the gap between two vertical wires. The film–air interface is populated with surfactant molecules. Additional soap is in solution, either freely, or in clusters called micelles. The film attaches to the wires with some contact angle in a region called the plateau border. The diagram is not drawn to scale. Approximate actual sizes are: wire diameter ~1 mm, wire spacing ~10 cm, film thickness ~1 μm, surfactant molecule size ~1 nm. The axes are defined as referred to in the rest of this article.

experiments with black films since they break too readily.

The film is assumed to move freely as a composite slab, with soap molecules on either side, coupled to, and moving with the interstitial fluid. The film itself can be considered 2D to the extent that the film is typically 10^4 or 10^5 times wider than it is thick. Any interstitial fluid flowing perpendicular to the film will be greatly overdamped since the Reynolds number is much less than unity at micrometer length scales. The flow is therefore expected to be 2D for all practical purposes. We will also discuss the 3D flow of the air surrounding the film, and its coupling to the film surface.

B. Brief flowing soap film history

Couder was the first to give serious consideration to soap films as an experimental platform for 2D fluid dynamics. In the experiments objects were dragged through a stationary soap film [Fig. 2(a)]. Findings on the stability of vortex streets,[7] and on the coarsening of vortices in 2D turbulence[8] were reported. More general observations made during the experiments are summarized in a third article.[6] A long turnaround time between experiments and the impossibility of steady state measurements are some drawbacks to the method.

Gharib and co-workers[9,10] built a device where the film actually flows down a channel, more like a conventional wind tunnel [Fig. 2(b)]. One draws a soap film from a solution reservoir, along rigid rails, and onto a sheet of rapidly moving pure water. The flow of the water sheet and the surface tension difference between the pure water and the soapy film drives the film forward. This surface tension difference limits the maximum speed of the film to about 30 cm/s[10] at a film thickness of about 6 μm.

Kellay *et al.*[11] developed a method that can attain speeds of several hundred cm/s by letting the film accelerate vertically downward. The design is outlined in Fig. 2(c) and consists of two steel wires attached to the bottom of a soap solution reservoir and held under tension by a weight immersed in a lower reservoir. Soap solution drips between the

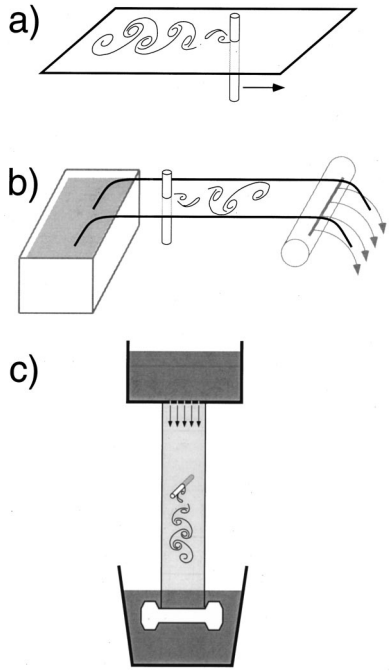

FIG. 2. Three experimental realizations of fluid dynamics experiments using soap films. (a) A stationary film through which obstacles are moved (Refs. 6–8). (b) The horizontal ''soap tunnel'' (Refs. 9 and 10) draws a film from a reservoir, across rigid rails, onto a moving water sheet. (c) An earlier version of the vertically falling soap film discussed in this article.

wires through small holes and perpetually supplies the falling film with new fluid. As in the design of Fig. 2(b), film must be drawn with a squeegee to start the flow. The method produces fast films, but there is little control over the flow rate and film width. Moreover, the solution never spreads well after being injected from the holes, leading to a very nonuniform film. This technique was the starting point for the new methods described in this article.

Two-dimensional fluid dynamics in a Taylor–Couette geometry has also been explored using soap films. The method was developed by Wu *et al.*[12] and proved successful for measuring Batchelor scaling in the turbulent dissipative range. A variation of their apparatus was used to measure the viscosity of a soap membrane.[13]

C. New apparatus

The design currently in use by the authors is outlined in Fig. 3. A typical element of solution will be followed during its downward trajectory. The letters and Roman numerals used in the description refer to those in Fig. 3. The fluid element starts in the upper supply reservoir (a) where it is driven downward into the feed tube (b) by a pressure head ΔP. A fluid metering valve (c) sets the flow rate from the feed tube into the nozzle (d). Two monofilament nylon guide wires (e) splay from the nozzle. Thinner nylon pull lines (f) are attached to the guide wires and hold them apart. As the fluid element is ejected from the nozzle, it stretches between the guide wires as it is accelerated by gravity in the expansion section (I) of the channel. The element rapidly gains area due to vertical (y) and horizontal (x) stretching. In the test section (II) the guide wires are parallel and the fluid

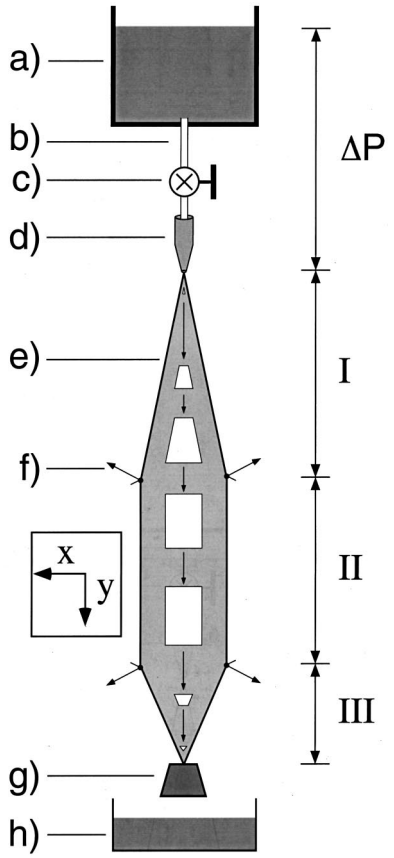

FIG. 3. Diagram of a vertically flowing film showing the evolution of a constant volume of soap solution. The terminology used is as follows: (a) upper supply reservoir, (b) feed tube, (c) metering valve, (d) injection nozzle, (e) guide wires, (f) pull lines, (g) tensioning weight, and (h) collection reservoir. Regions of the flow channel are: (ΔP) the pressure head, (I) expansion section, (II) test section, and (III) contraction section.

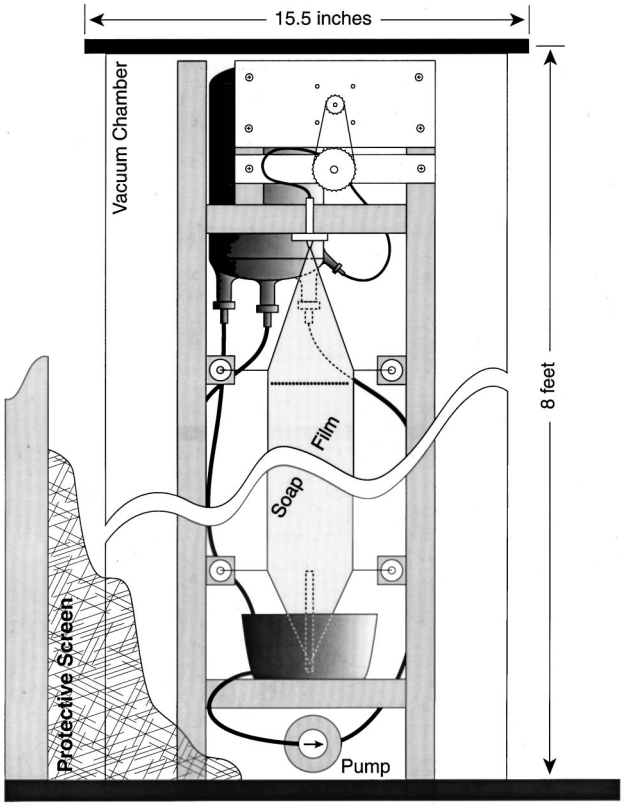

FIG. 4. Side view of soap film tower. Illustration is generally to scale, however, the angle at which the film spreads has been greatly exaggerated to conserve space. The entire apparatus is surrounded by 1/2 in. steel mesh in case of chamber rupture.

element has reached a near constant ''terminal velocity'' due to the balance between gravitational and air drag forces. During this time the soap film is between 2 and 6 μm thick and travels between 0.5 and 4 m/s, depending on the fluid injection rate. At the bottom of the channel the element encounters the contraction section (III) where the film thickens and slows in a process nearly the reverse of the expansion section (I). The film finally drips from the guide wire tensioning weight (g) into the bottom collection reservoir (h).

If the film breaks, one simply releases the tension on pull lines, allowing the weight to pull the guide wires together until they are touching. Once sufficient soap solution has dripped from the nozzle to wet the entire length of the guide wires, tension is reapplied to the pull lines, and a new film appears between them.

The general laminar and turbulent flow characteristics of vertically flowing soap films have already been described in a number of accounts.[14–18,2,19–21]

II. BUILDING A VERTICALLY FLOWING FILM

A variety of ways to build long lasting vertically flowing films are outlined in this section. All the designs are variations of the diagram in Fig. 3 and will be decomposed into four stages: (1) the fluid injection scheme, (2) the expansion of the channel, (3) the measurement test section, and (4) the deceleration or contraction section.

The apparatus usually stands about 2 m tall. In the simplest case the upper fluid reservoir is hung from a hook in the ceiling, the injection nozzle attached to it, and the pull lines operated by hand. It can however, be useful to erect a frame to hold each of the components. Options for frame materials abound, but we prefer a system of extruded aluminum tubes manufactured by 80/20 Inc. (www.8020.net).

Such a system is shown in Fig. 4. Reservoirs are located at both the top and bottom of the frame, and the solution recirculated between them using a magnetically coupled pump (Cole Parmer Inc.). Recirculation saves potentially costly particles introduced into the solution for flow tracking, allows for runs of extended length with an essentially unlimited supply of solution, and can maintain a constant pressure head to eliminate changes in the mean velocity caused by a reduction in the amount of solution in the upper reservoir. To avoid contaminating the solution during the recirculation process, all parts of the pump that are wetted are either stainless steel or Teflon. Wires for stretching the film are mounted on the frame sides, and both these and the flow valve, are computer controlled for accuracy and repeatability.

A. Fluid injection

Soap solution can be supplied to the flowing film in a variety of ways. Figure 5(a) is a variation on the method

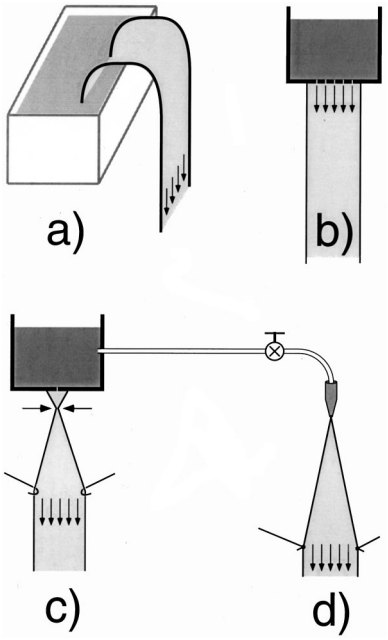

FIG. 5. Various methods of injecting the soap solution. Refer to the text for detailed explanations. In (a) the film is syphoned out of the upper reservoir. The channel terminates abruptly at the bottom of the upper reservoir in (b), and soap solution is fed through a series of holes. The number of holes is reduced to one in (c) and the guide wires are pinched (arrows) to a constriction before expanding again. A nozzle injects fluid directly onto the guide wires in (d). Variations (c) and (d) were most successful in producing long lasting films of uniform thickness.

developed by Gharib and co-workers[9,10] in which the soap membrane is perpetually renewed through a syphoning action. Beizaie and Gharib[10] explain how the film thickness can be controlled by varying the concentration of soap in the solution. However, once the film breaks it is relatively cumbersome to restart since it requires one to draw a new film across the curved guide rails using some sort of squeegee (a plastic ruler will suffice). Kellay *et al.*[11] developed the method depicted in Fig. 5(b), where the film guides are flexible stainless steel wires suspended from the bottom of a container and held under tension by a weight. Soap solution is injected through a series of small holes. The flow rate, and hence the film thickness, can be roughly controlled by varying the hole diameter and the pressure head of fluid in the reservoir. When the film breaks, it must be manually redrawn with a squeegee. The biggest drawback of this method is that the jets of soap solution emanating from the array of holes do not thin appreciably over the fall time of the film. The resulting film has such large thickness variations that one has difficulty seeing through it; it is as if looking through a glass sheet with very wrinkled surfaces.

The method evolved from Fig. 5(b) to 5(c), first by replacing the steel wires with nylon and then nearly pinching off the top of the channel. The injected film is homogenized in the small triangular region above the pinch point and then slowly expanded again below. The guide wires are held together by a pair of thin metal rods [located at the arrows in Fig. 5(c)] and held apart downstream by surgical steel hooks. The resulting film can be so uniform in thickness that it will exhibit no interference fringes across the entire channel

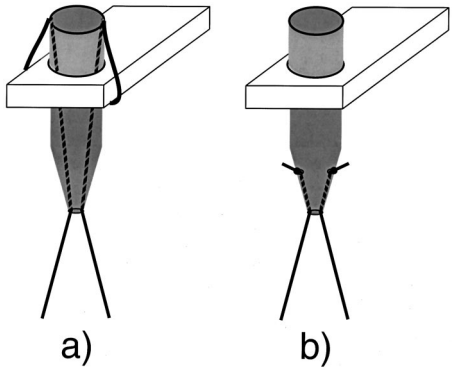

FIG. 6. Two methods of leading the guide wires into the fluid injection nozzle. The nozzle rests in a hole in a horizontal metal plate. Method (a) uses a continuous guide wire and makes for easy guide wire replacement. Method (b) is recommended when a tighter seal between nozzle and feed tube are needed. The guide wires exit the nozzle through small holes and knots prevent them from slipping out.

width. Film rupture rarely propagates across the pinched area, leaving the upper triangle intact. The film is easily regenerated by joining and reseparating the wires below the pinch point, without the use of a squeegee.

The injection scheme currently in use does away with the pinch point and injects the fluid directly from a nozzle onto the guide wires [Figs. 3 and 5(d)]. The disposable plastic tip of a milliliter micropipette[22] is used as the nozzle. The conical tip can be cut to the desired hole size and squeezed with a vise (before cutting) to change the cross sectional shape from circular to approximately elliptical. The guide wires lead into the nozzle as shown in Fig. 6. A soft silicone rubber tube is then pushed into the nozzle top and fluid is metered through the tube by maintaining a constant pressure head across a metering valve. This gives a much improved control over the film thickness. A metal plate supports the nozzle and the guide wire tensioning weight. The suspension method in Fig. 6(a) has the advantages that the guide wire and the nozzle can be easily replaced, since it is not directly attached to the nozzle, and that the nozzle itself does not support the tension on the wires. If a better seal between the fluid supply tube and the nozzle are required, small holes can be drilled into the nozzle to allow the guide wires to exit [Fig. 6(b)].

Though we currently use the nozzle method exclusively, it is not clear that it outperforms the pinched channel of Fig. 5(c). The nozzle method is, however, easiest to implement and guarantees easy film renewal after rupture. The uniformity of film thickness is quite sensitive to nozzle shape but we have not systematically researched this and encourage further experimentation. Acceptable results are obtained with an elliptical cross section of 1 by 2 mm. Small nozzle diameters produce more uniform films at slow flow rates, while larger sizes are recommended for high flow rates. The optimum nozzle diameter also depends on the size of the guide wires.

B. Channel expansion

We have had the greatest success with vertically flowing films which originate from a very narrow channel which ex-

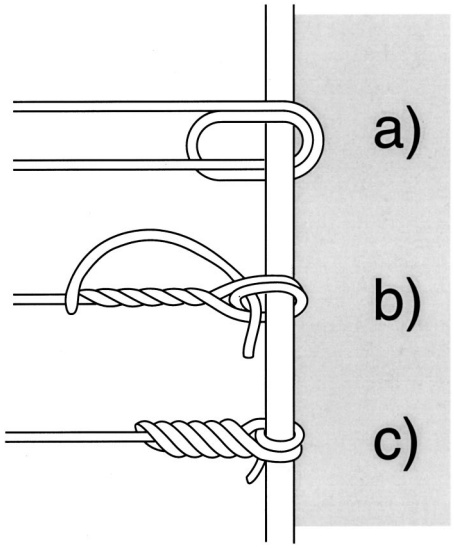

FIG. 7. Three steps for producing an effective knot between the pull lines (horizontal) and the guide wires (vertical). The soap film occupies the gray area. Flow disturbances near the guide wire are minimal if thin pull lines are used.

pands gradually. The channels we use generally expand over one vertical meter from 1 mm wide at the nozzle to a 5–10 cm wide in the test section. The details of optimizing the flow conditions and film uniformity will be discussed in Sec. III. As a general rule one adjusts the length of the expansion section for a given set of parameters such as flow speed, film thickness, and soap solution constituents. A more gradual expansion will lead to more a uniform film thickness. In our case the expansion section is usually limited to 1 m and the total channel length to 3 m due to the the height of the laboratory ceilings.

C. Channel test section

The test section is the area where the guide wires are parallel. It is in this 1 m section that experiments are usually performed. We have chosen to hold the guide wires apart here by either running them over surgical steel hooks, or by attaching thinner nylon pull lines directly to the guide wires. In the case of the hooks one can pull the guide wires across the hooks with one's fingers, given they are prewetted with soap solution. The hooks actually puncture the film [Fig. 5(c)] but do not affect the flow in the channel. Tying thinner nylon pull lines to the guide wires minimizes the time required to regenerate the film and causes the least intrusion to the flow. The pull lines must, however, be guided fairly accurately to ensure a reproducible channel width. We have had much success using bent syringe needles both as hooks and pull line guides. Tying the pull lines to the guide wires is best done with the type of knot outlined in Fig. 7.

No matter how high the tension in the guide wires, the surface tension of the film will bow them slightly inward. For a tensioning weight of several kg the test section will routinely be 1 mm narrower in the vertical midpoint of the channel. For channels wider than 5 cm this is negligible, but for narrower channels the guide wire bowing becomes a large fraction of the total channel width. Further increasing guide wire tension is impractical since it causes difficulty in operating the pull wires. When parallel channel walls are necessary, we use a ''channel within a channel'' method, where a second set of thinner wires is placed in the larger channel as in Fig. 8(c). This setup is very useful for studying laminar channel flows where it is important to have a well defined distance from the inlet of the channel. To study flow behavior near walls[15] we have used a variations of this method by inserting a single vertical wire, or a single vertical sheet into the film [Figs. 8(a) and 8(b)].

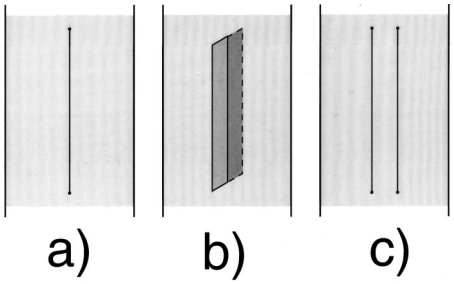

FIG. 8. Various techniques for studying flows near wire (a,c) or sheet boundaries (b). The wires in (a) and (c) are held in place by thin hollow rods perpendicular to the film. (c) Allows the study of flow through very narrow channels with perfectly straight walls.

D. Channel contraction

Various ways of collecting the fluid at the bottom of the channel are outlined in Fig. 9. In the original design the weight was immersed as in Fig. 9(a) (and is still in use in one

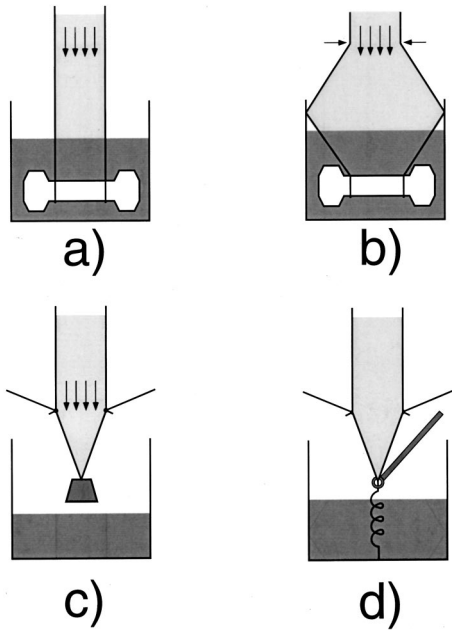

FIG. 9. Four possible ways of terminating the channel. (a) The original design, (b) a variation which slows the film near the bottom, thereby reducing foam production, (c) tying the guide wires to a single point on the tensioning weight makes for easier film renewal and eliminates the need for immersing the weight, and (d) passing the guide wires through a ring at the end of a support rod allows one to attach a spring or elastic band for tensioning. When there is not enough vertical space for a weight, the spring can be pulled in directions other than down.

of the experimental setups). There are some disadvantages however. For instance, the wires must be pinched together manually beneath the fluid surface to regenerate the film. Also, for high flow rates a significant amount of foam can be generated where the film impacts the reservoir fluid surface. Here the film thickens and undergoes accordion like buckling, which can trap air inside bubbles. The buckling can also send waves back through the test section of the film. This buckling can be minimized by a rapid expansion of the film as shown in Fig. 9(b), but is somewhat cumbersome to implement. More recent designs contract the channel at the bottom, either by tying both lines to one point on a tensioning weight [Fig. 9(c)], or by passing the wires through a loop at the end of a rod and applying tension with springs or elastic bands [Fig. 9(d)]. This method allows the guide wires to be moved entirely by the pull lines and cuts the film regeneration time down to seconds. The contraction is best kept gradual, though it can be more abrupt than in the expansion section. In a typical case the channel contracts from a 5 cm wide test section over 20 or 30 cm. More abrupt contractions apply unnecessary tension to the pull lines and can cause violent flows which may rupture the film.

After the contraction section the fluid is collected in a lower reservoir. It can be recirculated to the supply reservoir with a pump. We have used both gear pumps and diaphragm pumps. Prolonged recirculation will lead to a thickening of the mixture as some evaporation occurs from the surface of the film, and can cause a buildup of dust and other contaminants.

E. Other useful equipment

While debugging and fine tuning the apparatus, a monochromatic light source is very helpful to visualize the film thickness by optical interference from the front and back film surfaces. All photographs shown in this article, for instance, were illuminated with a low pressure sodium lamp. Other useful tools are a charge coupled device (CCD) video camera (with shutter control down to 1/10 000 s), a video monitor, and a video cassette recorder, which can be used to visualize and record intricate and rapid flows too small or fast for the unaided eye.

F. Materials considerations

Soap solution is surprisingly corrosive and prolonged exposure will corrode most metals including many stainless steels. To minimize corrosion problems, we recommend the solution come in contact only with anodized aluminum, Teflon, glass, or surgical stainless steel. The fluid metering valve should also be very corrosion resistant. An alternative to a valve is to clamp the fluid feed tube partially shut. This method is effective though not as reproducible. A resilient tubing made of silicone or Viton is recommended.

When using unanodized aluminum for the supporting structure, excessive corrosion can be avoided by attaching numerous Galvanized washers kept in good electrical contact with the aluminum. The washers corrode rapidly, and can be replaced periodically, while the aluminum is left nearly untouched.

If the soap solution is to be recycled, the tensioning weight must not corrode either as it will contaminate the soap solution. The weight can be plastic coated, or can be avoided altogether as shown in Fig. 9(d).

The guide wires and pull lines are best made of monofilament fishing line. Braided Kevlar wire, while offering much less stretch, led to short lived films. The authors are aware of varieties of nylon sheathed kevlar braids which may be ideal but they have not been tested as of yet. Guide wires should be of a heavy gauge, generally 0.5–1 mm thick, and capable of supporting about 15 kg. Thinner guide wires caused problems with film stability, probably because they cannot properly guide the very thick film near the injection nozzle.

Pull lines should be thinner (0.2 mm thick, capable of supporting about 2–3 kg) to minimize the intrusion on the flow. Thinner pull lines are also less rigid and more easily guided away form the pull points.

Even though flowing soap films can last for more than a day, breakage will generally occur more frequently during experimentation. Each rupture will send down a mist of soap solution which will cover an appreciable area (depending on the channel height) at the base of the apparatus. In the middle of the test section the fallout is less severe but one should take care to protect any delicate instruments, such as optical translation stages, by keeping them some distance from the film, or by wrapping them in plastic.

We have had problems in the past where soap films would suddenly have lifetimes of only a few seconds, where they were lasting for hours the previous day. This was usually caused the the replacement of some part of our recirculation system. We have found that the use of certain plastic or rubber types of tubing can, over time, release substances into the solution which causes it to turn turbid, and the film to rupture incessantly. Recently we switched to a system of Pyrex containment vessels, Teflon lined Tygon tubing (Cole Parmer), with a short section of silicone tubing between the reservoir and nozzle. The turbidity and rupture problems have ceased since these changes. We therefore recommend the use of the most inert materials possible.

III. OPERATION

The goals of operation are often to create a long lived film having constant thickness and flowing with a uniform velocity. Once an apparatus, such as in Fig. 3, has been built, the correct soap solution must be prepared, then injected from a nozzle of the correct shape into a properly shaped channel under the right ambient conditions to optimally achieve the operational goals. This section will commence by describing some typical situations and how they relate to the operational parameters.

A. Flow control and channel geometry

Figures 10 and 11 show some typical interference patterns (basically maps of the film thickness) of well behaved

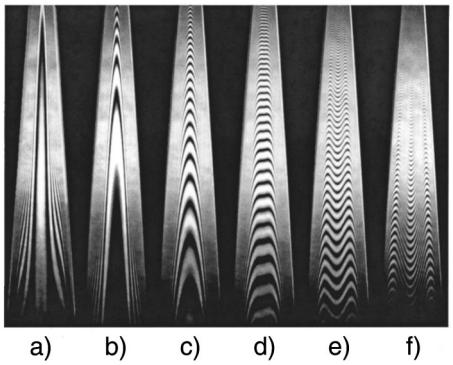

FIG. 10. Steady state photographs of the expansion section. The images progress from (a) a slow flow rate ($h\sim1$ μm and $v\sim1$ m/s), to (f) a high flow rate ($h\sim6$ μm and $v\sim4$ m/s). The interference fringes were made visible with a sodium lamp. Scale: 2 cm channel width at bottom.

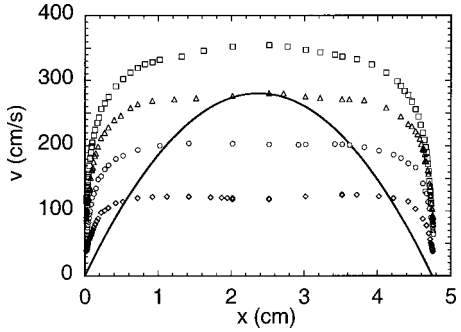

FIG. 12. Profiles of v_y across the channel for different film thicknesses: ($\diamond$=1.5 μm, $\bigcirc$=2.3 μm, $\triangle$=4 μm, $\square$=6 μm). The solid curve is a calculated parabola and serves to emphasize the non-Poiseuille nature of the flow, due to air drag on the film.

flows in the expansion section and test section, respectively. Quite some effort was put into adjusting the nozzle shape and size, as well as the channel symmetry, to achieve these images. Even while collecting images we encountered problems of the fluid wetting the nozzle unevenly leading to asymmetries in film thickness (probably due to small burrs on the nozzle). Usually these asymmetries will even out once the test section is reached.

The flow rate is increasing from left to right in the series of images in Fig. 10. For very low flow rates, the fluid in the film tends to separate symmetrically and cling to the guide wires, leaving a very thin film (<1 μm) in the center of the channel. The sharp tip of this separation will eventually meet with the nozzle tip and lead to a line of thin film in the center of the channel [Fig. 11(a)]. This separation can be avoided by using a smaller nozzle tip diameter, or by reducing the channel expansion angle. Thin films, moving at less than 1 m/s often exhibit violent instabilities in the test section of the channel, as is apparent on the left side of Fig. 11(a). This is due to the spontaneous generation of thin soap film at the point of contact between the film and the guide wire. This so-called marginal regeneration is nearly ubiquitous where soap films attach to surfaces and we refer the reader to other works[5,23] dedicated to this subject. Once the thin patches of film are generated, they float to the top in an unstable fashion. Interestingly, we never observe marginal regeneration in faster flowing films. One explanation is that the high shear rates near the guide wires, often in excess of 1000 s^{-1}, suppress the marginal regeneration instability, which usually has intrinsic time scales of 0.1–1 s.

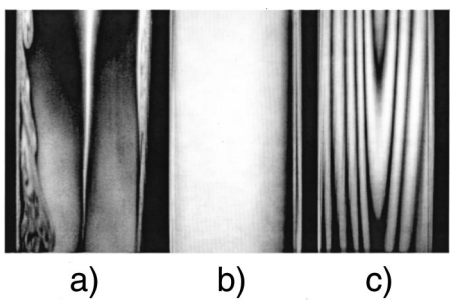

FIG. 11. The interferometric appearance of the test section for (a) thin films ($h<1$ μm), (b) medium films ($h\sim2$ μm), (c) thick films ($h>3$ μm). For (a), (b), and (c) the corresponding expansion sections appear as (a), (d), and (f) in Fig. 10. Scale: 5 cm channel width.

At slightly faster flow rates the separation of fluid near the nozzle lessens and the marginal regeneration is suppressed. The film in the center of the channel will still be thinner than the film near the edges. This thinner film also moves more slowly, as can be seen from the slight dip in $v_y(x)$ of the slowest curve in Fig. 12.

For medium flow rates the separation of Fig. 10(a) disappears. Figure 10(d) is the optimal situation leading to uniform films in the test section, such as in Fig. 11(b) where the film thickness varies by less than one quarter wavelength of light (~0.1 μm) over its entire width. The blunt fringes in the expansion section [Fig. 10(d)] are the hallmark for optimal operation, but are usually only achievable for a rather narrow range of flow rates for a particular channel expansion angle and nozzle design. For our 1 m long expansion section into a 5 cm wide test section, the optimal film thickness ranges between 2 and 5 μm with corresponding films speeds of 2–3 m/s. If such uniform films are essential to an experiment, the channel geometry can easily be adjusted to optimal conditions. The choice of soap solution can also play a large role, as discussed in Sec. III B.

For the highest flow rates a thicker jet of fluid shoots down the center of the channel and the interference fringes in the expansion section show a characteristic dip in the center [Figs. 10(e) and 10(f)]. The fluid jet persists weakly into the test section [Fig. 11(c)] and causes the fluid to move fastest there (Fig. 12, top curve). Four bright fringes are visible between the channel center and side in Fig. 11(c), corresponding to a total change in thickness of 0.8 μm, which translates to a gradual $\sim$15% change in film thickness.

If the channel expansion angle is too large, the center jet of fluid will separate from the channel walls and wander laterally in an unstable fashion. This situation is remedied by lengthening the expansion section.

For higher flow rates the film becomes supersonic and unstable with respect to transverse undulations of the film. As the flow rate is increased, film thickness increases and the transverse wave speed decreases. At the same time, the film moves faster. When the film speed exceeds the wave speed, shock waves appear (see Fig. 13) and the film eventually breaks.

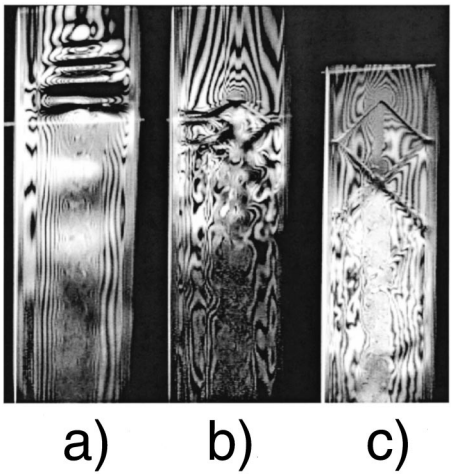

FIG. 13. Supersonic flow past the tip of a needle: (a) slightly subsonic, (b) slightly supersonic, and (c) fully supersonic. The needle tip is located at the same vertical position for each image. It most easily identified at the apex of the shock waves in (c). Shock wave displacements are out of the film plane. Interference fringes translate to film thickness. Scale: 2 cm channel width.

Vertically flowing films in air are thereby limited to thicknesses of about 6 μm traveling at about 4 m/s. One can decouple the relation between film thickness and velocity by tilting the entire flow channel, effectively reducing the force of gravity. The tilting of the channel can also be a very accurate way of controlling flow speed when trying to measure the onset of various instabilities. A series of photographs, by Rutgers *et al.*,[16] outlining the onset of 2D grid generated turbulence were taken using an inclined channel. Ecke and co-workers have made significant use of this technique.[2] And Beizaie and Gharib[10] have experimented with inclined versions of the apparatus in Fig. 2(b). Inclined channels can, however, suffer from bowing in the plane of the film due to gravity. Once broken, thick inclined films are also more difficult to regenerate.

B. Optimal soap solutions

We have obtained the best results with a mixture of 1%–2% liquid dishwashing detergent (Proctor and Gamble's Dawn Brand) and 98%–99% percent distilled water. Plain tap water appears to work equally well. The flowing films in the laboratory can last up to 24 h, and we have made films up to 20 m tall and 4 m wide which last for minutes. Significantly lower soap concentrations lead to more frequent breakage.

The soap solution is above the critical micelle concentration but we have not yet done a systematic study of the effects of solution constituents and concentration on film longevity. Much higher soap concentrations, or the addition of glycerol, make it much more difficult to generate uniform films. Such viscous fluids typically do not spread uniformly in the expansion section of the channel. Most of the fluid immediately separates from the guide wires and shoots down the center in a thick jet no matter how gradual the channel expansion. The thin film on the sides then dries out and causes the film to rupture. This was observed to happen with a solution of 25% glycerol, 2% Dawn, and 73% water. The bulk viscosity of such a mixture is scarcely twice that of water and one would not expect such a large effect on the film flow. Perhaps the addition of glycerol affects the dilatational viscosity (for definition see Edwards *et al.*)[24] of the film more strongly. We plan to study these effects more systematically in the future.

It should be noted that the soap solution will deteriorate with age and prolonged recycling is not recommended. For some experiments we do not recycle the solution at all, since it changes its characteristics due to evaporation, possible oxidation, and contamination with dust.

C. Surrounding conditions

Vertically flowing films, as described in this article, are very robust under almost any conditions. For instance, high humidity is by no means necessary to prolong film lifetimes. Any particular section of film is actually only in existence for about 1 s, from the time of inception at the injection nozzle, to the time of destruction at the bottom of the channel. Evaporation is likely to occur only within the air boundary layer surrounding the film.

Frequent film breakage can be prevented in a number of ways: keeping the solution fresh, cleaning the guide wires and nozzle with alcohol from time to time to remove soap buildup, avoiding improper channel geometries which lead to separation of the main fluid stream from the guide wires and can lead to stagnation areas where the film is not replenished, and staying away from abrupt termination of the channel, which can cause the film to buckle and rupture. The film should also be protected from excessive air currents, especially when performing scientific experiments. Air currents will blow the film out of the plane defined by the guide wires and can cause waves to travel up and down the channel. While a deflection of 1 mm will probably not severely affect the in-plane motion of the film, it does change the distance between the measurement instruments in an erratic way. Hot wire and laser Doppler anemometry can be made difficult by such deflections of the film. Enclosing the experimentation area with curtains is often sufficient. A good way to monitor the film surface is to shine a sheet of light (generated by passing a laser beam through a glass rod) onto the film with a grazing angle of incidence. If the film undulates, the line of light on the ceiling will wiggle correspondingly. We have been successful in suppressing waves entirely by placing two glass plates at 5 mm on either side of the film (see Rutgers *et al.*[15]). Wider films are more prone to deflections since they catch air currents more easily, and a given fixed motion out of the film plane costs comparably less elastic energy. By casual observation we note that evacuation of the air surrounding the film, described in Sec. IV, also appears to suppress film deflections. This remains to be verified using the laser light sheet technique.

D. Insertion of flow obstacles

In order to study 2D flow around objects, they must be inserted through the film. Any object which has been prewetted with soap solution can be thrust through the film if done carefully. Nonetheless, the film may still break quite fre-

quently while inserting the objects. Breaking a film ten times in a row while trying to insert a turbulence generating grid (comb) is time consuming, aggravating, and causes unnecessary corroding soap spray.

The following technique allows even dry objects to be pushed through the film. We observed that this can be done when the film is thicker than 10 or 20 μm. This is usually the case at the end of the channel where the film ''piles up'' before it drains into the collection reservoir. A flat plate can be used to similarly obstruct the flow further upstream in the channel and create a region of thick film at any convenient place. A small drafting triangle ruler works very nicely. It can be prewetted, or inserted at the bottom of the channel, moved up to the point where the comb or rod is to be inserted, and turned across the flow to temporarily create a section of thick film. The dry object can then be inserted and the ruler removed.

IV. VACUUM METHODS

Air plays a primary role in flowing soap films. It largely determines the vertical (y) and horizontal (x) laminar variations of v_y and also dampens out velocity fluctuations, turbulent and otherwise. Air also compromises the two dimensionality of the film since the air boundary layers extend over 1000 times the film thickness into the third (z) dimension. The issue of air drag in turbulent soap films is discussed more thoroughly by Rivera and Wu.[3] For laminar films the air drag can be modeled with a classical laminar boundary layer on either side of the film.[15] The drag force due to this boundary layer depends on the square root of the gas density. Thus, by placing a flowing soap film in a partial vacuum one can reduce the drag force by nearly a factor of 10. The effect on laminar and turbulent flows is dramatic[25] and a vacuum system is often a necessary piece of equipment.

A. Construction and operation

The first vacuum work was done by Rutgers[25] and a larger system is currently in use by Daniel and Rutgers. Both are supported by a flat plate (1 in. thick anodized aluminum in the latter case) with threaded holes for a vacuum pump, as well as electrical feedthroughs for the recirculation pump and stepper motors (which control flow speed and guide wire operation). Since the system will never go below pressures of 10 Torr, National Pipe Threaded holes and fittings attached with Teflon pipe tape are sufficient equipment.

To encase the support structure we used three sections of clear acrylic pipe, 14 in. in diameter and 0.25 in. thick from Dayton Plastics. Square aluminum plates 5/16 in. thick with 13.5 in. diameter holes sit between the sections. L shaped gaskets (Kurt J. Lesker, part number LG14B) form the seal between the pipe sections and the plates. The top of the vessel is sealed with a square plate 1/2 in. thick. Threaded rods can be run so as to connect the plates separating the sections (through the holes shown in Fig. 14). A winch and pulley system can then be used to lift any number of the sections by several feet so that adjustments to the film apparatus can be easily made. Since our pipe sections do not have perfectly smooth ends we found that a small laboratory vacuum pump does not have sufficient capacity to overcome initial leaks between the pipe sections and the gaskets. However, a large throughput Stokes pump (model 212H-11) was able to evacuate fast enough that the seals were sufficiently compressed by atmospheric pressure to effectively close any leaks.

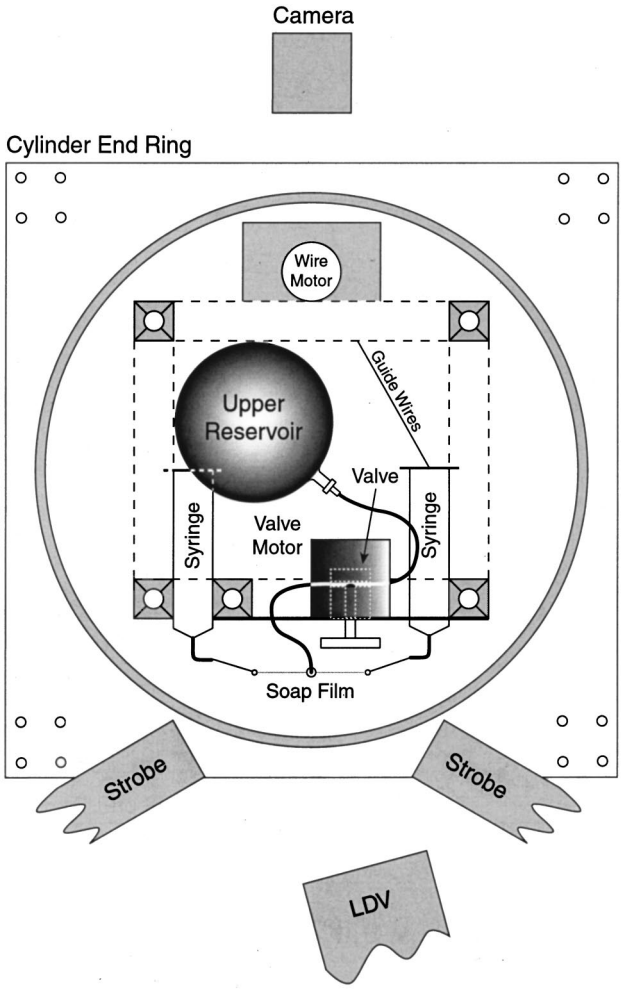

FIG. 14. Top view of soap film tower and vacuum chamber used by Rutgers showing placement of LDV head, as well as strobe and camera positions for doing DPIV.

Yet, the simplest way to build a vacuum vessel for a flowing film was probably designed by Ecke and co-workers.[19] A clear acrylic cylinder with vacuum tight end caps provides the main vacuum vessel, and as well acts as the rigid support structure to hold the guide and pull wires. The whole device can be tipped at any angle to control film speed. Access to the film is however more difficult in such a one piece system.

When either system is being pumped down for the first time, successive pauses should be taken to let dissolved gases, usually visible as small bubbles in the clear plastic pumping lines, escape from the soap solution. The vacuum pump line valve should be closed when the soap reservoirs start to boil violently. This occurs when the lowest pressure, the vapor pressure of the soap solution, is reached. Once evacuated, the system can be used exactly as the ambient

soap channel. Cavitation problems can arise however, because the soap solution remains near its boiling point. The recirculation pump should therefore be operated slowly and placed some distance below the bottom reservoir to operate it at a hydrostatic pressure above the vapor pressure. Cavitation can also occur inside the fluid injection nozzle and lead to the periodic ejection of small bubbles. We have not been able to eliminate this problem completely, but one can minimize it by using a sealed nozzle as shown in Fig. 6(b). Once a bubble is ejected from the nozzle it will leave a small bubble behind which is the nucleus for the next one. The bubble can, however, be flushed out by fully opening the flow control valve after temporarily bringing the system to a higher pressure.

For reasons not yet understood, the soap films last for somewhat shorter times in vacuum than their ambient counterparts. Mean film lifetimes of many minutes, with a renewal time of several seconds, are still quite adequate for performing most measurements.

V. MEASUREMENT TECHNIQUES

Once a flowing film has been established, one generally wants to measure something about its properties. Film velocity and film thickness are the two most important quantities and take up most of the following discussion, though flow visualization will also play a role.

A. Velocity measurements

1. Laser doppler velocimetry

Laser Doppler velocimetry (LDV)[26] has proven to be the most versatile velocity measurement tool for studying flowing soap films. The LDV method measures velocity at the intersection volume (scattering volume) of two tightly focused coherent laser beams. A photodetector measures backscattered light from small particles which pass through the optical interference fringes at the crossing point. The frequency of these bursts is translated directly into a velocity. The scattering volume is typically a prolate ellipsoid with a minor diameter of 100 μm and a length depending on the angle between the crossing beams. In 3D fluid measurements this ellipsoid is best kept as small as possible to reduce the uncertainty in the z position of the velocity measurement. Since a soap film is much thinner than the length of the ellipsoid, the film thickness determines the spatial (z) resolution. Moreover, a long scattering volume is advantageous since it allows for occasional out of plane motion of the film, without loss of data. However in most commercial LDV systems, longer scattering volumes also translate to less efficient scattered light collection optics. We originally used a TSI Inc. system with a 12 mm diameter focusing and collection lens and a 10 cm working distance. The scattering volume was over 1 mm long, and allowed for equally large amplitude waves in the film before any gaps in the data occurred. 1 W of laser power was, however, needed to get data count rates over 1000 Hz. Our newer TSI Inc. system has a scattering volume only 0.3 mm long, but requires a mere 0.1 W of power for data count rates in excess of 10 000 Hz. For film speeds of several meters per second such count rates convert to a 0.3 mm mean spacing between individual velocity measurements. There are, however, more frequent gaps in the data as the film wanders outside the scattering volume.

We initially chose to seed the film with polystyrene spheres (1 μm$\pm$2% in diameter). The sphere diameter is less than the film thickness and the particles have a mass density only 5% higher than the soap solution. The seeding density must be chosen so that on average only one particle occupies the scattering volume at any time. Since the length of the effective scattering volume is defined by the film thickness, seeding densities should be about 100 times higher than those required for equivalent measurements in bulk fluids.

Another option is to seed the flow with TiO_2 particles, the mean size of which is 0.22 μm. Before it is added to the solution, the TiO_2 (approximately 0.03 g per liter of solution) is added to 50 ml of purified water and mixed on a stirring plate to ensure that it is adequately dispersed. Because of their extremely small size, such particles may more accurately follow the turbulent dynamics of the flow at small length scales.[19]

In either case, commercial LDV systems focus the collection optics to accept backscattered light predominantly from the particles passing through the scattering volume. Normally this offers some protection from light scattered and reflected back from outside that volume. However, unique to working with soap films, or near fluid surfaces, there will also be a strong component of unwanted specularly reflected light from the surface. The point of reflection resides within the scattering volume which unfortunately means this unwanted light can be channeled directly back into the photodetector, overwhelming the Doppler signal, and saturating the detector. The film plane must therefore be kept at an angle with respect to the LDV optical axis so that all light reflected from the film surface bypasses the LDV collection optics.

Several other problems only occur in the extreme situation of very fast and thick films. Reflected beams can occasionally dance about due to undulations of the film surface. Here too, if the reflections encounter the collection optics, they will saturate the detector and cause gaps in the data stream. Another difficulty arises with very thick films which have just passed an obstacle. Such films can have significant small scale thickness fluctuations which reflect light in all directions. These may again end up saturating the photodetectors. This would also be a problem in a forward scattering geometry.

2. Hot wire anemometry

Hot wire or hot film anemometry is a suitable technique for measuring the velocity of the air surrounding the soap film. Measurements can, however, become difficult near the film due to possible undulations. As well, when the film breaks it sprays a corrosive mist which can damage a delicate hot wire and change the calibration coefficients. For these latter reasons it is unlikely that a hot wire could be used to measure the actual soap film speed.

3. Fiber velocimeter

Kellay *et al.*[11] and Rivera *et al.*[27] developed an alternative method to LDV for measuring velocity at one point as a function of time. The so-called fiber velocimeter optoelectronically measures the deflections of an optical fiber (0.5–1 cm long, 20–60 μm in diameter) which is thrust through the film. The fiber velocimeter is much cheaper than LDV and delivers a continuous analog signal.

There are some disadvantages to the fiber method however. The deflection of the fiber is proportional to the momentum transferred to it from the fluid and the exact point at which the film makes contact with the fiber (the effective lever arm). Thickness variations in the film will cause variations in deflection as will undulations of the film. Thus far we have measured fiber deflection to be linear with mean flow and have found no qualitative differences between turbulent velocity spectra taken with fiber and LDV. The fiber is currently undergoing more comparisons with LDV.

4. Homodyne correlation spectroscopy

This method was developed by Tong *et al.*[28] to measure instantaneous velocity differences between two particles in turbulent fluids. The method yields the cosine transform of the probability distribution function of velocity differences at an adjustable length scale L. The method was applied to soap films by Kellay *et al.*[11] and is useful in determining certain aspects of turbulent statistics.

5. Particle imaging velocimetry

The method of digital particle imaging velocimetry (DPIV) is showing increasing utility in the study of turbulent soap films.[2,3,19,29] Since DPIV is inherently a 2D method it is ideally suited for this type of work. To do DPIV, seed particles are added to the flow and then imaged twice in short succession. The velocity field can then be obtained from local correlations between these two images. The main difference from PIV methods in bulk fluids is that the seed particles should have diameter less than the film thickness of 5–10 μm. Larger particles will not adequately follow a turbulent flow field and may introduce thickness variations not accounted for by classical 2D methodology.

Doing DPIV in vacuum is complicated somewhat by the presence of the cylinder wall. The brightest scattering is achieved when the strobes, particles, and camera are linearly aligned. Some deviation from this is of course necessary to keep the strobes from direct view of the camera (an aperture placed near the film can help). However, with the chamber in place, light from the strobes scatters from the cylinder surface, saturating the image. It is therefore necessary to keep a large angle between the strobes and the camera–film axis and to place the strobes as close to the cylinder as possible. This minimizes the illuminated cylinder area and keeps it from view of the camera (see Fig. 14).

B. Flow visualization

Visualizing flow is an extremely important aspect of any program of fluid dynamics experimentation and there are various methods of doing so with flowing soap films.

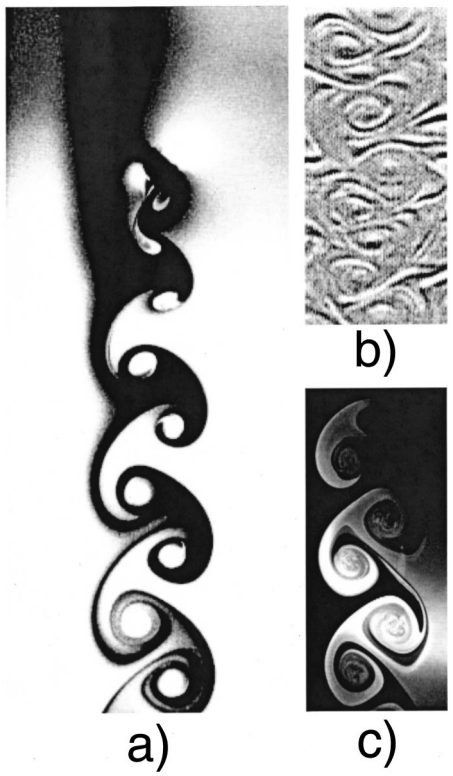

FIG. 15. Three different flow visualization techniques of a vortex street: (a) advection of a film thickness variation, (b) shadowgraphs of a thick film, (c) fluorescent dye visualization. Vortex streets are about 1 cm wide.

1. Optical interference

The simplest visualization method requires no addition of contrast agents to the flow at all. It relies on the optical interference between the front and back surfaces of the film, which is the source of the familiar colors of soap films and bubbles. A quarter wavelength change in film thickness ($\sim$0.1 μm, in water) will change the interference condition from constructive to destructive. Thickness variations in the film are therefore visible as dark and bright fringes, especially when viewed under monochromatic light. Looking at a typical photograph of a soap film flowing past a cylinder [Fig. 15(a)], it becomes clear that the contrast variations are acting as a tracer in the flow. Dark film is being advected into the wake of the cylinder. More images of this type have been published by several authors.[9,6,16]

One can argue that the advected thickness variations are not just a tracer, but a passive scalar in the flow. Thickness variations should be a small percentage of the total film thickness for this to be true. For Fig. 15(a) we estimate the changes at 5%–10%. Since a flat film is the minimum energy configuration, thickness variations must have a finite lifetime. If this lifetime is much longer than the typical eddy turnover time, then thickness is in practice a passive scalar. Figure 15(a) shows that the interface between dark and bright stays remarkably sharp, indicating the desired slow relaxation of thickness variations. More quantitatively one can estimate the time required for an indentation in the film to heal. Consider a 2 μm thick film with an 0.2 μm indentation on either side. Take the diameter of the dimple as 0.4 cm. Under monochromatic light, this would appear as two

concentric interference fringes. The curvature of the film creates an excess pressure gradient of approximately 0.5 dyne/cm^3 around the dimple, forcing fluid back inside the depression. For a pure fluid the gap would heal rapidly, since the surface would flow freely with the film center. However, the surfactants on a soap film surface resist flows with net divergence since the resulting surfactant concentration gradients cause counter balancing surface forces. The interstitial fluid therefore moves back into the dimple as if flowing between semi rigid plates; a very slow process given the small ''plate'' spacing and the minute pressure gradient. The problem is analogous to the draining of a stationary vertical soap film, described in great detail by Mysels *et al.*[5] In that case the pressure gradient due to gravity is at least 1000 times (pressure at a depth of 1 cm in water) larger than in our hypothetical dimple. The vertical films take hundreds of seconds to thin by draining, implying that a dimple needs at least that much time to heal. This is practically infinite compared to the millisecond eddy turnover times of our flowing soap films.

Even in a film which is otherwise perfectly smooth, such as in Fig. 11(b), one can observe flow patterns downstream from obstacles. Thus, the interaction between the film and the object must create small changes in film thickness which are then advected downstream as passive scalars. The generation of these thickness variations is not completely understood, but may result from the minuscus surrounding the object being partially wrapped into shedding vortices.[19]

2. Shadowgraphing

For very thick films the interference visualization method fails in practice because fringe spacings become too close to be resolved with a camera. In this case one can use a shadowgraphing technique. Parallel light is brought in from a distant source and passed through the film. The slight curvature in the film between thin and thick regions bends the light away from parallel. The light is then focused into a camera [see Fig. 15(b)].

3. Dye methods

Dye molecules can be dissolved in the solution and used as a more traditional tracer stream. Harris and Miles[30] have successfully visualized flow patterns in soap films by adding 0.05 g/l fluorescin dye to the soap solution. Two separate fluid supply lines were fed into the same injection nozzle so that half of the flowing soap film was dyed and half undyed. The film was then exposed to 200 mJ/pulsed UV laser light bursts and the flouresced light was imaged onto a CCD camera. Figure 15(c) is an image (photo courtesy of Harris and Miles[30]) of the wake of a rod which punctured the film at the dye line. The time between frames was limited by the 10 Hz repetition rate of the laser. The similarity between Figs. 15(a) and 15(c) further support the claim that thickness is as good a passive scalar as dye.

4. Particle decoration

Couder and co-workers[6,8] both pioneered the use of soap films for 2D fluid dynamics experiments, and were the first to decorate the surface of the film with small particles for flow visualization. Photographs were exposed long enough to show short particle tracks which corresponded directly to the velocity director field. These experiments were done on stationary horizontal films [see Fig. 2(a)] which made it relatively easy to sprinkle on the particles. As is the case with any particle seeding or decoration technique, one must be positive that the particles are following the flow. We experienced one situation where this was not the case when we sprinkled 100 μm hollow glass spheres onto an inclined film flowing at about 2 m/s. We found evidence that the spheres could detach from the surface of the film and continue in a straight line, while the fluid circulated within a vortex.

C. Film thickness measurement

Film thickness is an extremely important parameter in these experiments. It relates directly to the 2D fluid density in the 2D Navier–Stokes equations and determines the gravitational force per unit area in the vertical films. It directly affects the deflection of the optical fiber velocimeter, and in theory, is even directly related to vorticity (see Chomaz and Cathalav[31]), considering the balance between the centrifugal and surface elastic force terms in a vortex. Unfortunately, it has been rather difficult to measure.

A crude but useful method was to measure the local conductivity of the moving film by puncturing the film with two platinum needles separated by several mm. A linear relationship between film thickness and conductivity was established. The curve can be calibrated at very thin films where the Newton color scale is applicable. The method has been used infrequently however, since conductivity also depends on the ionic nature of the solution and thus requires recalibration for each batch of soap solution. The technique is of course intrusive. Below we describe some more sophisticated and accurate methods which are in use, or being developed by various research groups.

1. Interference

Optical interference methods seem like the obvious solution to the thickness measurement problem, but have proven impractical to date. Counting interference fringes under monochromatic light only gives the difference in thickness between two points, and not the absolute thickness. Counting fringes also becomes difficult. For thin films one can assign definite colors to absolute film thicknesses using the Newton color scale.[4] However, for films thicker than 1 μm the method fails since the colors only alternate between pink and green and offer little information about absolute film thickness. If the flow is laminar, one can always reduce the film speed to a point where the color is well defined and then slowly increase the flow rate while keeping track of how many interference fringes pass the point of observation. However, this does not work for turbulent films where thickness variations occur in a much more haphazard fashion. We have tried to measure absolute thickness at one point by simultaneously interfering multiple laser lines from a krypton ion laser. Within the noise of the data it proved practically impossible to calculate the absolute thickness of a several micron thick moving film.

2. Dye methods

Fluorescent dyes offer an elegant method for imaging film thickness locally, and across large areas. If the dye is uniformly mixed into the soap solution then the intensity of a fluorescense image is directly proportional to the film thickness. A UV pulsed laser system, as described in Sec. V B 3 may, however, be prohibitively expensive for just the purpose of measuring film thickness. Wu of this article, has imaged the thickness of a slowly moving film by heavily seeding it with dyed polystyrene spheres[32] and illuminating it with the 514 nm line of an argon ion laser. The results are promising but show some departure from a linear relation between film thickness and fluorescent intensity due to constructive and destructive interference between the film surfaces and either the 514 nm light or the downconverted fluoresced light. A similar measurement can be performed without dyes. The intensity of light scattered directly from a dense seeding of undyed particles will also be proportional to the film thickness.[33]

3. Infrared methods

Last, one can measure thickness using IR light. Gharib and Mackey have reported[34] a method using a thermal imaging system on a film flowing over a cold background. The measurement relies on the thermal emission of the film itself.

An IR point measurement device has been developed by one of us (X. L. Wu). It takes advantage of the sharp IR absorption peak centered at 3 μm. The absorption length at this wavelength in water is comparable to the typical film thickness. A parallel beam of broad band IR light is directed through the film. The transmitted light is filtered about 3 ± 0.1 μm and measured with a cooled InAs infrared detector (EG and G Judson series J12). The frequency response of the system ranges from dc to at least 50 kHz. The method has proven successful and will be used to measure the film thickness while concurrently measuring velocity with an LDV.

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