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Combined dye-streak and hydrogen-bubble visual observations of a turbulent boundary layer

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The turbulent boundary layer over a flat plate was observed visually using two dye injectors and a normal bubble wire. One dye injector was a standard wall slot; the other one was a small Pitot probe which could be placed anywhere in the flow. The purpose of these experiments was to improve understanding of the relationships between the bursting of low-speed streaks near the wall and the flow field farther away from the wall.

On the basis of these observations, it seems that (i) each lift-up is associated with a disturbance which originates in the logarithmic region and is characterized by a mean motion towards the wall, and that (ii) such disturbances are generated by the interaction of an earlier burst from further upstream with the fluid motion in the logarithmic region.

1. Introduction

1.1. *Motivation*

These tests were motivated by some questions arising from earlier studies of various workers, particularly those by Corino & Brodkey (1969), Grass (1971) and Kim, Kline & Reynolds (1971). Kim *et al.* used anemometry and visualization techniques to study the turbulent boundary layer near the wall. They found that the following sequence of events occurred in such flows: (i) the appearance of a relatively low-speed region of fluid near the wall; (ii) the 'lift-up' of this 'low-speed streak' from the wall followed by some form of 'oscillatory growth' and (iii) ultimately, the 'breakup' of any signs of coherency in the visual representations of this structure. This entire three-stage process was called 'bursting' and was also the subject of the investigations to be discussed next.

Corino & Brodkey (1969), using a dark-field illumination technique in successive strips of the flow, reported that an element of accelerated fluid entered their field of view ($0 \leqslant y^+ \leqslant 90$, $0 \leqslant x^+ \leqslant 125$) from a region upstream and farther away from the wall at some time after the appearance of a low-speed wall streak. Such inward motions, which were labelled 'sweeps' by Corino & Brodkey, were not described by Kim *et al.* (1971) because the techniques used do not make them visible. Corino & Brodkey suggested that the interaction between the accelerated and the retarded flow is fundamental to the ejection process. This stimulated Willmarth & Lu (1972) and Wallace, Eckelmann & Brodkey (1972) to measure separately the contribution of the inward-moving accelerated elements of fluid ($u > 0, v < 0$; hence $uv < 0$) to the total Reynolds stress $\overline{|uv|}$. They found that the conditional average of the contributions to the Reynolds stress from these motions was about the same as that from the outward motion of retarded fluid ($u < 0$, $v > 0$; hence $uv < 0$ also). One purpose of the present tests was to seek the existence of relationships between bursts and the other fluid motions described by Corino & Brodkey, Wallace *et al.* and Willmarth & Lu over a greater spatial and temporal separation. The results presented here confirm their observations and extend them, particularly to interactions which occur after lift-up. They thus provide a more coherent picture of the entire 'cycle' of events associated with the creation of turbulent shear.†

1.2. *Limitations of the visual technique*

In the description of events which will follow, the word 'associated' is used to describe the relationship between a disturbance to the flow in the logarithmic region and the subsequent appearance of a lift-up from the wall. Such a weak term must be used because visual studies cannot demonstrate causality; they can only show spatial and temporal relationships between various motions. In this particular case, the dye method used makes visible a disturbance to the outer flow upstream of, and prior to, wall-dye indications of an incipient lift-up, but the dye traces cannot prove that the outer disturbance causes the lift-up.

Because the events reported here happen too fast to be analysed reliably in real time, even at the low flow speeds used (free-stream velocity = 0·21 ft/s), it was necessary to take motion pictures; see Offen & Kline (1973).‡ These movies could then be studied frame by frame. As a result the highly three-dimensional flow field is only viewed in 'two and a half' dimensions: neither the dye nor the bubbles disappear from the field of view when the fluid they are marking is displaced in the spanwise (i.e. third) direction, but the presence of this lateral motion is usually not detectable.

During the discussion of the visual observations in the next sections, the flow field will frequently be described in terms of vortex-like structures. The term 'structure' is used very specifically to mean any shape, or pattern, which is made visible in an instantaneous photograph of hydrogen bubbles and which can be described by a common fluid phenomenon or geometrical term. These structures appear to be vortices because a sequence of closely spaced bubble lines from a normal wire assumes one of the following patterns: (i) contortions into a cylindrical shape§ or (ii) the development of an S-shaped kink in each time-line.

These two situations are sketched in figure 1. If a mass of fluid rotates as a unit with a vorticity vector that points mainly along the streamwise direction, and if this fluid passes, or has recently passed, over a hydrogen-bubble generating

† The results presented here have been abstracted from Offen & Kline (1973). The reader who wishes more details, as well as quantitative results from related experiments, is referred to this report.

‡ *A Visual Study of the Temporal and Spatial Relations between Bursts and the Outer Flow in a Turbulent Boundary Layer*, filed with the Engineering Societies Library, 345 E. 47th Street, New York, 10017.

§ This cylinder is not a right circular cylinder, nor is its generating line a straight line.

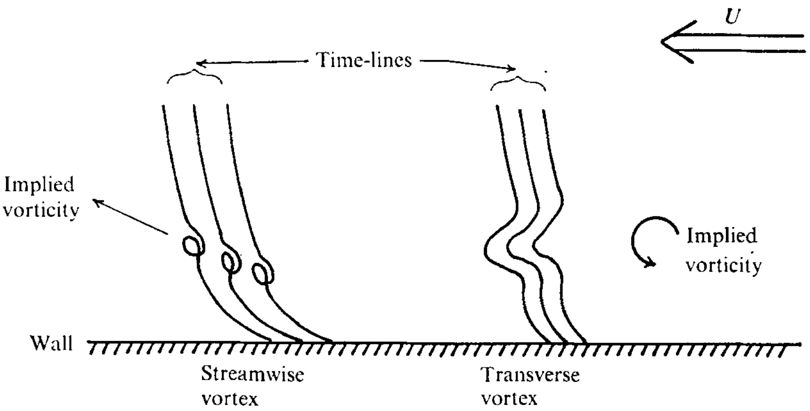


FIGURE 1

wire, the time-lines curl over on themselves to take on a cylindrical appearance. This pattern is depicted in the left half of figure 1. On the other hand, fluid whose vorticity is in the same direction as that due to the mean flow, but with a value that is temporarily larger than the mean, will possess a streamwise velocity excess, relative to the surrounding fluid, at one location and a deficit at the opposite side of the vortex. This flow pattern is labelled a transverse vortex and is depicted in the right half of figure 1. The general shape of either of these two patterns is similar from one example of a given vortex type to another example of the same type, but considerable variation is seen from one vortex to the next in length, diameter, orientation and rotational speed.

The discussion above implies that one can infer a flow structure directly from a single photograph of time-lines; since this is not true in general, an explanation is required. At the instant of its generation along a bubble wire, a time-line marks those fluid particles which are just then located along the straight wire. The shape of this time-line at any later moment, then, represents the *cumulative effect* of the flow on this collection of fluid particles in the time interval since their generation; it does not give an instantaneous picture of the structure where one sees it. The photographs included with this paper (figures 4–7, plates 1–4) can be used to explain this statement. Near the bubble wire the time-line patterns are orderly, but near the downstream edge of the photograph the shapes are chaotic. Since the location of the bubble wire is arbitrary, and since the pictures obtained with different choices for this arbitrary location are similar, the positions of the ordered and chaotic patterns are not fixed in the laboratory frame of reference. Instead, they are functions of the fluid motions between the bubble wire and the point of observation.†

Fortunately, this difficulty of pattern interpretation does not prevent us from using time-lines in the present investigation because we are interested in spatial

† As a consequence, the average distance between the bubble wire and the zone of chaotic patterns is a measure of some kind of macroscale of the turbulence. However, the relationship between this visually observed distance and the conventional macroscale, which is based on the integral of the autocorrelation function, is not known.

and temporal relations between events, not in instantaneous structures. Our results are all based on differences observed among the patterns on several photographs† of the flow that are separated by finite time interval. Hence, we identify a flow structure when we find a configuration which changes according to the model of that structure during this time interval. Furthermore, we have found that the patterns are not altered drastically between successive observations; the changes seem to be confined to size and orientation. The patterns do move, and hence do represent a flow structure, but their basic nature does not change too rapidly; it is therefore legitimate to display the structural description using an instantaneous time-line pattern as in figures 4–7.

The motion pictures were analysed in detail for periods of only 1–1½ min for each arrangement of the dye injector and bubble wire. The purpose of this study was to determine characteristic behaviour patterns, but not necessarily precise statistical data for these patterns. The quantity of data analysed was sufficient to ensure that the patterns which were seen were, in fact, characteristic and repetitive, as well as to give an indication of the frequency of occurrence of the observed events. Such information can be used not only to provide qualitative descriptions of the flow field, but also as a guide to the design of appropriate quantitative experiments.

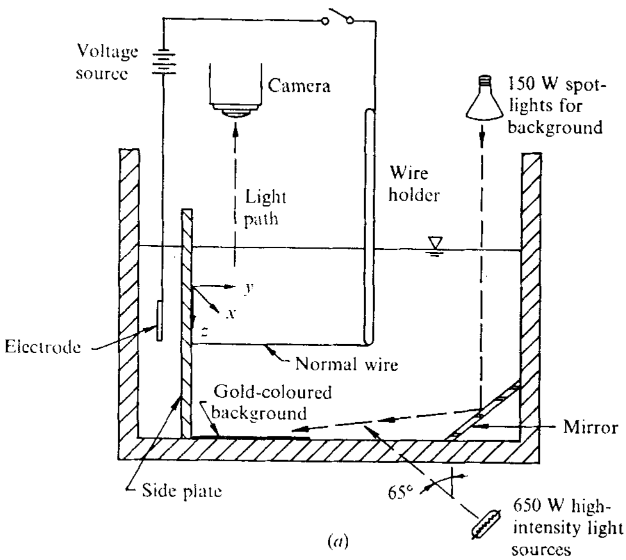
2. Experimental apparatus and procedure

2.1. *Water channel*

The water channel system used in this investigation is similar to the one used by Kim *et al.* (1971), the only difference being that the present channel is 21 in. wide while theirs was 36 in. wide. A sketch of the test section and visualization devices is presented in figures 2(*a*) and (*b*). The boundary layer was developed on a flat vertical lucite plate set inside the water channel. The plate is smooth, 12 in. tall, ½ in. thick and 13 ft long, including the gradual transition region between the channel wall and the side plate at the entrance to the channel. Further details can be found in Kim *et al.* (1971). The same free-stream velocity, approximately 0·21 ft/s, was used for all runs. In order to obtain a thick well-developed turbulent boundary layer at the test section, early laminar-to-turbulent transition was forced by placing a ½ in. diameter rod across the side plate just downstream of the gradual transition. The viewing area was located 6 ft from the trip, 5 in. from the bottom of the channel and 5 in. from the free surface of the water. The boundary layer was approximately 3½ in. thick, which corresponds to a non-dimensional distance $y^+ \simeq 350$. The momentum-thickness Reynolds number was about 600.

Since the flow properties of this apparatus and geometry have been studied extensively (Kim, Kline & Reynolds 1968; Schraub & Kline 1965; Runstadler, Kline & Reynolds 1963), no velocity profiles were taken. The phenomena reported by the previous investigators when they used the same hydrogen-bubble wire

† In the motion pictures and *in situ* this may be several hundred; in still-frame analysis it is usually two frames.



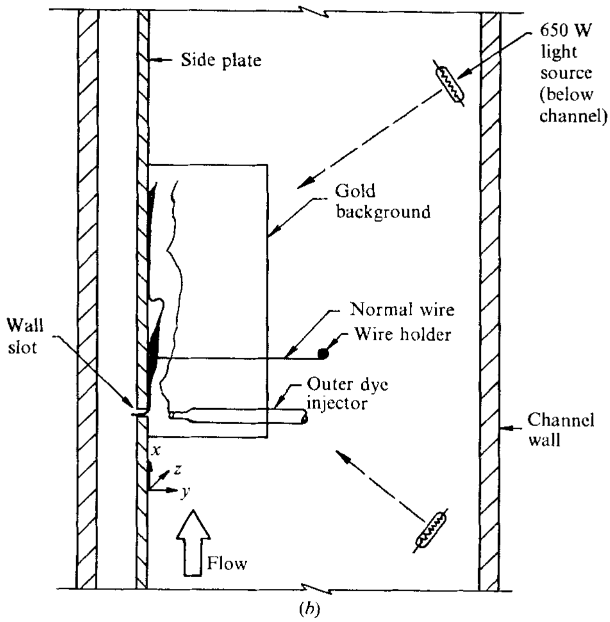


FIGURE 2. (*a*) End view of section of channel showing arrangement for photography of side view with normal wire (dye injectors not shown). Flow is normal to the plane of the paper. The boundary layer extends about half as far from the wall as the gold background. (*b*) Top view of section of channel showing arrangement for photography of normal wire and two dye streams (background lights and mirror, voltage source and dye sources not shown). Flow is from bottom to top parallel to the plane of the paper.

Test description	Outer dye injector: Nominal y^+	Outer dye injector: Δx^+†	Bubble wire Δx^+†
Influence of outer flow on bursts	50	0	+200
	100	−275	+200
	200	−400	+200
Influence of bursts on outer flow	100	+475	+525

† Δx is measured from the wall dye slot. Positive values represent locations downstream of the slot.

TABLE 1. Relative location of visualization devices

set-up were also seen during this study. Moreover, the purpose of this experiment was to provide only qualitative data, so that the exact details of the profiles were not needed.

2.2. *Co-ordinates and vortex nomenclature*

Standard Cartesian co-ordinates will be used to describe the test set-up and fluid motions (see figures 2*a*, *b*). The mean flow is aligned with the x axis, which is often called the streamwise direction. The y axis, or normal direction, is perpendicular to the wall, whereas the z axis, or spanwise direction, is parallel to the wall and perpendicular to the mean flow. Although the vortices observed usually have some components in all three directions, when the vortex lines are dominated by the ω_x component, they are called streamwise vortices; when the orientation is dominated by ω_z, they are designated transverse vortices. The streamwise vortices frequently have a noticeable component in the normal direction; in this case they are called 'upward-tilted streamwise vortices'.

2.3. *Flow visualization techniques*

2.3.1. *General description.* Two dye injectors and a hydrogen-bubble wire were used simultaneously to visualize the fluid motions. The dye injectors were used for two reasons: first, because it is difficult to distinguish between bubbles from two separate wires when the bubbles from both wires intermingle in any region; and second, because an additional purpose of this experiment was to clarify the relations between wall-dye and normal-wire visualization of bursts for a later investigation. The injectors will be described later (§§ 2.3.3 and 2.3.4). As shown in figures 2(*a*) and (*b*), the bubble wire was a normal wire, and all the views were side views; that is, the line of sight was in the transverse, or z direction. An 8 in. long piece of 0·002 in. diameter platinum wire was used to generate the bubbles. This wire could be situated at various streamwise distances directly downstream of the centre of the wall slot. The outer injector was also situated at the same spanwise position. The relative locations of the three visualization devices are given in table 1 for each experimental set-up used.

Kodachrome motion pictures were taken of the combined bubble and dye views. These permanent records of the flow structure were analysed later using an L-W Photo Optics Model 224-A film analysing projector. Although movies were made and analysed with the outer dye injector placed at $y^+ \simeq 50$, 100 and 200, all the photographs presented with this paper come only from those film sequences taken with the injector at $y^+ \simeq 100$.

2.3.2. *Lighting arrangement.* An unusual illumination system had to be used because the optimum lighting arrangements for bubbles and dye differ by 90° in orientation. Hydrogen-bubble time-lines should be illuminated by a bright source which is located at the rear side of these lines and makes an angle of about 65° with the line of sight of the camera (Schraub *et al.* 1965). The background must be dark. In contrast dye should be illuminated from behind with a diffuse source, such as a bank of fluorescent tubes covered by frosted glass. With some experimentation it was found that a weakly illuminated golden or orange background would produce a sufficient contrast to the red and blue dye used to make it clearly visible. At the same time, this background also provided adequate contrast to the white bubbles, especially when they were illuminated in the manner best suited for them. Therefore, light was directed onto the golden background from two 150 W spotlights, using mirrors in the channel, as shown in figure 2(*a*). The brightness of the background was controlled by the angle of the mirrors. The bubbles were lit by two 650 W high-intensity quartz–iodine movie lights shining up through the bottom of the channel. The lamps were placed to the side of the viewing area (i.e. farther away from the wall than the outer edge of the viewing area); one was slightly upstream and the other slightly downstream of this area (figure 2*b*).

2.3.3. *Wall dye slot.* One dye injector was a wall dye slot, similar to the one used by Runstadler *et al.* (1963). Small quantities of dilute food-colouring dye† were seeped into the flow through a carefully made slot in the wall which measured 0·003 in. in the streamwise direction. The $\frac{1}{4}$ in. spanwise length of the slot was chosen to ensure that one would see only one burst at a time.

2.3.4. *Outer dye injector.* The second dye injector was a flattened Pitot probe that had been used for measurements in air. Its outer dimensions were 0·013 in. in the direction perpendicular to the flow and 0·034 in. in the direction of the flow (figure 3). This size corresponds to a Reynolds number of approximately 14 at $y^+ = 50$ and to 22 in the free stream, based on local mean velocities and the probe dimension perpendicular to the flow. Both these values are below the critical value for the onset of vortex shedding. However, if the dye injection rate is allowed to become too large, the issuing dye behaves like a jet, and vortices appear along the interfaces between the jet and the flow. Experiments showed that the magnitude of these vortices could be minimized by positioning the probe so that the jet had no spanwise velocity component and left the probe at an angle of about 55° to the mean flow (see figure 3). Even though the injection rates that were actually used were never high enough to produce these vortices, this orientation was always used.

The extent of the flow disturbance produced by the outer injector was determined by two methods. First, the injector was placed just upstream of the

† Made by high dilution from the water of the operating channel to minimize density gradients.

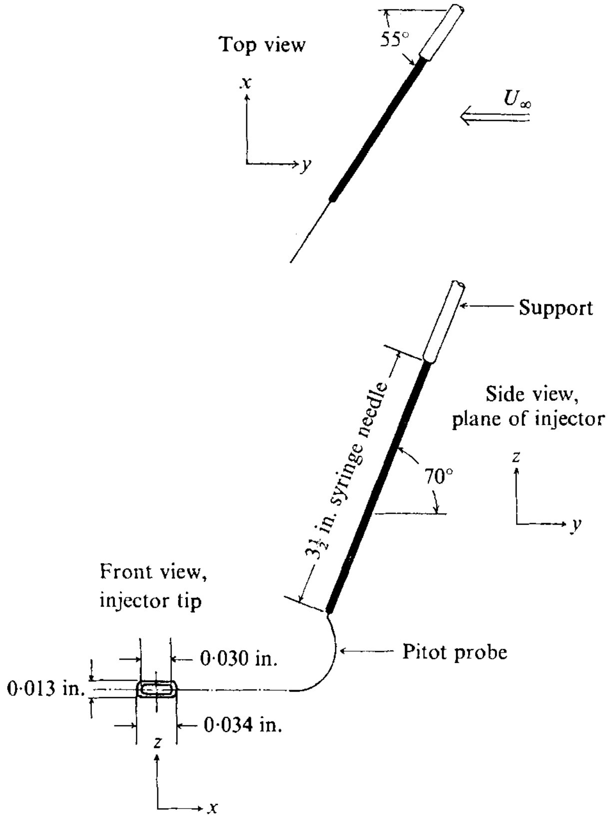


FIGURE 3. Outer dye injector.

bubble wire and well beyond the edge of the boundary layer. The movies taken of the dye streaks and bubble time-lines with the injector in this configuration were compared with scenes that had been filmed at the same location but with the injector removed. A laminar wake was found to exist behind the injector. Flow disturbances were seen occasionally and were found to originate at random locations within the viewing area. They appeared at approximately the same rate with and without the injector. However, when the injector was in place, the perturbations all developed in the wake (which, having an inflexional profile, is unstable in the classical sense); when the injector was removed, the disturbances grew around their origins (taking into account convection by the mean flow). Thus, the wake behind the dye injector seemed to control the location of the flow disturbances, once they began, but it was not responsible for them.

As a second check, motion pictures of the flow with the outer dye injector located at $y^+ \simeq 50$ were compared with those taken when the injector was placed at $y^+ \simeq 200$. In both cases a region bounded by the bubble wire, a line through $y^+ \simeq 50$ and a line located about $100x^+$ units downstream of the bubble wire was checked for the average length of non-quiescent periods and the fraction of the total time the flow was non-quiescent. The flow was deemed to be quiescent unless the time-lines showed the existence of either a streamwise or a transverse vortex within the region of interest. Only 20–30 s of film (real-time equivalent) were studied, so a rough comparison is all that should be expected. When the injector was located at $y^+ \simeq 50$, the average length of non-quiescent flow periods was 2·4 s, and the flow was non-quiescent for 56 % of the time. By comparison, when the injector was situated at $y^+ \simeq 200$, the results were 2·0 s and 69 %, respectively. Given the short samples, it seems reasonable to believe that the differences are not due to the presence or absence of the probe and hence, that the probe does not significantly alter the rate of vortex formation, bursting or inward accelerated motions.

3. Burst chain of events

3.1. *Disturbances moving inward*

In this subsection the evidence that led to the postulate of an association between flow disturbances which move in from the logarithmic region and subsequent lift-ups, or bursts, from the wall will be presented. Possible flow structures that could be responsible for these perturbations to the outer dye filament will be discussed later (§ 3.1.3). In the following description the term 'sweep' will be used to refer to disturbances that are observed as a perturbation of the outer dye with a net translation towards the wall.†

3.1.1. *Relationships prior to lift-up.* The most significant data were obtained with the outer injector located upstream of the wall dye slot and at $y^+ \simeq 100$ (see table 1). Since the evolution of a motion can be visually observed and demonstrated only by a time sequence of photographs, two frames have been reproduced from the motion pictures for each event that is described here. Typical groups of scenes from the movie which indicate the relationship between disturbances to the outer flow and lift-ups are presented in figures 4–7 (plates 1–4). In all the references to the figures, the area of interest on the photograph is marked by pairs of arrows or pairs of brackets along the edges of the picture. For example, if a reference is made to a figure during the discussion of a sweep, the reader should look for a displacement of the outer dye line towards the wall located in the region of the photograph where the appropriate pair of brackets or arrows intersect. These marks, and their page references in the text, are listed below the photographs. When two photographs are used to show the development of a structure, the top one precedes the lower one in time. The horizontal displacement between the two is equal to the distance a particle in the free stream travels during the time Δt given in each figure caption. Since most of the patterns observed in the outer dye were convected with a speed that was close to the free-stream velocity, the displacement of the photographs brings corresponding features of the outer flow into alignment with each other when they are superposed.

The first sequence of two photographs (figures 4*a*, *b*, plate 1) shows a ragged, or peaked, disturbance in the outer dye, whereas the second group (figures 4*c*, *d*, plate 1) depicts a smoother oscillation. (The salient structural features of figure

† This nomenclature is adopted from Corino & Brodkey (1969), who used it to describe high-speed fluid elements that move into regions of low-speed fluid near the wall.

4(*d*) are re-drawn on figure 4(*e*) and clearly labelled to aid the reader in interpreting the photographs in figures 4–7.) In the first view of each sequence (figures 4*a*, *c*), the sweep is seen at an early stage of its development, but no simultaneous movement of the wall dye can be detected near this sweep. In the second photograph of each pair (figures 4*b*, *d*), the dye representation of the sweep is larger. More important, it has moved closer to the wall, and the wall dye has begun to lift up. The importance of these groups of pictures is that they show *the beginning and growth of a disturbance in the outer flow, as made visible by the outer dye, upstream of, and prior to, the appearance of a low-speed streak in the wall dye.* Although both a ragged and a smooth sweep are shown, no consistent difference was found between the nature of the lift-ups which were associated with each of these types of sweep.

The next two pictures, figures 5(*a*) and (*b*) (plate 2), present a direct contrast to the four scenes in figure 4. *The outer dye's path is nearly a straight line for a reasonable distance from the injector, and no lift-up is developing in the wall dye.* Although a sweep can be seen in the downstream half of figure 5(*a*), it is associated with the previous burst.†

In order to quantify the relationship between sweeps and lift-ups, a section of the motion picture was analysed in detail. Eighteen of the 31 sweeps observed during a 76 s period were associated with subsequent lift-ups.‡ Only one lift-up was observed that could not be related to a previous sweep. This could be due to the fact that the associated sweep did not pass through the outer dye filament or that the lift-up was related to some other phenomenon. Movies which had been taken with the outer dye injector situated at $y^+ \simeq 200$ were analysed in a similar fashion. These indicated that nearly three quarters of the disturbances at this location which had a significant velocity component towards the wall were associated with a lift-up, and about 85 % of the lift-ups could be related to a previous disturbance near the injector.

3.1.2. *Relationships after lift-up.* The sweep generally continued to move towards the wall after the low-speed fluid element had begun to lift away from the wall. Nearly three quarters of the sweeps reached their closest proximity to the wall downstream of the head (forewardmost part of the ejected dye filament) of the bursting wall dye. An example of this can be seen in the lower left half of figure 4(*d*). The wall-ward moving disturbances which were made visible by the outer dye at $y^+ \simeq 100$ had an average mean trajectory of about 6° relative to the plane of the wall, which agrees reasonably well with the findings of Corino & Brodkey (1969). Unfortunately, the two-dimensional nature of the motion pictures prevented us from making any reasonable observations about the spanwise relationships between bursts and sweeps that have come near the wall.

† We follow here the notation of Kim *et al.* (1971) in calling the total sequence of outward moving fluid and period of high turbulence production a 'burst', and the first portion of the burst sequence 'low-speed streak lift-up'. Thus in saying that sweeps initiate lift-ups, we are also saying that sweeps initiate bursts.

‡ The reader should be cautioned against trying to calculate a mean time between bursts from these data. Mean burst periods refer to bursts that pass a given point in space; the data presented here are for all the bursts observed anywhere within the 18 in. long viewing area.

The arrival of outer fluid ahead of, or adjacent to, bursting fluid is consistent with what one would expect from continuity. The leading portion of a lift-up occupies a transition region between rapidly moving fluid ahead of the burst and slower fluid within the burst. Thus, for a control volume located about this front section of the burst, the streamwise mass-flux defect must be compensated by fluid inflow from above or from the sides.

The experiments also confirm the discovery by Corino & Brodkey (1969) of frequent sweeps which come to the wall behind lift-ups and seem to terminate the ejection process. Although no data were collected on these sweeps, they are mentioned occasionally in the text and figures. They will be called 'cleansing sweeps' to distinguish them from the other sweeps. An example can be seen in figure 4 (*a*).

3.1.3. *Sweep structure.* An attempt was made to deduce the flow structure which is responsible for sweeps by placing the outer dye injector at $y^+ \simeq 100$ and just upstream of the hydrogen-bubble wire. The movies that were taken with this experimental set-up showed that all the sweeps contained an element of fluid whose streamwise velocity was different from that of its surroundings. This fluid did not need to have a velocity component towards the wall. If the velocity difference between this 'foreign' element of fluid and its environment was relatively small, then the disturbance grew slowly and was not associated with the formation of vortices. However, if the velocity was significantly different from that of its surroundings, the sweep grew more rapidly and was related to the appearance of vortices. Typically, when large velocity differences occur over a short distance in the normal direction, a high-shear zone is formed, and vortices seem to appear along these zones.

Two types of vortical motions, which are seen frequently with hydrogen-bubble visualization of the turbulent boundary layer, possess the $u > 0$, $v < 0$ velocity combination that implies a sweep. One is a transverse vortex (vortex line perpendicular to the plane of the time-lines from a normal wire; see figure 1) whose orientation is such that it brings fluid down towards the wall and then moves it forward, in the direction of the mean flow. The lower, rear part of the vortex has the requisite velocity components.

The other circulatory motion that has the proper velocity combination in some region is an upward-tilted streamwise vortex; that is, a vortex whose vorticity is dominated by the streamwise component but which also has a significant component normal to the wall (although the spanwise component of vorticity can be neglected for the purposes of this discussion, it is usually present; in fact, a streamwise vortex would be difficult to detect in a side view of hydrogen-bubble time-lines if it were not for the presence of a small amount of ω_z). If the part of the vortex farthest away from the wall passes the dye injector, dye will be seen to move towards the wall and faster than the local mean velocity. This observation holds irrespective of whether the streamwise vorticity component points upstream or downstream.

3.2. *Description of sequence of events during bursting*

Since the movies portrayed both hydrogen-bubble time-lines and dye-marked lift-ups, the temporal and spatial relationships between the various events during a burst could be investigated. The following sequence was observed. Simultaneously with the appearance of the first oscillations in the wall dye, or at most very shortly thereafter, the time-lines displayed the existence of a narrow zone of high shear. The streamwise extent of this zone corresponded approximately to the length of the oscillations seen along the wall. The shear was made visible by the existence of similar kinks in successive bubble lines. The kinks, which look like a demarcation between two parts of a bubble line that have been rapidly shifted relative to each other (see figure 1), are all located along the same curve. This curve is, of course, not a straight line. Either a streamwise or a transverse vortex formed along this line after a certain interval, and frequently this first vortex was followed by the appearance of others nearby. Most lift-ups of the wall dye were seen some time after the formation of one of the above-mentioned vortices and began to leave the wall where the vortex came closest to the wall. In the case of a streamwise vortex, this location corresponded to the rear end of the vortex line, whereas for a transverse vortex it was along the edge of the circulatory motion closest to the wall.

In summary, the data which form the bases for the above description show that 8 out of the 14 high-shear zones observed were formed at the same time as the appearance of the first oscillations in the wall dye; during the other six burst sequences, the high-shear zone was generated an average of 0·8 s after perturbations were seen along the wall. This high shear always occurred before a vortex was detected, and the average time lapse was 0·7 s. In 10 out of 15 events the vortices preceded the beginning of a significant continuous motion of the dye away from the wall by an average of about 1 s; in two cases the start of the lift-up coincided with the formation of a vortex, in two others the lift-up preceded the development of the associated vortex, and in one situation the earliest stage of the lift-up did not appear to be correlated with any vortex.

3.3. *Effects of bursts on downstream outer flow*

In order to search for the existence of a relationship between bursts and the outer flow downstream of the bursts, the movable dye injector was placed 2–3 in. downstream of the location of the average lift-up. The bubble wire was then situated near the movable injector (see table 1). This arrangement of the visualization devices enabled us to observe the close association between bursts and the formation of sweeps near the head, or forwardmost part, of the bursts. Examples showing the presence of these two events close to each other are given in figures 6 and 7 (plates 3 and 4).

Figure 6 (plate 3) depicts the formation of a smooth sweep just ahead of a wall-dye-indicated burst. Several moderately strong shear zones can be seen near the sweep, and the bubble lines appear to indicate that a transverse vortex is beginning to form just ahead of the bursting fluid. However, the only precise flow structure one can find to really link the two events is that due to the requirements of continuity. As mentioned earlier, the arrival of outer fluid at the wall just downstream of a burst is consistent with continuity, particularly if the normal velocity component of the bursting fluid is large.

Figure 7 shows the development of a sawtooth-shaped sweep. In figure 7 (*a*) the sweep is beginning to grow directly on top of the head of a burst (i.e. at the same x station, but farther away from the wall than the forwardmost part of the lifted wall dye). Even though the sweep appears to have been created, or at least triggered, by the burst, it is still a motion that is mainly influenced by its present location at about $y^+ = 100$. Therefore, it travels with a velocity which approximates the mean velocity at $y^+ \simeq 100$, whereas the burst's velocity is still strongly influenced by its origin near the wall. As a result, the sweep gets ahead of the burst before arriving at the wall (figure 7*b*).

In figures 6 and 7 (*b*) one can see that the sweep has become involved with a vortical motion which extends from a location at, or close to, the wall out into the logarithmic region. These circulatory motions are typical of what one sees during interactions between wall-dye-indicated bursts and outer-dye-indicated sweeps. Generally they can be classified either as transverse vortices or as upward-tilted streamwise vortices. It was shown in § 3.1.3 that these same descriptions characterize the bubble pictures observed during the formation and growth of sweeps which are seen upstream of subsequent bursts.

Since both the dye-filament and the bubble-line patterns described here are so similar to those seen prior to, and upstream of, wall-dye lift-ups, it seems reasonable to postulate that *the interaction between bursts and the flow in the logarithmic region produces sweeps which, in turn, influence the generation of bursts farther downstream*. This, in turn, implies that the inward-moving disturbance, which is responsible for the start of the bursting process, does not originate in a bulge in the superlayer. (However, we have not excluded a possibility that the bulge and the disturbance may both be parts of the same vortex-like structure.)

The conclusion that sweeps originate in the inner zones of the boundary layer agrees with the results of Corino & Brodkey (1969), who found that the correlated turbulent motions, or 'eddies', are created in what they termed the 'generation region' ($5 \leqslant y^+ \leqslant 70$) and then diffuse out into the relatively stable 'core region'. Rao, Narasimha & Badri Narayanan (1971) have also suggested that "the origin of the bursting phenomenon cannot be traced directly... to the outer interface".

The quantitative analysis of the movies which led to the above conclusions revealed that, during a 1 min period, 30 sweeps and seven bursts were counted. Most of the burst events were either multiple ejections or displayed large, low-frequency oscillations in the normal velocity. Each initial lift-up, each subsequent ejection and each outward-moving part of such low-frequency oscillations was found to be associated with the development of a sweep. In fact, only five of the sweeps could not be traced to bursting fluid; that is, 83 % of the sweeps seemed to be caused by the interaction of (i) fluid which had been ejected from the wall region with (ii) the turbulent motions in the logarithmic region.† The hypothesis of a close relationship between bursts and subsequent sweeps is strengthened by the observation that three weak bursts (small volume of fluid involved and low velocity away from the wall) were seen and all three were

† The 17 % not traceable to bursts should not be used, in our opinion, to indicate a lack of connexion, but suggests only the incompleteness of the techniques used. We consider 83 % identification remarkably high.

associated with weak sweeps (small disturbance amplitude and low velocity component towards the wall). In 18 cases one ejection appeared to be the cause of one sweep, in five cases double ejections were associated with a single sweep, and in one situation a single lift-up seemed to create two sweeps close to each other.

4. Comparison between visual observations and standard velocity measurements

Numerous investigators have deduced hypotheses about the nature of the flow structure from one of two types of data: measurements made with velocity probes, or visualization studies. These two sources of information have not always yielded the same results, and the character of these differences suggests that structural features of a turbulent flow such as bursts and sweeps are described better by their spatial characteristics than by their temporal ones. In this section we shall present the arguments that have led us to this suggestion.

A probe, which is an instrument fixed in space, generates a temporal record of the velocities of successive elements of fluid that pass over it. This device can signal the passage of organized fluid motion only if the motion consists of elements which move in a related manner as each in turn passes over the probe. To be detectable, the relationship between the motion of any two of these elements must not only be unique, but it must also be distinguishable from the background turbulence. An example of such a patch of fluid whose elements all move in a related and distinct manner as they pass any given point is the irrotational fluid in the intermittent outer region of a turbulent boundary layer.

In contrast, however, the flow within a wholly turbulent region does not seem to contain sets of fluid elements which move in a coherent manner. Consider, for example, the passage of a succession of streamwise vortices past a probe located near the wall in a turbulent boundary layer. The velocity of the vortex measured by the probe is influenced by the following three characteristics of such vortices: (i) each successive vortex has a different diameter, angular velocity and orientation; (ii) the velocity perturbations (in the directions of the Cartesian co-ordinates) due to the angular rotation of the fluid are of the same order of magnitude as those of the background turbulence; and (iii) the overall streamwise motion of each vortex is influenced by large-scale fluctuations which vary with time.† Although the velocities in different parts of the vortex will bear some relationship to each other owing to the common vorticity, any such resemblance between the velocity of the section of the vortex which first passes the probe and that which passes later is usually small relative to the other fluctuations and, hence, of little use in a vortex detection scheme.

The flow visualization techniques, on the other hand, present a series of views of the fluid motions over a finite region. This is particularly true of hydrogen-bubble time-lines, which yield a two-dimensional picture, but it is also a valid statement for dye filaments, because they do show some spatial characteristics of the flow. Therefore, events are detectable by visualization techniques when the

† The steady velocity component due to convection by the mean flow can be neglected in this discussion.

fluid motions at one location bear some relationship to those at several other locations (which have not been arbitrarily preselected by the use of fixed probes), and only such situations have been described and given names.

For example, any one of the previously mentioned streamwise vortices becomes visible using time-lines for two reasons: (i) similar vortical motion exists along a curved line in space at a given instant of time; and (ii) the relationship between the motion at one location on this line and the motion at another location on the same line does not change radically during the lifetime of the vortex. The primary effect of the large-scale motions is to move the whole vortex. However, since this 'sloshing motion' does not destroy the vortical appearance of the motion, the large fluctuations do not interfere with the interpretation of the visual data as they do in the case of fixed-point velocity measurements. Similarly, the principal (short-term) effect of the small-scale motions is to contort the curved vortex line. Again the rotational image of the flow is not masked by these small fluctuations, whereas they reduce significantly any velocity correlation which could be measured by a fixed probe owing to the passage of a vortex. Thus, since the vortical appearance of the motion remains vortical irrespective of angular velocity, diameter or orientation, the shapes of the time-lines are similar for different streamwise vortices and remain distinguishable from the background turbulence.

These differences between the fixed probe and the optical techniques may explain why it has been so difficult to detect the visual phenomenon called a 'burst' from single (or even two) probe velocity records. But, more important, the differences suggest that while *bursts and vortices can be characterized by their spatial uniqueness, they may not be characterizable by a temporal record at one or two points.*†

This distinction between 'spatial coherence' and 'temporal coherence' can be further clarified by considering, as an example, a rigid stick in the flow. Assume that the centroid of the stick moves with a random linear velocity and also that the stick is subjected to a random rotation about its centroid. Let the stick move in a turbulent medium of equal density, opacity, etc., such that a velocity probe does not indicate the presence of the stick solely as a result of any material differences. Under these conditions, an observer will not be able to detect the passage of the stick past a single reference point by measurements which are made only at that point. The velocity at any point on the stick at any time is indistinguishable from the velocity of the surrounding medium. Nevertheless, the stick retains its identity in space and represents a coherent structure within the turbulent fluid motion.

Yet another factor differentiates the interpretations based on visual observations from those based on fixed-point measurements. The eye has a natural tendency to follow a recognizable pattern, when it finds one, and to watch it

† This may not apply to the low-speed streaks near the wall. Owing to their long spatial coherence, their repeatable flow direction parallel to the wall before they lift up and their limited response to the higher frequency and larger amplitude motions which are present in the outer flow, the fluid motion past a fixed point due to a low-speed streak should be noticeably slower than the mean velocity at that location for a detectable amount of time. This was, in fact, observed by Schraub & Kline (1965) and Kim *et al.* (1968).

evolve. For example, if the stick in the paragraph above were coloured red, the eye could easily find and follow it in a low-speed flow. Previous investigators (e.g. Corino & Brodkey 1969; Kim *et al.* 1971) described bursts and inward-moving sweeps, in part, from a frame of reference which followed these motions; i.e. their eyes moved with the structure studied. Such a method of analysis, unlike a fixed-point measurement, emphasizes those characteristics of the phenomenon which are based on its spatial coherence.

5. Summary

The following is a summary of the burst cycle and its relationships with the outer flow as deduced from simultaneous dye streaklines, bubble time-lines, and dye injected through a wall slot. The outline of the cycle will begin with the description of the motions observed in the outer flow.

The logarithmic region alternates between periods of relative quiescence, when adjacent bubble lines remain parallel, and periods of significant turbulence, when bubble lines become quite contorted. During the quiescent periods, the outer dye flows in a nearly straight line parallel to the wall, but, during the non-quiescent times, the dye filament deviates from this straight-line pattern. At first these deviations take the form of either a sinusoid, a (three-sided) parallellogram or a sawtooth. However, smaller perturbations subsequently alter the dye patterns, making them evolve into unrecognizable shapes.

Many of these disturbances have a significant velocity component towards the wall. Such a wall-ward moving perturbation is observed in nearly every case just prior to the appearance of oscillatory motions in the wall dye. Furthermore, the oscillations at the wall are first seen downstream of the outer disturbance. The wall-dye disturbances grow slowly and eventually lift up, as documented by previous investigators (Runstadler *et al.* 1963; Schraub *et al.* 1965; Kim *et al.* 1971). At the same time the hydrogen bubbles show that the velocity field becomes perturbed in the region directly above the oscillating wall dye. The disturbances in this zone generally look like patterns one would expect in the presence of vortices, and these seem to dominate the logarithmic region $20 \leqslant y^+ \leqslant 200$. During the end of the burst's oscillatory growth stage, the interaction between the bursting fluid and the motion in the logarithmic region causes the formation of another large vortex-like structure. This vortical system extends down to the proximity of the wall. It creates a large wall-ward moving disturbance in the outer dye flow, which, it is believed, is associated with another lift-up process farther downstream. Thus the complete sequence involves relations at several different places over a period of time.

If one focuses attention closer to the wall, one finds that the sequence of events which leads to a lift-up usually starts with oscillations in the wall dye. Simultaneously with, or shortly after, the appearance of these wall perturbations, a long, narrow, high-shear zone forms just above the region of wall-dye movement. Vortices form along the apparently unstable shear line. This process of high-shear-zone formation and subsequent vortex generation repeats itself a few times until lift-up occurs. Although the ejection is probably triggered by a wall-ward moving disturbance coming from the outer flow, the bursting fluid appears to be drawn away from the wall by one of these vortices.

Since individual bursts vary greatly in size (volume of fluid involved), velocity and duration, it appears that the only unifying concept is the temporary existence of a distinguishable pattern in space. The small portion of such a pattern that passes a single fixed point in space, such as a velocity probe, may not show any unique features. This would mean that a burst can be characterized by a spatial coherence, or uniqueness. However, further investigations are required to determine if the bursts have unique measurable temporal characteristics at one or a few points.

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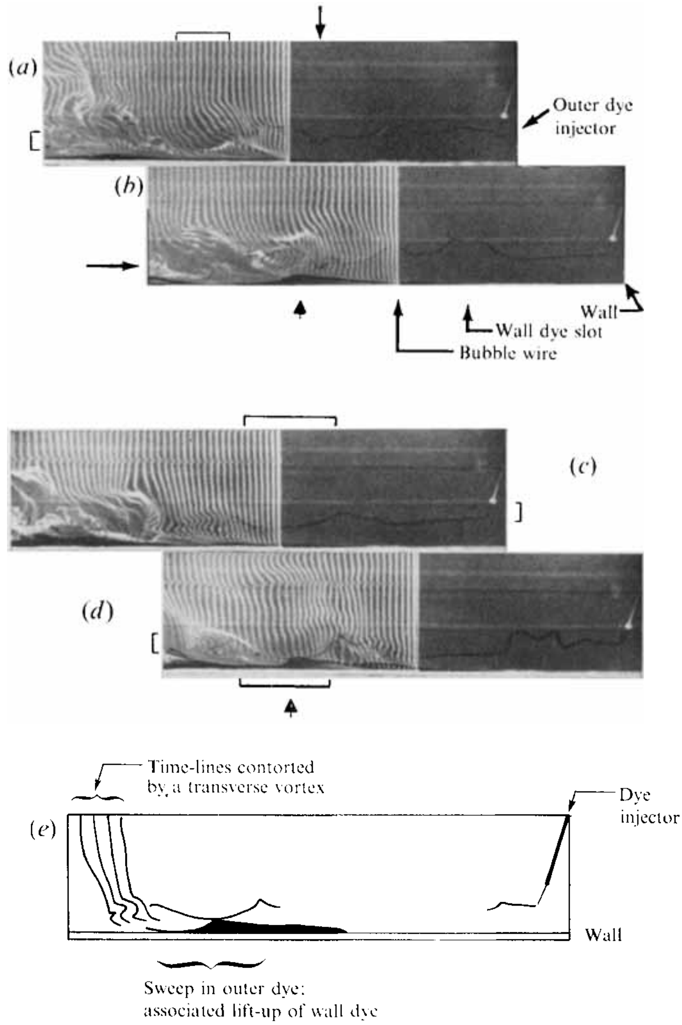

FIGURE 4. (*a*), (*b*) Photographic sequence of a ragged sweep and a subsequent lift-up. (*c*), (*d*) Photographic sequence of a smooth sweep and a subsequent lift-up. Flow is from right to left, and the pictures are displaced by the distance a particle with velocity U_∞ travels during the time interval $\Delta t = 1{\cdot}5$ s between views. Outer dye injector located at $y^+ \simeq 100$. (*e*) Sketch of the important structures in (*d*).

Figure	Reference	Symbol	Description
(*a*) (*b*)	p. 232 p. 232	←	Ragged sweep of outer dye (intersection of lines through pairs of arrows)
(*b*)	p. 232	▲	Subsequent lift-up of wall dye (dark area just above the wall, extending to the right, i.e. upstream, of the arrow below (*b*))
(*a*)	p. 233	⌐	Cleansing sweep of an earlier burst
(*c*) (*d*)	p. 232 p. 232	⊓	Smooth sweep of outer dye (see intersection of brackets)
(*d*)	p. 232	▲	Subsequent lift-up of wall dye (above, and to the right of, arrow)

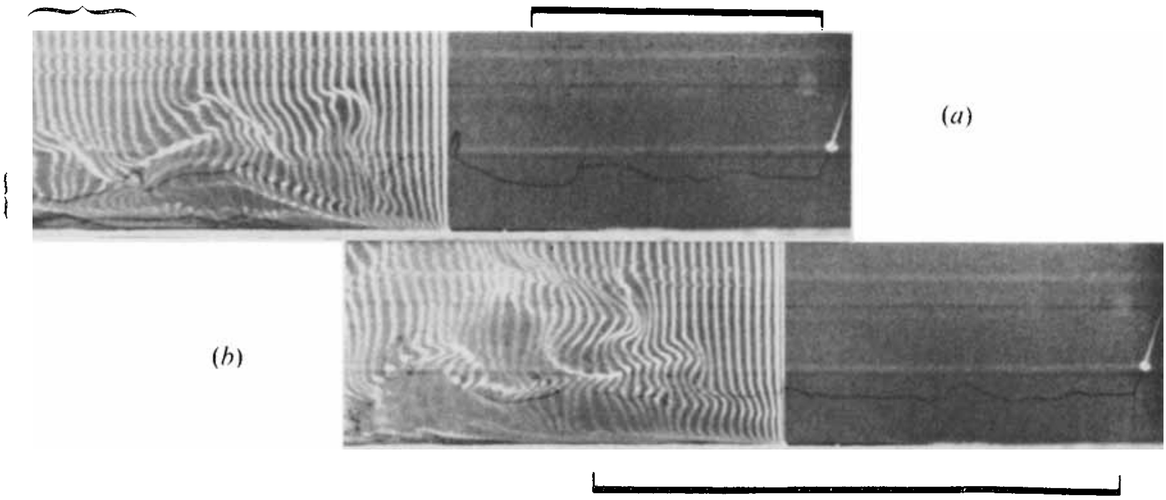

FIGURE 5. Photographic sequence showing absence of sweeps in the outer dye and consequent absence of a wall-dye-marked lift-up. Explanation is the same as for figures 4(*a*) and (*b*). Displacement of photographs is based on $\Delta t = 2{\cdot}5$ s.

Figure	Reference	Symbol	Description
(*a*), (*b*)	p. 232	┌──┐	Extent of region of no sweep in outer dye
(*a*)	p. 232	⏞	Sweep in outer dye associated with a previous burst

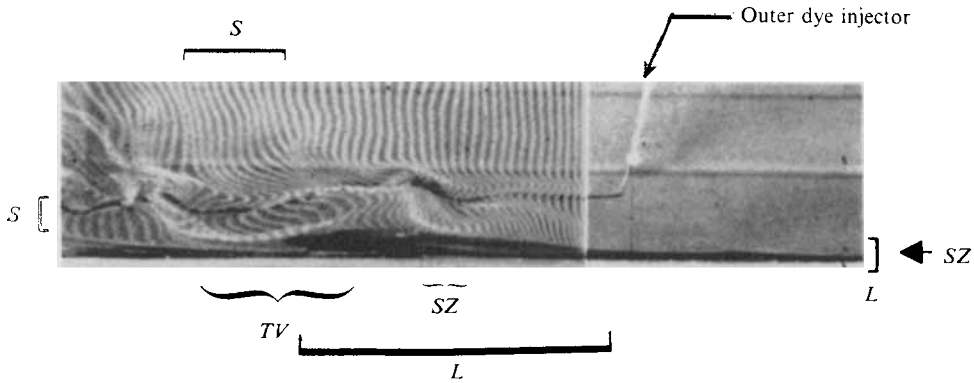

FIGURE 6. Photograph of burst and subsequent smooth sweep. View is similar to figures 4 and 5 except that the outer dye injector is located closer to the normal bubble wire.

Reference	Symbol	Description
p. 234	*L*	Lift-up of wall dye
p. 234	*S*	Smooth sweep of outer dye
p. 234	*SZ* ◄–*SZ*	High-shear zone above bursting wall dye (intersection of brace and arrow)
p. 235	*TV*	Transverse vortex and high-shear zone. Vortex bounded by outer dye sweep and wall; high-shear zone lies along lower edge of vortex

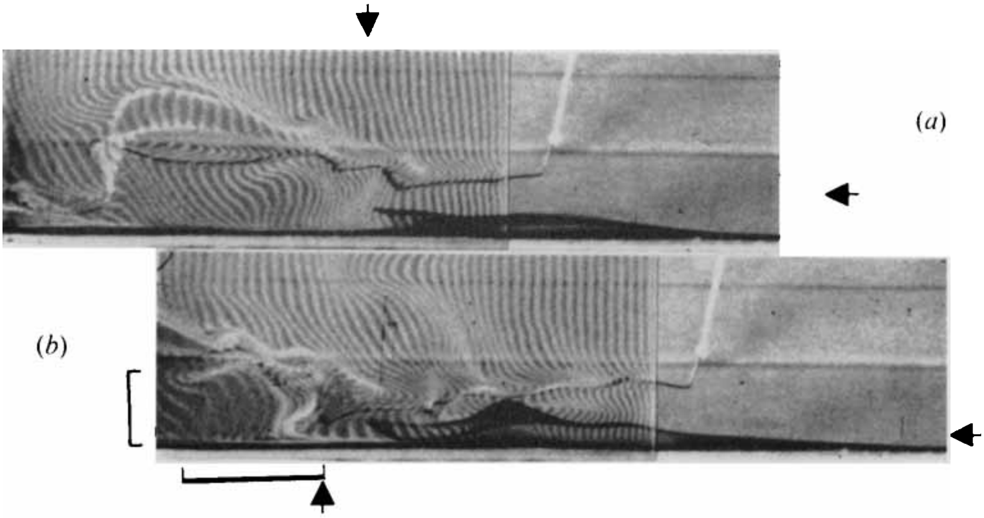

FIGURE 7. Photographic sequence of burst and subsequent sawtooth sweep. Explanation is the same as for figures 4–6. Displacement of photographs is based on $\Delta t = 1{\cdot}2$ s.

Figure	Reference	Symbol	Description
(*a*)	p. 235	◄–	Sawtooth sweep above head of wall-dye-marked lift-up
	p. 235	◄–	Same sawtooth sweep, now ahead of lift-up
(*b*)	p. 235	└──┘	Transverse vortex close to the wall and associated with the sweep