J. Fluid Mech. (1978), *vol.* 89, *part* 2, *pp.* 251–272
Printed in Great Britain

A stereoscopic visual study of coherent structures in turbulent shear flow

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(Received 13 September 1977 and in revised form 3 February 1978)

A visual study of a turbulent boundary-layer flow was conducted by photographing the motions of small tracer particles using a stereoscopic medium-speed camera system moving with the flow. In some experiments, dye injection at the leading edge of the flat plate helped to delineate the outer edge of the boundary layer. The technique allowed the three-dimensional aspects of the flow to be studied in some detail, and in particular allowed axial vortex motions in the wall region to be identified.

The flow was found to exhibit three characteristic regions which can be roughly divided into the wall and outer regions of the boundary layer and an irrotational region, unmarked by dye, outside the instantaneous edge of the boundary layer. Briefly, the outer region of the boundary layer was dominated by transverse vortex motions that formed as a result of an interaction between low-speed and high-speed (sweep) fluid elements in that region. The present results clearly show that bulges in the edge of the boundary layer are associated with transverse vortex motions. In addition, the transverse vortex motions appear to induce massive inflows of fluid from the irrotational region deep into the outer region of the boundary layer. The outer edge of the boundary layer thus becomes further contorted, contributing to the intermittency of the region. Furthermore, the outer-region motions give rise to the conditions necessary for the dominant wall-region activity of ejections and axial vortex motions. It is not the energetic wall-region ejections that move to the outer region and give rise to the contorted edge of the boundary layer as has been suggested by others.

The wall-region axial vortex motions were intense and lasted for a time short compared with the lifetime of outer-region transverse vortex motions. The present results strongly suggest that wall-region vortex motions are a result of interaction between the incoming higher-speed fluid from the outer region of the boundary layer and the outflowing low-speed wall-region fluid. This is in direct contrast to all models that suggest that axial vortex pairs in the wall region are the factor that gives rise to the outflow of low-speed fluid trapped between.

Although all the elements necessary to make up a horseshoe vortex structure riding along the wall were present, such a composite was not observed. However, this could be visualized as a possible model to represent the ensemble average of the flow.

Finally, the massive inflows from the irrotational region were observed to precede the appearance of low- and high-speed fluid elements in the boundary layer, thus completing the deterministic cycle of individual coherent events.

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1. Introduction

The development of a structural approach to turbulence research in the recent past has been rapid and dramatic. The advances have led to the evolution of a crude mechanistic picture of turbulent shear flow which consists of a deterministic sequence of events occurring randomly in space and time. Both visual studies and anemometry studies have contributed to the development; the visual studies have provided the skeletal structure and the anemometry studies have added the muscle to the structural picture. But there is still disagreement among investigators as to the exact physical picture and interrelationship of the various coherent structures that have been observed. The importance of the three-dimensional aspects of turbulence, at least in shear flows, is generally recognized, but the visual studies to date have been two-dimensional views. The lack of a complete picture of the coherent structures, in three dimensions, may very well be the cause of the different interpretations of the structural features of turbulence.

Stereoscopic photography, suggested by Praturi (1972), was selected as the visualization technique to obtain a three-dimensional picture of the coherent structures occurring in all regions of a turbulent boundary layer. The purpose of the present study was to clarify the nature of such structures and to find the interrelationships between them (Praturi 1975; Praturi, Hershey & Brodkey 1975).

At this stage in the development of the field, it seems pointless to offer an extensive review so the reader is referred to the recent review articles by Davies & Yule (1975), Laufer (1975) and Willmarth (1975). We shall of course cite below various articles in the literature where appropriate, especially where comparisons can be made. However, so as not to offend the many workers in the field, we should mention at the start the excellent work on visual studies by Kline *et al.* (1967), Corino & Brodkey (1969), Clark & Markland (1970, 1971), Kim, Kline & Reynolds (1971), Grass (1971), Nychas, Hershey & Brodkey (1973), Offen & Kline (1974) and Falco (1974), as well as the extensive anemometry measurements made in the wall region by Rao, Narasimha & Badri Narayanan (1971), Gupta, Laufer & Kaplan (1971), Wallace, Eckelmann & Brodkey (1972), Willmarth & Lu (1972), Lu & Willmarth (1973), Eckelmann (1974), Brodkey, Wallace & Eckelmann (1974), Blackwelder & Kaplan (1976) and Wallace & Brodkey (1977). We also mention the work on the outer region by Fiedler & Head (1966), Kaplan & Laufer (1969), Kibens & Kovasznay (1969), Kovasznay, Kibens & Blackwelder (1970), Blackwelder & Kovasznay (1972), Antonia (1972), Hedley & Keffer (1974) and Sabot & Comte-Bellot (1976).

In the foregoing articles, the association of turbulent activity in the wall region of the boundary layer with the bursting phenomenon has been fairly well established. What remains ambiguous is the detailed description of the bursting phenomenon. While the existence of a decelerated fluid region, and associated local instability, ejection of fluid elements from the decelerated region and the higher-speed sweep event gained support, the existence and role of streamwise vortices in the wall region suggested by the hydrogen-bubble visual studies remained unclear. It is quite possible that these streamwise vortices were not observed by Corino & Brodkey (1969) and Nychas *et al.* (1973) owing to the two-dimensional limitation of their experimental technique. The ejections observed by these authors may be a part of the streamwise vortices. A three-dimensional visual study of the wall region should be able to resolve this ambiguity. Most of the studies agreed on a value of about $100z^+$ units for the mean spanwise streak spacing and that the mean bursting period scales with the outer-flow variables u_0 and δ. Despite different burst detection schemes, the association of the production of Reynolds stress with coherent events in the wall region is reasonably well established. What needs to be established, therefore, is the presence of vortex-like structures (streamwise vortices, hairpin vortices, etc.) in the wall region and how they relate to other coherent events (ejections, sweeps, decelerated flow, etc.).

The outstanding features of the outer region of the boundary layer are transverse vortices and interfacial bulges. The transverse vortices found by Nychas *et al.* (1973) were suggested to be the same as the interfacial bulges reported by Kaplan & Laufer (1969), Kovasznay *et al.* (1970), Blackwelder & Kovasznay (1972) and Sabot & Comte-Bellot (1976). Both events have a striking similarity in character and in their association with the wall-region bursting phenomena. Both events occur randomly in space and time and have a rotational motion with transverse vorticity. They also seem to have the same convection characteristics. While the transverse vortices were studied in relation to wall-region activity, the interfacial bulges were studied in relation to both the wall-region bursts and the irrotational flow outside the boundary layer.

There seems to be a definite cause-and-effect relationship between the outer-region events and the inner-region bursting phenomena (see Nychas *et al.* 1973; Offen & Kline 1974). The prevailing view of this relationship is described in both directions by various authors. This, no doubt, is due to the lack of a complete picture of the events in the entire boundary layer. In trying to make a composite model from the available fragmentary information, the opinions of authors polarized into two opposing views of the connexions between the outer- and inner-region events. To form a cyclical relation between the events in the two regions of the boundary layer, the authors of various investigations have postulated eddies, pressure-field effects, instabilities, etc. What is the real case remains to be determined.

Once again, it is hoped that the present qualitative three-dimensional visual observations of the entire boundary layer will provide further insight into the mechanistic picture and may help to remove some of the conflicts and confusion.

2. The experimental programme

Stereoscopic photography was used to record the three-dimensional motions of fluid elements along a flat-plate turbulent boundary-layer flow. Small solid particles were suspended in the flow to trace the fluid motions and a medium-speed camera with a stereoscopic lens was used to photograph the particle motions. Dye injection at the leading edge of the flat plate in front of the trips in some of the movies helped delineate the outer edge of the boundary layer. This marking was suggested to us by Peter Bradshaw; without the dye, one could not tell where the instantaneous edge of the boundary layer was located since there were small particles both inside and outside the boundary layer. The equipment and the basic principle were essentially the same as those used by Nychas *et al.* (1973). A completely new photo-optical system was developed and the flow loop was modified to accomplish stereoscopic photography of the flow. The details of the experimental facility used in the current study were reported by Praturi *et al.* (1975) and Praturi (1975).

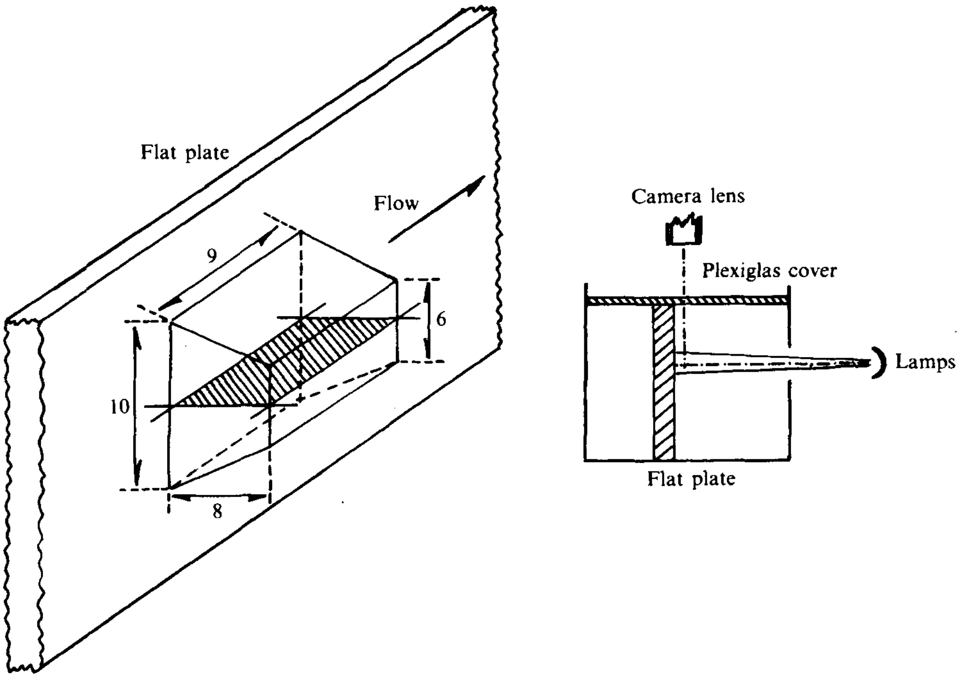

FIGURE 1. Field of view and camera viewpoint, dimensions in centimetres.

Briefly, water was used as the flow medium with Pliolite† particles in the size range 62–74 μm as tracer particles. The flat-plate boundary layer was tripped by a saw-tooth trip. A model HS-16C Benson–Lehner camera was used with a Bolex stereo lens to record the particle motions. Kodak No. 7278 Reversal film was used at a filming speed of 66 frames/s. The focal length of the stereo lens is 12·5 mm, the maximum aperture being 2·8. The close-up turret on the stereo lens allowed photography at a focusing distance of 2 ft. The field of view obtained with the photo-optical system and the camera viewpoint are shown in figure 1. The dimensions of the flow field correspond to about $950x^+$ units in the streamwise direction, 850 y^+ units in the transverse direction and $1000z^+$ units in the spanwise direction. A complete discussion of the merits and possible limitations of the visual technique of using small tracer particles with dark-field illumination can be found in Corino (1965), Corino & Brodkey (1969), Brodkey, Hershey & Corino (1971) and Nychas (1972).

To follow the development of flow events along the boundary layer, the photo-optical system was convected with the flow as was done in our previous visual studies. The convection speed used for most of the films was matched to the average velocity at $y^+ \simeq 60$, which was about 70 % of the free-stream velocity u_0. Some films matching 100 % of the free-stream velocity and one with no motion at all were also taken. Of particular interest in this work were axial vortex motions in the wall region. Some preliminary movies indicated that the wall region extended out to about $100y^+$ units; thus, after several trials, the cited matching speed at $y^+ \simeq 60$ was selected. This was arbitrary. The Reynolds number Re_θ was about 900 and the friction velocity was

† Commercial name of polyvinyl toluene butadiene, made by Goodyear Chemicals, Akron, Ohio.

estimated to be 0·8 cm/s. The Reynolds number is relatively low and the general pattern to be described is no doubt somewhat changed at higher Reynolds numbers (Falco 1974, 1977). The conditions were the same as those used by Nychas *et al.* (1973).

3. The experimental results

The stereoscopic system developed in the present study was used to produce 150 stereoscopic films of a turbulent boundary-layer flow over a flat plate. Each run involved one traverse of the camera along the length of the plate. In 38 of these runs, a violet dye solution was injected at the leading edge in front of the trips. These films will hereafter be referred to as dye–particle films. One run was made of the flow with the camera held stationary (Eulerian view). As the stereo films cannot be satisfactorily reproduced in three dimensions, the flow phenomena are presented in the form of simple sketches and descriptions. The structure of the flow can be seen in the movies with some effort and is not the easiest thing to describe. The main advantage of the stereoscopic viewing was to allow axial vortex motions to be identified; this could not be done satisfactorily in our previous two-dimensional movies, which provided essentially an x, y view. Unfortunately special projection equipment, a special screen and special glasses are needed for stereoscopic viewing. The movies can be viewed as a side-by-side stereo pair with ordinary projection systems. Thus for the interested reader a short film has been prepared to show the equipment and a representative selection of the films.† A sample stereo pair is included as figure 2 (plate 1). The visual analysis of the stereo movies consisted of observing the individual events, identifying the events in a number of runs and making a thorough study of each of the events and their relationships with other events.

3.1. *Nature of the flow field*

Nychas (1972), who used the same flow system, described the flow regime as a turbulent boundary layer with an average thickness of approximately 420 y^+ units (4 cm). A visual examination of the dye–particle films confirmed this description. The boundary-layer thickness, as determined by the average width of the dark region in these films, averaged about 450 y^+ units. Analysis of the stereo films revealed the existence of three characteristic regions: the wall region ($0 < y^+ < 100$), the outer region of the boundary layer ($100 < y^+ < 450$) and an irrotational region ($450 < y^+$) beyond the instantaneous edge of the boundary layer. The boundaries of these regions are approximate and there is an overlap. The edge of the boundary layer was determined by observing the dye–particle films. The irrotational region is the flow not marked by the dye and thus includes regions that penetrate deeply towards the wall.

3.2. *Co-ordinates and vortex nomenclature*

To make clear to the reader the co-ordinate system and the terminology used to describe the events, the convention used to describe vortices (and circulations) is

† Request *A Stereoscopic Visual Study of a Turbulent Boundary Layer* from the Department of Photography, 148 West 19th Avenue, Columbus, Ohio 43210. There is a $15.00 service fee for loan use to cover mailing and replacement.

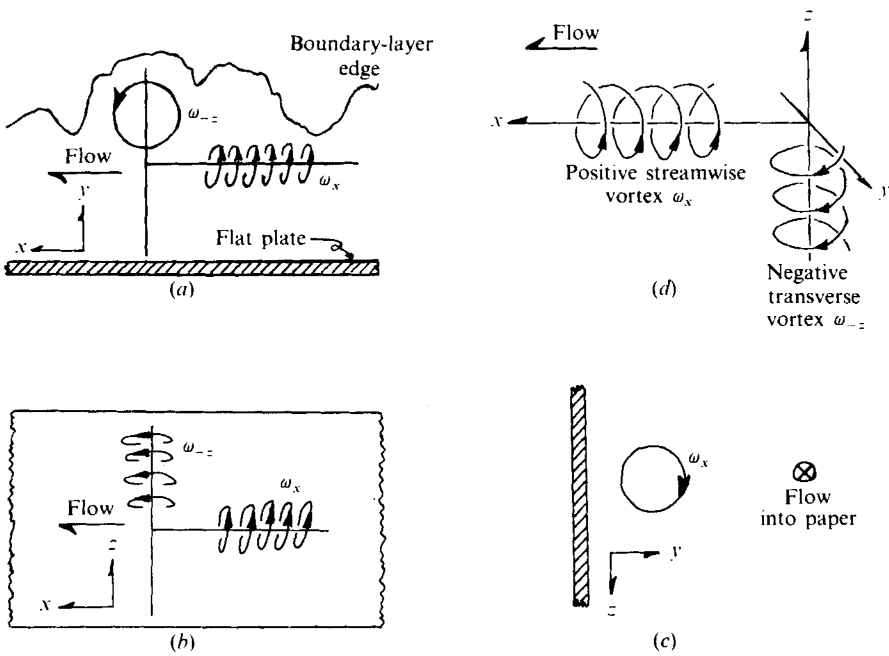

FIGURE 3. Co-ordinate system to define vortex motions. (*a*) Side view. (*b*) Top view. (*c*) End view. (*d*) Three-dimensional view.

shown in figure 3. The $+x$ co-ordinate is parallel to the flat plate and in the direction of flow. The $+y$ co-ordinate is perpendicular to the plate and away from it. The $+z$ co-ordinate for our vertically oriented plate is parallel to the plate and down from the top (right-hand rule). The streamwise vortex ω_x shown in the figure has its axis of rotation parallel to the x co-ordinate. If the sense of circulation is away from the plate on the top of the vortex, it is called a positive streamwise vortex and denoted as ω_x, i.e. the advance of a right-hand screw would be in the $+x$ direction. This can best be seen in the end view, but is shown in all views. The axial-oriented vortices are also being carried forward by the flow relative to the plate, so that the individual particles making up the vortex appear to have helical paths. The vorticity of a transverse vortex has only a z component and the circulation in a negative vortex ω_{-z} appears (top view) as a counter-clockwise rotation from the camera viewpoint. This negative transverse vortex corresponds to that commonly observed by Nychas *et al.* (1973) and called by them a forward transverse vortex. A streamwise vortex with a small vorticity component in the z direction will be denoted as $\omega_{x,z}$. Similarly, a streamwise vortex $\omega_{x,y,z}$ will have small vorticity components in the y and z directions. If a vortex has significant vorticity components in more than one co-ordinate, it will be called a tilted vortex and will be denoted as ω_{x-z}, no comma being used, i.e. ω_{x-z} is a tilted vortex with an axis pointing about equally downstream $(+x)$ and up from the bottom $(-z)$. The axis of rotation of this vortex is, of course, in the x, z plane, parallel to the flat plate, and the particles in such a vortex can and often do have helical paths.

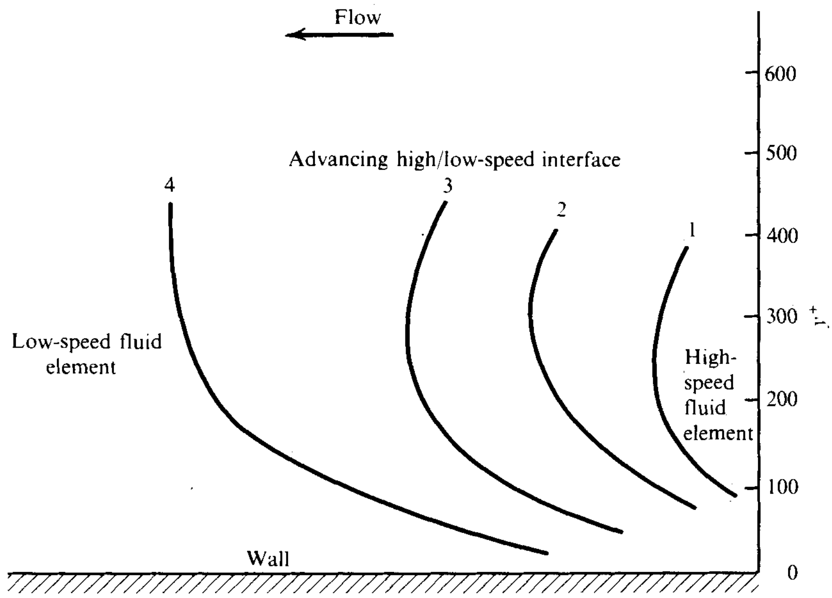

FIGURE 4. High- and low-speed fluid elements.

3.3. *Decelerated and high-speed fluid elements*

The decelerated and high-speed fluid elements of the boundary layer observed in the present study were very similar to those described by Nychas *et al.* (1973). The decelerated fluid had a quiescent, laminar-like structure. Except very close to the wall, the low-speed flow appeared to be a plug flow across the entire boundary layer. In the films, deceleration of the flow could be detected only after the appearance of a high-speed front. The tracer particles in the decelerated fluid slowed down, but it was the cumulative effect of the slowed-down particles in the low-speed fluid and the advancing high-speed fluid front that helped to establish the two elements. The demarcation line between the high- and low-speed fluid elements was much sharper in the wall region than in the outer region. The high-speed front entered the field of view at about $y^+ = 200$ and gradually expanded and replaced the decelerated fluid. However, there was always a narrow region between the flat plate and the high-speed fluid which contained low-speed fluid. The appearance of the high-speed front and its gradual progression are depicted in figure 4. The particle paths in the high-speed fluid were linear and mostly directed towards the wall at a small angle. The numbers marking the fronts show the order in time.

3.4. *Inflows and outflows*

The inflows and outflows observed were associated with the irrotational region of the flow, which is not marked by the dye. Rotational motions were absent in this region and only motions of a more linear type were observed. During the quiescent stages of the flow (non-active periods in the boundary layer), the irrotational region resembled a potential flow riding over a wavy surface (the turbulent/non-turbulent interface as marked by the dye).

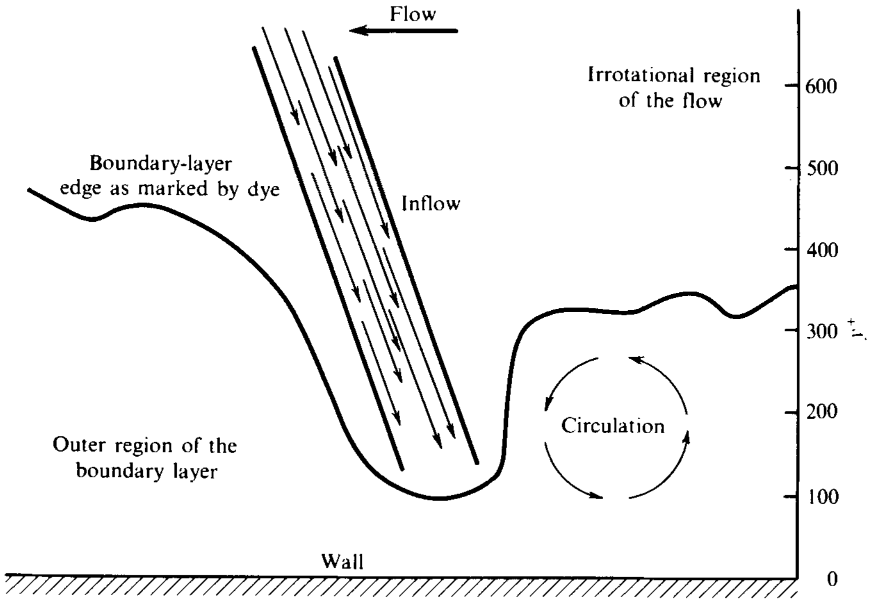

FIGURE 5. Inflow from the irrotational region.

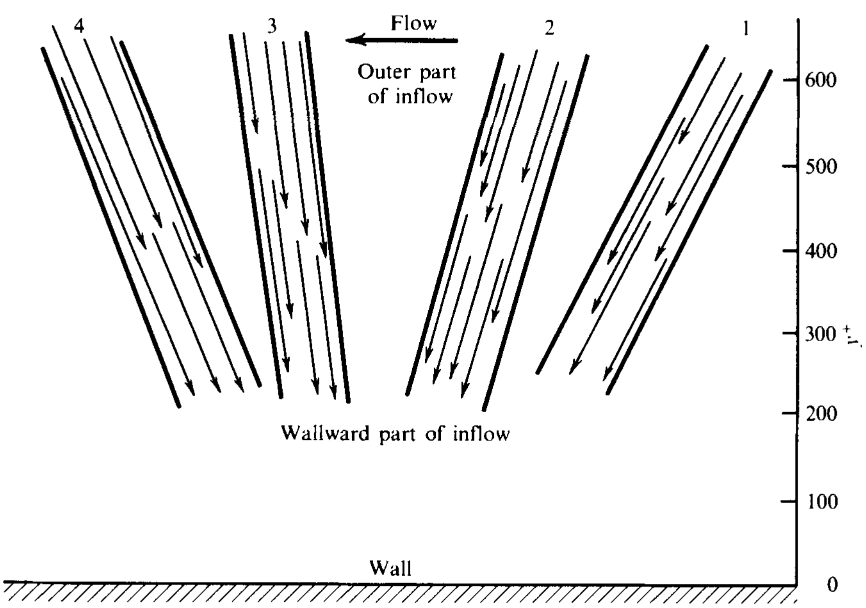

FIGURE 6. Progression of an inflow.

The main coherent events in the irrotational region were massive inflows. These events occurred just before and during periods of intense turbulent activity in the boundary layer. They modified the shape of the turbulent/non-turbulent interface as marked by the dye as shown in figure 5, an example of a typical inflow. This is a view observed in the convected co-ordinate frame. The lateral (y) extent of such inflows was from 300 to $700\,y^+$ units. The streamwise (x) extent was from 100 to $300\,x^+$ units.

When first observed (see figure 6) an inflow was typically directed towards the wall, its wallward part being ahead of its outer part. As it was convected in the flow, it penetrated and pushed the turbulent/non-turbulent interface towards the wall. Thus the outer edge of the boundary layer was further contorted, increasing the intermittency of the region. The wallward part of the inflow slowed down and assumed the final position shown in figure 5 before disappearing from view. Figure 6 gives the states of development of the inflow as it moved downstream relative to the convected camera. As shown in figure 5, a vortex-like circulatory motion (about 200 y^+ units in diameter) was observed in the dyed outer region of the boundary layer immediately behind the inflow. Typically, an inflow was observed at almost the same time as a high-speed fluid element was observed in the outer region of the boundary layer. The appearance of this typical inflow was usually followed by the formation of a transverse vortex ω_{-z} on the high-speed front. The inflow occurred slightly ahead of the high-speed front. It is difficult to say which came first, but it did appear that the inflow initiated the shear field necessary for the formation of the negative transverse vortices ω_{-z}.

Apart from the typical inflow, other types of inflow were also observed and may be described as variations of the typical one. They are described in detail by Praturi (1975) and since they were less often observed will not be described here except to say that one of them looks very much like what Nychas *et al.* (1973) describe as a high-speed fluid element directed towards the wall which gives rise to both a forward (ω_{-z}) and a reverse (ω_z) transverse vortex.

The outflows occurred in conjunction with inflows and appeared to be the reaction to the inflow event required to satisfy local continuity in the region. The outflows were less coherent and smaller in magnitude and frequency in comparison with the inflows. The results from the dye–particle films indicated that the outflows always originated in the outer region of the boundary layer while the entire inflow events consisted of fluid from the irrotational region. As described by Praturi (1975), one outflow was also observed that was not a reaction to an inflow but an outflow from the outer region.

3.5. *Vortices in the outer region of the boundary layer*

The most significant feature of the outer region of the boundary layer is the formation and convection of transverse vortices ω_{-z}. Other motions, observed more rarely, were streamwise (ω_{-x}) and tilted (ω_{x-z}) vortices. As mentioned previously, the vortices were formed at the high-speed front that existed between low- and high-speed fluid elements, usually after an inflow was observed. In the sequence of events, ejections from and vortical motions in the decelerated fluid in the wall region followed the appearance of vortices in the outer region.

The details of the outer-region transverse vortices observed in the present study were much the same as those given by Nychas *et al.* (1973). As they suggested, the transverse vortices were observed to be formed at a high-speed front, apparently owing to a Helmholtz-type instability. Both the low- and the high-speed fluid participated in the formation. Fluid from the inflow event itself did not become part of the vortex. The vortices were highly coherent and stayed in the picture until they disappeared from the field of view. They moved in the flow almost parallel to the flow and with about the same velocity as the mean flow. When they stayed in the picture

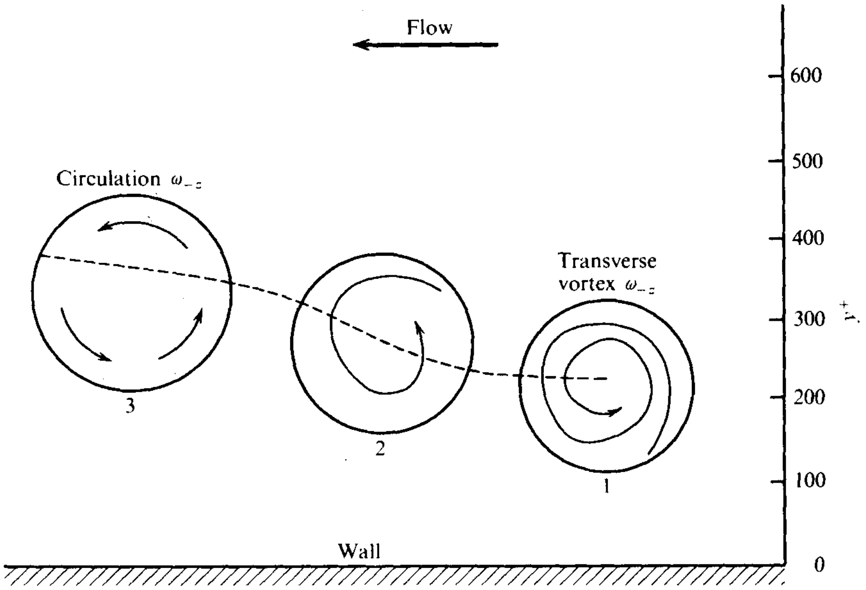

FIGURE 7. Enlarging and weakening of a transverse vortex.

long enough, they were observed to grow weaker and larger as they moved slightly away from the flat plate until they became gentle circulations as shown in figure 7.

The vast majority of the transverse vortices occurred between 100 y^+ and 300 y^+ with diameters ranging from 150 y^+ to 200 y^+ units. The vortices observed further from the plate had larger diameters and were weaker than those observed closer to the wall. A few vortices were seen as far away as 600 y^+ units from the plate. The largest diameter observed was 400 y^+. Although stereoscopic viewing enables one to observe the flow in three dimensions, one has the same limitations as those that occur for the eyes. One limitation is the difficulty in judging accurately distances in the direction of viewing compared with other directions, i.e. size is easy to judge in the x, z plane just as it is in a two-dimensional view, but is more difficult to judge when depth perception is involved. Thus we did not attempt to establish the z^+ extent of the vortices. Films of the x, z plane would allow an accurate estimate of the z^+ distance, but with our system we have not been able to obtain such films as yet. Stereoscopic viewing did allow rotation to be sensed, and this allowed us to establish the existence of the streamwise and tilted vortex systems. The various outer-region vortices did not seem to be connected, i.e. we did not see a combination of transverse, tilted and axial vortices forming a horseshoe-type vortex loop.

For a description of the rare events, streamwise and tilted vortices in the outer region of the boundary layer, the reader is referred to Praturi (1975).

3.6. *Ejections*

Ejections are rapid outward movements of fluid from the decelerated wall-region fluid and were observed after the appearance of transverse vortices on the high-speed front in the outer region of the boundary layer. They occurred immediately on the wallward side of the vortex or at a position slightly upstream. The ejections originated

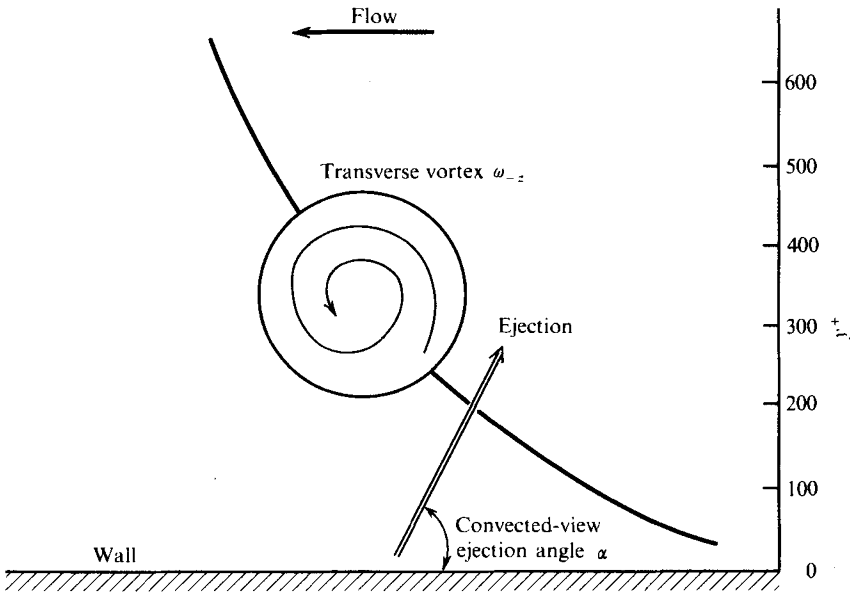

FIGURE 8. Typical ejection event.

at a y^+ of about 25† and travelled up to a y^+ of 100 or more. In some rare cases, they travelled up to $300\,y^+$. These ejections were small-scale straight-line motions. They moved at angles of 45–90° to the plate as observed in the convected frame. Figure 8 illustrates a typical event.

Most of the ejections, after reaching a distance of about $100\,y^+$, were swept away by the oncoming high-speed front. A few of the ejected particles were seen to be trapped in the transverse vortex in the outer region of the boundary layer. Some of the ejected particles, after moving to a y^+ distance of about 50, appeared to initiate vortical motions within the wall region.

3.7. *Vortical motions in the wall region*

The vortical motions in the wall region consisted of (i) motions of single particles around part of a circle, (ii) streamwise vortices with small components in other directions ($\omega_{-x,z,y}$) and (iii) transverse vortices ($\omega_{-z,x,y}$).

The circular motions observed were the path lines of single tracer particles, which did not make even one complete rotation. They occurred at random in space and time at all locations in the wall region. Such motions can be pictured as part of the background turbulence.

Streamwise vortex motions were observed in the decelerated wall-region fluid and some of these motions appeared to have been initiated by ejections. Those ejections which seemed to start the streamwise vortices had ejection angles α close to 90° (convected view). The vast majority of the streamwise vortices, however, were the result of an interaction between the high-speed flow and the narrow region of retarded fluid trapped between the high-speed element and the wall. These motions are shown in

† In this region, it is not possible to pinpoint events with the present overall system because of the large scale of the region being photographed.

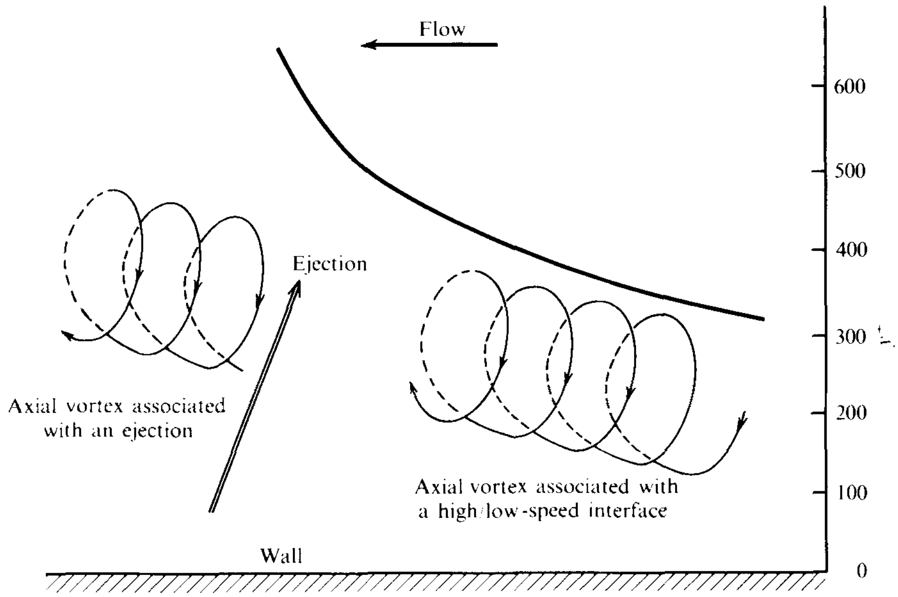

FIGURE 9. Streamwise or axial vortices in the wall region.

figure 9. The solid lines represent the top (towards the viewer or camera) and the dashed lines the bottom (away from the viewer) of the vortices. Surprisingly, they are all negative with the convention used (ω_{-x}). This is a second limitation or artifact of stereoscopic viewing, i.e. it is difficult to sense what is the direction of rotation of a streamwise vortex when looking at it along its axial length. This limitation is also associated with depth perception in that it is difficult to tell if it is the top or bottom of the vortex which is moving out. The smaller the depth to be sensed, the more difficult the problem. The sense of rotation would be unequivocal if looked at in a y, z plane, perpendicular to the axis of rotation of the vortex. One would expect, of course, an approximately equal balance between ω_{-x} and ω_x. The streamwise vortices typically had a diameter of $50\,z^+$ units and length of $100\,x^+$ units. Their axes had slight y and z components. The small diameter of $50\,z^+$ units (small depth perception) is the reason for the difficulty in establishing the correct sense of rotation. There may well be vortical motions smaller than these and closer to the wall. The present large-scale view precluded any possibility of observing such small-scale motions.

Quite a few of the streamwise vortices in the wall region changed their axis of rotation while being convected in the flow. Most of them tended to become transverse vortices $\omega_{z,x,y}$ (see figure 10).

The transverse vortices observed in the wall region were similar in magnitude and were formed by the same factors, i.e. ejections and high-shear zones. These vortices $\omega_{-z,x}$ did not change their axes of rotation and remained as transverse vortices as long as they were in view.

The vortex structures in the wall region were more intense than the vortex structures in the outer region. They remained as a cohesive unit for a shorter time, rarely making more than three complete rotations about their axes.

The vortical motions in the wall region may also be classified as primary and

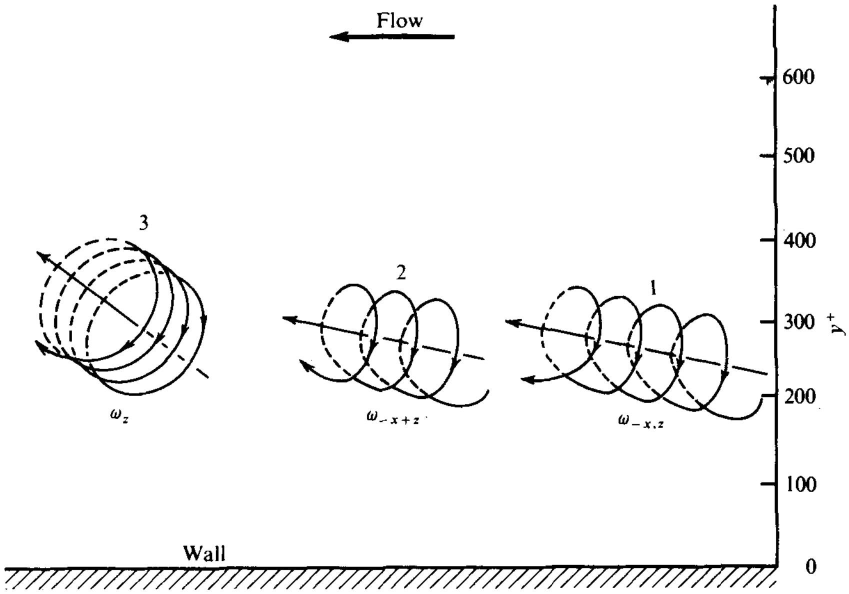

FIGURE 10. Streamwise or axial vortex in the wall region as it changes its axis of rotation.

secondary events. The ejections and the vortices associated with ejections are to be called primary wall-region events while other vortical motions (motions around part of a circle and vortices not associated with ejections) are called secondary events. The velocity gradient between the high- and low-speed fluid elements was smaller during the occurrence of secondary wall-region events than during the occurrence of primary events. The secondary vortex motions were less intense, or less cohesive. Another major difference between the two types of wall-region events was that the secondary events did not seem to be related to other observed events in the wall region.

In the visual observation of the stereo films, one has a feeling of actual vortex motion with these small-scale events even though one could rarely follow a given individual tracer particle making a complete rotation. What one saw was a number of particles taking part in what appeared to be vortex motions. Initially, therefore, there was some suspicion that the vortex motions observed in the wall region may be manifestations of the convected view of the camera. In the stereo films, the camera convection velocity matches the local mean velocity at $y^+ \simeq 60$. Stereo movies in which the camera convection speed matched the local mean velocity at $y^+ \simeq 400$ were analysed to check the existence of the vortical motions in the wall region and they were indeed observed in the same fashion. Vortex-like motions were observed in the run where the camera was held stationary. Individual tracer particles which were part of the vortex structure were observed to form a helical spiral in this Eulerian view. Thus the existence of real vortex motions in the wall region was established.

4. A phenomenological picture of the flow

A phenomenological model is proposed which attempts to explain the structural features observed in boundary-layer flows. The visual analysis of the stereoscopic films presented in the previous section is the basis of this model, but use has been made of our earlier work and that of others. At this point the flow picture will be presented without reference to other work but in the next section the model will be discussed in the context of other work. It has to be emphasized at the outset that sharp lines of demarcation do not exist between the different regions and events. The distinct features and motions of the events and regions permitted their characterization. The presence of free-stream turbulence causes variations in the size, orientation, speed and intensity of flow events. The basic character of the events, however, does not change. In fact, it is the basic character of the events that enables differentiation between them. Unless otherwise stated, the frame of reference used in the description is that of the camera moving with the flow (convected view). Thus motion in the outer region of the boundary layer and in the irrotational region will be convected past the viewer, while motion of the inner region will move at speeds below or slightly above that of the convected view (again, the convected view was matched at $y^+ \simeq 60$). Reverse fluid motions can be observed and are, in actuality, positive motions with speeds smaller than the convection speed of the camera.

The appearance of a high-speed front is chosen as the starting point of the phenomenological model. Downstream of the front, fluid in the low-speed element moves slower than fluid in the high-speed element. The low-speed fluid is characterized by a quiescent, laminar-like flow while the flow in the high-speed fluid is primarily axial with a small component towards the wall. The presence of the high-shear zone on the front between the high- and low-speed fluid elements leads to a Helmholtz-type instability and culminates in the formation of a transverse vortex in the outer region of the boundary as sketched in figure 11 (a) and in more detail in figure 4. In this and subsequent parts of figure 11 the location of the instantaneous boundary-layer edge is also sketched.

During the second stage of the cycle, the transverse vortex is convected in the flow and the wall region becomes active as characterized by ejections and vortical motions. Ejections appear to be a direct result of the transverse vortex in the outer region and not the other way around. Since the transverse vortex motions are a result of the high-speed front, it may be that ejections are really directly dependent on the high-speed front itself, i.e. ejections could be a consequence of low-speed fluid being trapped between fingers of high-speed fluid, thus being forced (by continuity) inwards, away from the wall. The ejections started in the region $5 < y^+ < 30$ and travelled to the region $y^+ \simeq 100$, where they interacted with the high-speed front. The stronger ejections penetrated the shear zone, entered the high-speed fluid and were carried away. In rare cases, strong ejections were observed to travel out as far as $y^+ \simeq 300$. However weaker ejections, especially those with an ejection angle of about 90° in the convected view, became part of the vortical motions at the high-speed front in the wall region. The vortical motions in the wall region (streamwise vortices $\omega_{-x, y, z}$ and transverse vortices $\omega_{-z, x}$) appear to be the result of the shear zone at the front between the wallward-moving high-speed fluid and the trapped, but outflowing, low-speed

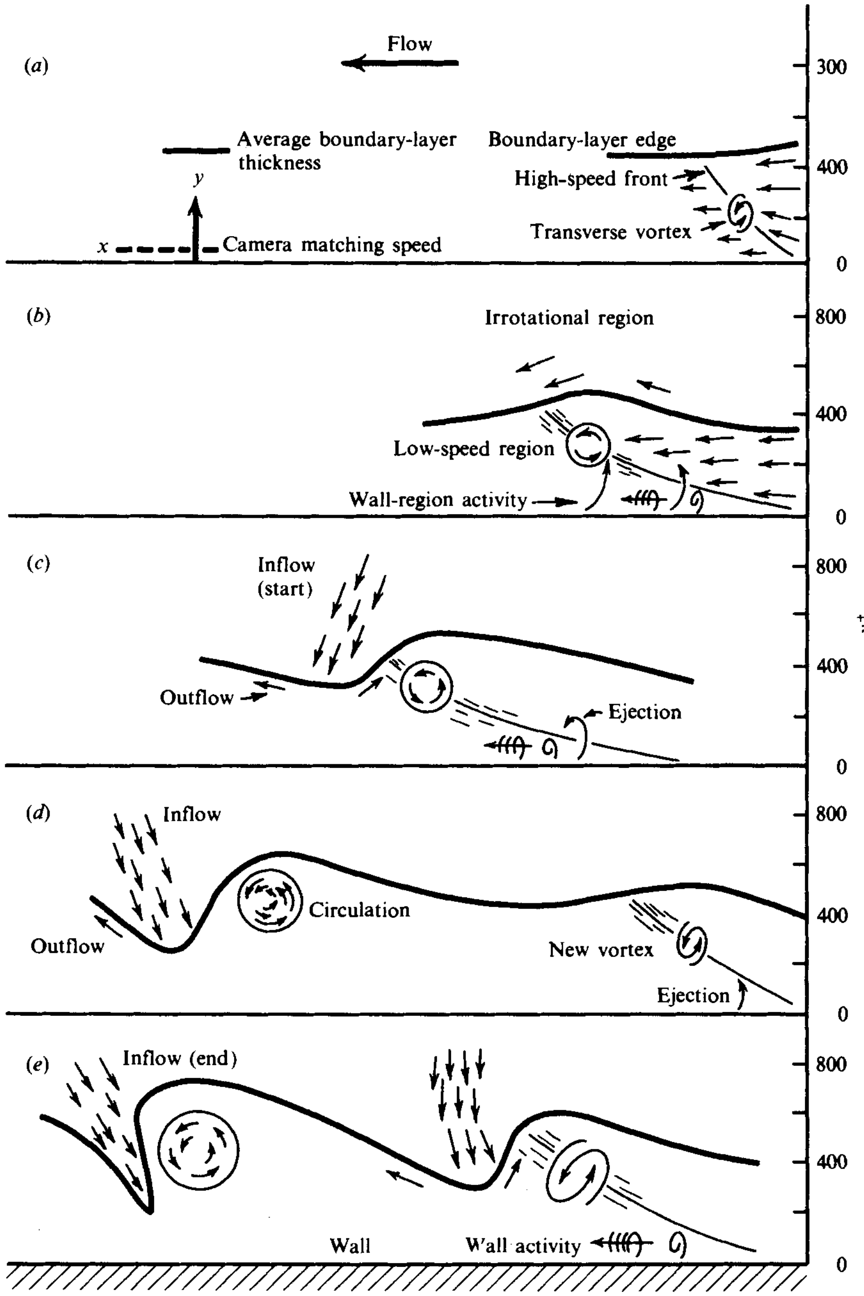

FIGURE 11. Sketch of the progression of the flow.

fluid moving around the fingers of high-speed fluid. This stage is shown as figure 11 (*b*) and in more detail in figures 8–10.

The third stage of the cycle is characterized by the decay of the transverse vortex and the cessation of activity in the wall region. The transverse vortex, as it travels downstream, becomes bigger in diameter and less intense, ultimately turning into a

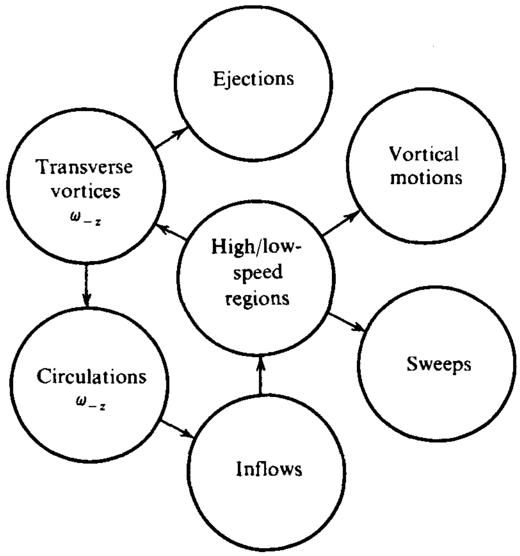

FIGURE 12. Model interactions.

gentle circulation as shown in figures 11 (*c*) and (*d*) and in figure 7. The transverse vortex usually moves slightly away from the wall. At the same time, the high- and low-speed fluid elements disappear and become a region characterized by a more uniform flow. The shear zone is consumed by the transverse vortex as it is convected downstream. The gentle circulation, moving slightly away from the wall, then appears as a bulge in the turbulent/non-turbulent interface. This circulation induces an inflow of fluid from the irrotational region. At this point in the cycle, the flow in the boundary layer is slower than that in the irrotational region. The relatively higher momentum of the fluid from the irrotational region reinforces the inflow as it moves towards the wall in the shape of a jet. Owing to the overall velocity gradient, the wallward part of the inflow slows down to a much lower speed than that of the part away from the wall. The inflow appears to deflect backwards in the convected view of the camera. The initiation and convection of the inflow are sketched in figures 11 (*c*)–(*e*) and in more detail in figures 5 and 6. The outflow (figures 11*c*, *d*) comes from the boundary-layer fluid and appears to be a reaction (maybe due to continuity) to the inflow.

Events follow each other rapidly and a second sequence following the first is illustrated. At higher Reynolds numbers, the events would be closer together and the outflow might well become part of the circulation motion. Fluid in the inflow event is eventually swept away by the oncoming high-speed fluid and probably entrained into the boundary layer by engulfment.

Figure 11 is a two-dimensional section through a three-dimensional structure. The high-speed front is not uniform across the flow in the lateral direction and would seem to be more like fingers with low-speed fluid below and trapped between the fingers. These fingers are very long and correspond to the high/low-speed streaks in the wall region. In this shear region, small axial vortices lie along these fingers. Note that, in this model, the axial vortex motion is caused by the fingering effect rather than the other way around as in some models that suggest that the low/high-speed streaks are caused by extended axial vortex pairs. Actually, the same general vortex pattern would be observed in both cases, but in the present model the vortices are many and small and the pattern would be weaker as it is a consequence rather than a causative factor.

Figure 12 depicts schematically the phenomenological model and illustrates the interrelationships between the coherent structures. *The high-speed front is pictured as the main causative step* in the formation of the transverse vortices and the short-lived axial vortices that were observed in the wall region.

5. Discussion

It is necessary to discuss the present model, which is for the most part based on the stereoscopic films and on earlier work at Ohio State, within the context of other work. The present large scale of view necessary to observe both inner and outer events and to relate them to one another precludes obtaining details of the region very near the wall ($y^+ < 50$). For this region, the films by Corino (1965) offer a better view. It is hoped that this discussion will allow some insight to be gained into what is known, what still seems to be unresolved, and what might be some of the causative factors giving rise to the structured sequence observed during boundary-layer flow. It will be convenient to divide the discussion into four parts: the wall region, the outer region of the boundary layer, the irrotational region and an overview.

5.1. *The wall region* ($y^+ < 100$)

The sequence of events observed in the wall region contained all the elements previously reported by Corino & Brodkey (1969) and Nychas *et al.* (1973). It is the combination of these studies with the three-dimensional view of the present work which permits the structuring of the detailed model presented in the previous section, in particular with regard to wall-region vortex motion. In this work no evidence was found to contradict the hypothesis by Nychas *et al.* that ejections are induced by the pressure field set up by the transverse vortex motion along the high-speed shear front in the outer region. However, as indicated from the present three-dimensional view, it may also be that ejections are a simple continuity consequence of low-speed fluid being trapped between fingers of high-speed fluid and having nowhere else to go but away from the wall.

Corino & Brodkey said that tight rotation of fluid elements was observed on very few occasions. This was a consequence of their small extent of view ($0 < y^+ < 45$). Recall that most of the axial vortex motion observed in the present work centred around a y^+ of about 50. A reinspection by Kastrinakis *et al.* (1977) of the movies taken by Corino (1965) at higher Reynolds numbers (and consequently with a larger view) indicated that axial vortex motions definitely existed. The stereoscopic view used in the present work enhanced the ability to see vortex motions compared with the two-dimensional view used by Nychas *et al.* The loop motions described by them (see their figure 7) no doubt correspond to the vortex motions of the present work. Recall that most of the vortices in the wall region did not make more than one complete rotation about their axes.

The wall-region study of a boundary layer by Kim *et al.* (1971) is of particular significance to this study. Their experimental technique (hydrogen bubbles) is considerably different from the present method and their camera was stationary. The wall region studied by them extended from 0 to 100 y^+, which corresponds to the wall region of the present study. The events which they described can be closely associated with the sequence of events observed in this study. The lifting of the low-speed streaks corresponds to the ejections. They also found streamwise vortices in the wall region associated with the lift-ups. The nature of the streamwise vortices reported by them corresponds to those observed in this study. Most of the vortices in both studies did not make more than one complete rotation. In the wall region, streamwise vortices are more abundant than transverse vortices. Wavy motion of the lifted-up streak, which was reported to be more common than transverse vortices, could be interpreted as ejections swept away by the high-speed fluid, although this is speculative. Their suggestion that the wall-region 'bursting' is directly responsible for large eddy structures in the outer region ($y^+ < 100$) is questionable as the reverse of this seems more probable from the present study and that by Nychas *et al.* Their contention that the inflexional velocity profile is a result of the lifted-up low-speed streak is in conflict with the present study. The present study and the work of Corino & Brodkey and Nychas *et al.* showed that the inflexional velocity profile is a result of the high-speed fluid advancing into the low-speed fluid, which gives rise to the Helmholtz instability associated with the high-speed front. It must be noted here that the visual observations by Kim *et al.* were based on interpreting the shapes of hydrogen-bubble time lines and that the results of the present study were based on direct observations of fluid motions and flow structures in three dimensions. The hydrogen-bubble time lines represent the cumulative effect of fluid motions on them since their formation, while the tracer particles in the present study depict the instantaneous fluid motions. The study by Kim *et al.* did not include the structure of the flow outside the wall region and their experimental technique was not adequate to observe some structural features (high/low-speed elements). These limitations were in part removed in the work of Offen & Kline (1974) by the use of dye injection in the outer region. In every case, Offen & Kline's results confirmed those of Nychas *et al.* (1973) and the present results.

A great deal of information has accumulated that supports the suggestion by Nychas *et al.* (1973) that the wall-region activity is caused by conditions in the outer region. This is supported by the present visual studies, as well as those studies that show that the wall region scales on outer variables (Rao *et al.* 1971; Lu & Willmarth 1973; Brodkey *et al.* 1974; and others).

The intermittent nature of the wall-region activity has been demonstrated by a number of the previous studies, for example those by Gupta *et al.* (1971) and by Eckelmann (1974).

5.2. *The outer region* ($100 < y^+ < 450$)

The transverse vortices formed at the front between the high- and low-speed fluid appear to be the cause of ejections and one of the main means of momentum exchange between the high- and low-speed fluid elements as suggested by Nychas *et al.* As the transverse vortices travelled downstream, they expanded in size, became less intense and transformed the two-speed region into a more homogeneous one. Motions in the high-speed fluid of the outer region of the boundary-layer were almost parallel to the flat plate, with a slight inclination towards the wall. The low-speed ejections from the wall region, which penetrated into the high-speed elements, were carried away by the high-speed fluid.

The study of vortex structures in a shallow channel by Clark & Markland (1970, 1971) qualitatively supports the phenomenological model presented here. Their results indicated that streamwise vortices dominate the wall region while transverse vortices dominate the outer region. Their results also showed that vortex structures are bigger and less intense further from the wall.

Offen & Kline (1974) studied a turbulent boundary layer using two dye injectors and a hydrogen-bubble wire with one of the dye injectors located in the outer region of the flow ($100 < y^+ < 200$). Their study suffered from the same limitations as the work of Kim *et al.* (1971) in that (i) their movies did not present an instantaneous picture of the entire flow field, (ii) the movies were two-dimensional and (iii) the view was Eulerian. With these differences in view, Offen & Kline's results can be discussed and compared with the results of the present study. Their results can be stated as follows: a large-scale disturbance was observed both before and after the appearance of a wall-region ejection and vortices. The large-scale disturbance appeared to be moving towards the wall at a small angle (6°, non-convected view). Associated with the large-scale disturbance were vortex motions, which were interpreted as either transverse (ω_{-z}) or upward tilted streamwise ($\omega_{-x,y,z}$) vortices. They also called the large-scale disturbance a sweep ($u > 0$, $v < 0$). The sweep appeared to be moving at a higher speed than the surrounding fluid and the bursting fluid near the wall.

As already mentioned, these results are similar to the earlier results by Nychas *et al.* (1973). The large-scale disturbance of Offen & Kline is clearly the sweep described in our earlier work.

5.3. *Irrotational region* ($450 < y^+$)

An important deduction from the present study is that the inflows are fluid from the irrotational region and that they are induced by the circulation in the outer region of the boundary layer. The outflows observed were a reaction to the massive inflows, to satisfy continuity requirements. The outflows occurred at the same time as the inflows but not usually on the same x, y plane. From the movies with dye, the outflows seemed to originate in the outer region of the boundary layer, not in the irrotational region. The inflows and outflows reported by Nychas *et al.* (1973) are no doubt the same as those observed in the present study. The inflows are responsible for the deep indentations observed in the boundary layer by Falco (1977). The inflows also explain how the turbulent energy is transferred to the boundary layer from the irrotational region, how intermittency occurs deep in the boundary layer, and how entrainment by engulfment can occur. The inflows make enormous positive contributions ($u > 0$, $v < 0$) to the Reynolds stress.

Kovasznay *et al.* (1970) studied the outer intermittent region of a turbulent boundary layer. They reported that the interface separating the turbulent and non-turbulent regimes appeared to be a highly corrugated surface convecting in the flow at a velocity slightly lower than that of the irrotational region. The irrotational region appeared to be riding over the bulges of the interface. From their results, they concluded that a large-scale motion exists which is strongly correlated with the shape and motion of the turbulent/non-turbulent interface. The large-scale motions seemed to be individual bulges or bursts with a streamwise extent of $\frac{1}{2}\delta$ to δ. They considered the interface to be formed by these individual bulges occurring at random. Near the interface, the fluid moved away from the wall on the backs and towards the wall on the fronts.

Kovasznay *et al.* hypothesized that bursts in the interior of the turbulent region, coming out as a lump of fluid, emerge as bulges at the interface.

The similarities between the results of Kovasznay *et al.* and the present results are obvious. The bulges at the interface correspond to the large vortex-like circulations found in the present study and in Nychas *et al.* The motion of the irrotational-region fluid following the interface around the bulge and becoming the dominant motion corresponds to the huge inflow of irrotational-region fluid induced by the vortex-like circulation. The rotational direction of the bulges indicates a negative transverse vortex motion as observed here. However, a lump of fluid coming out all the way from the wall was not observed in the present study. This apparent difference was explained by Nychas *et al.* by noting that ejections, outflows and forward transverse vortices, when averaged together, might very well appear as a lump of fluid coming from the wall region.

Blackwelder & Kovasznay (1972), using the same techniques as Kovasznay *et al.* (1970), studied space–time correlations in a boundary-layer flow. Their results revealed rotational motions in the interfacial bulges. This picture is consistent with the present observations. Their results suggested that events in the buffer region influence the structure of the turbulent/non-turbulent interface. Their data in the wall region showed ejections from a decelerated region. The results of Kaplan & Laufer (1969) supported the ideas of Kovasznay *et al.* (1970). Antonia (1972), using conditional sampling of u, v and Reynolds-stress (uv) fluctuations, studied the intermittency at the outer boundary-layer edge with both rough and smooth walls. His results indicated that the features of wall-region events need not be directly responsible for the observed features of the bulges at the outer edge of the boundary layer.

5.4. *An overview*

There are two major points of deviation of the present model from most of those presented previously by others. First, it is the events in the outer region of the flow that kick off the action in the wall region, and, second, the vortex motions in the wall region are a result of the interaction between the high-speed fluid and the narrow region of retarded fluid trapped between the high-speed element and the wall.

On the first point, a number of authors have suggested the tempting idea that the energetic wall-region ejections (or bursts) travel to the outer region of the boundary layer and give rise to the bulges in the turbulent/non-turbulent interface (e.g. Blackwelder & Kovasznay 1972; Kim *et al.* 1971). In the present work, it is clearly shown that the bulges are associated with the transverse vortex motions in the outer region, and that these motions (the front between the high- and low-speed elements or the vortex motion) give rise to the conditions necessary for wall-region activity such as ejections.

On the second point, a number of authors have suggested models that involve counter-rotating pairs of vortices in the wall region that give rise to the outflow of low-speed fluid trapped between the vortices. Examples are the horseshoe vortex suggested by Theodorsen (1952), the vortex pairs suggested by Townsend (1970) and by Bakewell & Lumley (1967), the hairpin vortices suggested by Willmarth & Tu (1967) and Kline *et al.* (1967), and variations and permutations by others since. In these models, the axial-vortex wall motion is the causative factor and the outflow of low-speed fluid and inflow of high-speed fluid the result. *In direct contrast* to this, the present idea is that the vortex motions in the wall region are the result of the interaction between the incoming high-speed fluid and the outflowing low-speed fluid. In the picture of Nychas *et al.* (1973), the transverse vortex action in the outer region gave rise to pressure changes that caused the outflow of low-speed fluid (ejections). This may well be true, but the present work suggests the possibility that these ejections are merely a consequence of continuity, i.e. the low-speed fluid is trapped between fingers of high-speed fluid and has nowhere to go but outwards.

From overall anemometry measurements, it would be hard to establish exactly which of the two mechanisms suggested above is correct. They both give about the same picture *on the average*. It is important to emphasize on the average. One mechanism *requires* instantaneously counter-rotating axial vortex pairs while the other *does not*, but does not rule them out. In fact one would expect them to exist often, and they definitely would be observed on an integrated or overall average.

A brief comment on what the average picture might look like is in order. The picture can be constructed from the sketch in figure 11(*b*) or figure 11(*e*) for the second sequence. There is a relatively large outer-region transverse vortex structure (plus some tilted vortices) which is followed by the wall-region activity, which consists mainly of ejections and axial vortex motions. It is not difficult to visualize that ensemble averaging these structures over many events will result in a horseshoe vortex structure riding along the wall as first suggested by Theodorsen (1952) and currently being investigated by others. Indeed this may well be the best model for the flow; however we should not expect actually to see this structure in the flow, except on the average.

Finally, some comments are in order as to the direction of visual studies for the future. The nature of turbulence in our minds has clearly changed drastically over the last ten years or so. We want to model turbulent flows more accurately; thus we need measurements to describe what has been seen. Clearly anemometry results are needed, but just as clearly these will have to be carefully conditioned to bring out the sequence of events now known to exist. Just any conditioned measurements will not do. It would seem to us that simultaneous anemometry and visual studies are needed. Fortunately, these are now in progress at several laboratories around the world. From this work and extensive anemometry work, properly conditioned, should come a better ability to interpret turbulent flow in terms of conservation of turbulent energy and of circulation. In addition reliable mechanistic models of turbulent shear flows that will enable reasonable predictions to be made should be possible. In effect, we need to make turbulence more understandable so that we can treat it as a laminar flow, albeit complex.

The support of the National Science Foundation and The Ohio State University in conducting the present study is appreciated. The advice and help of H. C. Hershey throughout the course of the investigation is particularly recognized. Thanks are also due to C. E. Patch and K. Wolfe, who typed the manuscripts.

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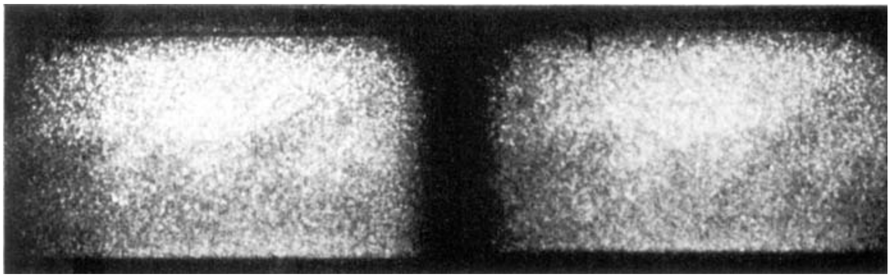

FIGURE 2. Stereopair of boundary-layer flow.