J. Fluid Mech. (1969), *vol.* 37, *part* 1, *pp.* 1–30
Printed in Great Britain

A visual investigation of the wall region in turbulent flow

By E. R. CORINO† AND ROBERT S. BRODKEY
Department of Chemical Engineering, The Ohio State University,
Columbus, Ohio, 43210

(Received 14 October 1967 and in revised form 24 December 1968)

The objective of this study is to investigate for turbulent flow the fluid motions very near a solid boundary, and to create a physical picture which relates these motions to turbulence generation and transport processes. An experimental technique was developed which permitted detailed observations of the regions very near a pipe wall, including the viscous sublayer, without requiring the introduction of any injection or measuring device into the flow. This technique involved suspending solid particles of colloidal size in a liquid, and photographing their motions with a high-speed motion picture camera moving with the flow. To provide greater detail, the field of view was magnified.

Fluid motions were observed to change in character with distance from the wall. The sublayer was continuously disturbed by small-scale velocity fluctuations of low magnitude and periodically disturbed by fluid elements which penetrated into the region from positions further removed from the wall. From a thin region adjacent to the sublayer, fluid elements were periodically ejected outward toward the centreline. Often there was associated with these events a zone of high shear at the interface between the mean flow and the decelerated region that gave rise to the ejected element. When the ejected element entered this shear zone, it interacted with the mean flow and created intense, chaotic velocity fluctuations. These ejections and resulting fluctuations were the most important feature of the wall region, and are believed to be a factor in the generation and maintenance of turbulence.

1. Introduction

The importance of fluid motions in the wall region has been known ever since Prandtl (1904) proposed the boundary-layer hypothesis. In its most general context, this hypothesis suggests that in the fluid adjacent to the wall, the viscous effects are important enough to strongly influence the fluid motions. Turbulent flow has usually been divided into three areas: the turbulent core, the transition or buffer region, and the sublayer region. The latter is usually referred to as the laminar sublayer, but because of the unsteady nature of the flow in this

† Now associated with the Esso Research and Engineering Company, Linden, New Jersey.

area, the term 'viscous sublayer' is more appropriate. The *wall region* is often referred to as being the combination of the viscous sublayer and the buffer region.

Although its nature is not fully known, the wall region is sufficiently well characterized to indicate its extreme importance in the control of transport phenomena and the generation and maintenance of turbulence. The relatively small amount of mixing within the sublayer compared to that of the core causes the transport in this region to proceed in part by molecular mechanisms, and consequently, it occurs more slowly here than elsewhere. A large number of articles have appeared which attempt to predict the rates of transport by assigning various characteristics to this region, and develop models or relations from these assumptions. A long list of these could be made; however, for our purpose, let us just cite a few of the more familiar theories: Deissler & Eian (1952), von Kármán (1939), Lin, Moulton & Putnam (1953), Deissler (1955), Higbie (1935), Danckwerts (1951), Harriott (1962), Hanratty (1956) and Toor & Marchello (1958).

Most of these treatments have one thing in common. They begin by assuming a particular character for the wall region. From these assumptions, equations for heat and mass transfer rates or coefficients are developed. These equations usually contain one or more parameters which must be evaluated from experimental data. Upon evaluating the parameters in this fashion, nearly all the models can be made to predict the proper dependency of the transfer coefficient over a certain range. Outside this range the predicted dependency is usually incorrect. There is a variety of assumed models, and most of these can be made to agree with the same experimental data which demonstrates the insensitivity of the results to the assumptions. This insensitivity precludes any possibility of deciding which of the models, if any, accurately depicts the true nature of the wall region. Clearly, a more direct understanding of the nature of the wall region is needed, and based on this understanding, a mechanism should be formulated that will allow prediction of heat and mass transfer rates without the need of adjustable constants from heat and mass transfer data, and will depend only on the parameters measured from the turbulence itself.

The importance of the wall region in the generation and maintenance of turbulence is well known. Since the kinetic energy of turbulence is continuously dissipated to internal thermal energy through viscous effects, a continuous supply of new turbulence must be created within the flow if the quasi-steady-state character of the turbulent flow is to be maintained. The source of the energy is the mean flow, but as yet the mechanism of transfer is unknown. Visualization of what is occurring in this region might allow the mechanism of transfer to be better established.

The number of investigations reporting quantitative measurements of turbulent characteristics within the sublayer region is limited despite the acknowledged importance of this region. Ludwieg & Tillman (1949) measured local mean velocities to $y^+ \sim 15$ for flow over a flat plate, and Reichardt (1951) did the same for channel flow to $y^+ \sim 2$. Measurements of the turbulent characteristics within the sublayer were made by Klebanoff (1954) in boundary-layer flow and Laufer (1954) in pipe flow. Both used air as the fluid and hot wire probes for the measurements. Laufer showed that a maximum in the u'_x/U^* distribution occurred at

$y^+ \sim 15$. Even at $y^+ \sim 1{\cdot}5$ the u'_x value was nearly 50 % of the U^* value at $N_R = 50{,}000$. The other components, while smaller, all have finite values at $y^+ = 3$ which was the nearest position to the wall reported.

Laufer presented an energy spectrum on a wave-number basis for both the u_x and u_r components. In both cases as the radial position of measurement was moved toward the wall, there was a definite shift in the wave number range toward larger values, i.e. smaller eddy sizes. Klebanoff's spectra not only showed this, but showed a decrease in the contribution to turbulent energy by the low wave-number range as the wall was approached. Additional evidence of the same effect was reported by Hinze (1959) who used Laufer's data for pipe flow and calculated the integral and dissipation length scales. Both scales showed a decrease with decreased distance from the wall. It might also be noted that the concept of increasing eddy size with distance from the wall is tacitly assumed in Prandtl's mixing length theories.

Laufer also presented a plot of the distribution with distance from the wall of the terms of the turbulent energy equation. The only term he could not measure or estimate was the one for pressure velocity correlation, and he calculated it by the difference. Townsend (1956) corrected these plots for the effect of the steep velocity gradient near the wall. They are also presented and discussed by Brodkey (1967). These curves dramatically illustrate the importance of the region $5 \leqslant y^+ \leqslant 20$. Within this region, at $y^+ \sim 11{\cdot}5$, the production of turbulent energy is a maximum as is the dissipation of this energy. In addition, the region shows a loss of energy by diffusion of kinetic energy out of it, and a gain caused by the diffusion from pressure effects into it. Also, there is a loss from the region due to the viscous transfer of kinetic energy especially towards the wall in the region $y^+ < 5$. A similar plot for the region removed from the wall shows that the production and dissipation of turbulent energy both decrease rapidly with increasing y^+. These regions also show a consistent loss due to the diffusion as a result of pressure effects, and a consistent gain due to the diffusion into the region of kinetic energy from the wall area. Far out in the core of the pipe, the loss by dissipation is just balanced by the influx of kinetic energy.

Other investigators have employed visual-photographic experimental techniques. Fage & Townend (1932) and Fage (1936) used an ultramicroscope to examine fluid motion very near a solid boundary for turbulent flow in a square tube and a circular pipe, respectively. They used a magnification of $\times$ 200 which gave them a field diameter of 0·03 in. In the region of $0 \leqslant y^+ \leqslant 4$ they noted that the fluid elements continually exhibited departures from truly rectilinear flow. Fage & Townend measured the angles between the particles and the tube axis at various positions from the wall. The maximum angles observed occurred in the plane parallel to the wall (maximum angle 27°), and were larger than those occurring in the plane perpendicular to the wall (maximum angle 10°). The intensity of turbulence in the region was independent of Reynolds number. However, the ratio of disturbed to quiescent periods increased with Reynolds number over the limited range studied.

Nedderman (1961), by a technique of still photography and using small air bubbles in water to mark the fluid elements, measured instantaneous velocities in the region of $0 \leqslant y^+ \leqslant 30$ in pipe flow. At $N_R = 12{,}000$ and 19,000 he observed a wide distribution of values about the mean velocity profile. He concluded that the flow was disturbed at least to $y^+ = 1$. The field of view was $0{\cdot}196 \times 0{\cdot}196$ in. square, and 0·04 in. in depth. The bubble concentration was quite dilute so that in any given photograph only several bubbles were present. Nedderman noted that at no time did any of the bubbles present appear to be moving in a similar (connected) fashion at the same instantaneous velocity. From this he concluded that the eddy scale must be smaller than the field of view. Finally, he reported that on a few occasions he saw two particles, one directly behind the other (that is, at a different depth along the line of sight), with the one at a greater y^+ position moving more slowly than the one at the smaller y^+ position.

Kline & Runstadler (1959) used dye injection and visual-photographic techniques to make a detailed investigation of the boundary layer over a flat plate. Their study revealed that the wall region possessed a distinct structure and a definite, non-regular time-dependent motion. Since that time Kline and his co-workers have developed the dye injection and hydrogen bubble techniques in order to obtain extensive visual and quantitative results on artificially tripped turbulent boundary layers. The results have been presented in reports by Runstadler, Kline & Reynolds (1963) and Schraub & Kline (1965), and in the recent article by Kline, Reynolds, Schraub & Runstadler (1967).

Kline *et al.* (1967) have incorporated their work and the earlier work of others to formulate a picture of the turbulent boundary layer. In addition, quantitative data were presented so as to further relate the picture to more conventional observations. They divided the boundary layer into a number of distinct regions measured from the plate surface. In the region $0 \leqslant y^+ \leqslant 10$, they reported the presence of a very regular pattern distributed in a spanwise direction and emphasized that although dominated by viscosity, eddy motions are both three-dimensional and present throughout the entire region. The pattern consisted of streaks of low $\overline{U}_x$ velocity fluid alternating with high $\overline{U}_x$ velocity fluid. The streaks had a much greater axial dimension than the other two dimensions and were the result of stream-wise vorticity. While the pattern was quite regular, the streaks were destroyed and re-established with a random distribution so that their existence at any given position was limited. The mean streak spacing was found to be a function of Reynolds number and a correlation was presented. These low $\overline{U}_x$ velocity streaks were observed to develop a wavy configuration, and then were observed to be suddenly ejected or be lifted outward from the wall in a thin loop-like filament. These filaments moved outward into a region somewhat further removed from the wall where they were broken up by interaction with the flow. The region $0 \leqslant y^+ \leqslant 10$ was reported to be the position of origin of such filaments. The process of ejection appeared to be random in both space and time. The frequency of occurrence, however, was found to be markedly dependent on Reynolds number and a correlation was presented. The angles the ejected elements made with the wall showed a wide distribution from a maximum angle of approximately 26° downward to 0°. All were directed downstream. The filaments were ejected into the region $8 \leqslant y^+ \leqslant 12$ where they began to oscillate. The oscillation amplified as the streak continued outward from the wall until they were disrupted in the region $y^+ \geqslant 10$, most being less than $y^+ \leqslant 30$. This was reported to be a region of great turbulent activity. Kline *et al.* suggested that the ejection process is a primary mechanism for the production of turbulent kinetic energy. They further suggested that the 'bursts' could be the result of an instability mechanism and appear to play a role in the transport of turbulent kinetic energy to the outer regions of the flow. The authors also reported a general increase in the size of the eddies and a decrease in intensity as the distance from the wall increased. This was supported by hot wire traverses which also showed that in the $0 \leqslant y^+ \leqslant 10$ region the pulses caused by fluctuations were positive, but in the $10 \leqslant y^+ \leqslant 40$ region they were negative.

Parallel to this, we have been investigating the wall region during fully developed turbulent pipe flow. The results were first presented by Corino (1965). The present paper is a report of this work and an effort to integrate our observations and interpretations with those of others. As will become apparent, all the various techniques employed complement each other. The information available is contained in a limited number of works and certainly more is needed. The lack of knowledge concerning this region is due in part to the difficulties of obtaining accurate measurements and observations within it. This is a result of the extremely small dimensions involved. For example, in a 2 in. pipe for liquids (trichloroethylene) at a Reynolds number of 50,000, the entire sublayer region is contained in 0·004 in. ($y^+ = 5$). Any probe or injection device introduced into the region will have a dimension of the order of magnitude of the region. In addition, for liquids, the necessity of providing physical strength to the probes causes them to be larger than those used in gases. What is required is a method of investigation which can reveal the character of the wall region and yet does not require the introduction of any measuring device into the flow.

2. The experimental facility

The technique developed for the visual-photographic study of the wall region employs colloidal sized particles suspended in the fluid as tracers, and requires no tracer injection or the introduction of any measuring device into the flow. High-speed motion pictures of the magnified wall region were taken as the camera was transported downstream with the flow. This is to our knowledge the first time that such pictures have been obtained. In a circular pipe, this region would not normally be visible because of light refraction at the pipe wall. The problem was eliminated by using in the flow system a liquid that had the same refractive index as the glass pipe, and surrounding the pipe with a viewing cell of the same fluid. The following is a brief description, with considerably more detail available in the thesis by Corino (1965).

Figure 1 is a sketch of the flow system. The flanges between the glass pipes were equipped with standard Teflon gaskets and were carefully aligned to minimize disturbances. The meters were calibrated by weighing the efflux collected for a timed interval. The filter could remove all solids larger than $5\,\mu$.

Trichloroethylene was selected as the test fluid primarily because its refractive index (1·474) closely approximated that of glass (1·473–1·477). Since the light source used was not monochromatic, no attempt was made to achieve agreement in the third decimal place of the refractive indices of the pipe and fluid. In order to mark the fluid elements so that the motions would be visible, very fine particles of magnesium oxide were suspended in the liquid. These particles had an average diameter of $0{\cdot}6\,\mu$. The particle concentration was dense enough so that a large number of particles appeared within the field of view simultaneously, but sufficiently dilute so that particle–particle interaction almost never occurred. The test fluid appeared perfectly clear and colourless in normal light and only

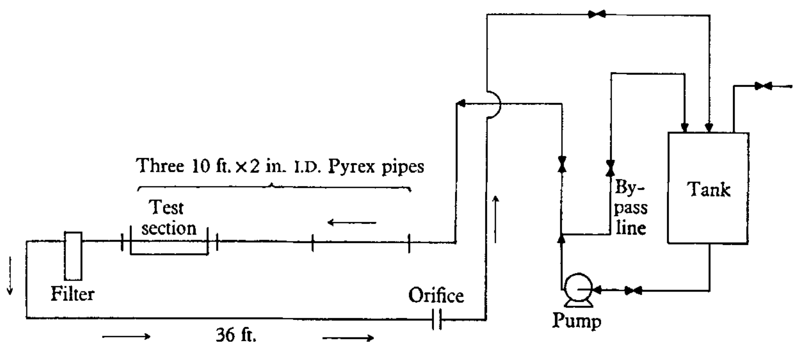


FIGURE 1. Flow system.

under dark field illumination were the particles visible. Then they appeared as bright points of light against a dark background (scattered light). It should be emphasized that these particles were suspended in the fluid at all times, and no injection was required during a run.

The photo-optical system is shown in figure 2. Since the particle motions were very rapid, a 16 mm Fastex WF 3 high-speed motion picture camera, with Kodak no. 2475 recording film rated at ASA 2000, was used at filming speeds of 650–1000 frames per second. These correspond to shutter speeds of 0·00051–0·00033 sec. The lens system of the camera was adapted to produce images of the area of interest of $\times$ 4·3 and $\times$ 2 magnification. These magnified images greatly enhanced the ability of the system to define the fluid motions within the very narrow wall region. Because of the high filming speeds, the magnification, and the dark field illumination, a very intense light source was required. An ultra-high pressure d.c. mercury arc lamp. Osram HBO-109, was used, and the beam was focused by means of a spherical mirror through adjustable slits into the field of view. The use of a mercury arc lamp and not a monochromatic light source prevented the complete elimination of any effect of refraction, but the small effect which remained was used to good advantage as a means of locating the inside pipe wall in the photographs.

In the work to be described it was a distinct advantage to have the capability of moving the entire photo-optical system downstream with the flow during photography. This naturally required that the field of view be kept in focus during the movement, and also that no mechanical vibrations which might effect the photo-optical system be present. To accomplish this an 8 ft. lathe bed was aligned with the pipe (to within 0·03 in.) and bolted to the concrete floor. The lathe carriage, which is designed to slide along the ground steel tracks was fitted with a heavy steel frame, which supported the camera and light source. This carriage was driven down the lathe bed at constant speeds (up to 1 ft./sec) by an hydraulic piston. In this manner the entire photo-optical system could be moved with the flow, and at any pre-selected speed. This meant that any local mean axial-velocity in the wall region could be matched by the carriage velocity, and, there-

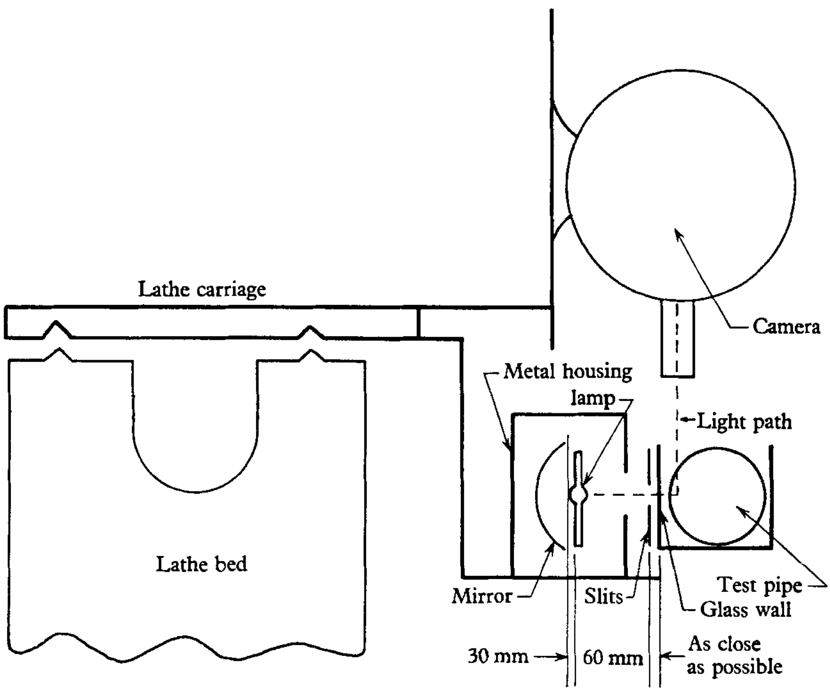


FIGURE 2. Optical system.

fore, a particular segment of fluid could be kept in view as the fluid motions developed. A calibrated nichrome resistance ribbon was mounted on the lathe bed and used to monitor and measure the carriage velocity with the aid of a sliding contact mounted on the carriage.

In the development of an experimental facility such as this, a great deal of attention had to be given to the adequacy of different parts of the system to perform the desired tasks and provide meaningful results. Effects considered were: those of joints in the glass line on the flow, the entry length necessary to assure fully developed turbulent flow, the concentration of particles, particle shape, possible agglomeration of particles, temperature rise during flow, possible modification of the fluid viscosity by the particles, Brownian motion of the particles, light refraction at the wall, and the adequacy of the particles to accurately follow the fluid motions. By experimental and theoretical methods satisfactory answers to all the problems were obtained, and it was concluded that the movies obtained are indeed a picture of the fluid motions. The conditions of operation of the photo-optical system involves a compromise between a number of factors: the limited light available to expose the film, the camera transport speed, the framing speed, the quality of image desired, and the magnification required for reasonable interpretation. The conditions previously cited were found to be the best compromise for these experiments. An extensive discussion of all of this can be found in Corino (1965).

3. Camera viewpoints

Although the camera line of sight of necessity must be at right angles to the light beam, there is some choice as to the position of focus.

3.1. *Wall view*

In figure 3, as part (*a*) shows, the light beam enters the field at right angles to the line of sight of the camera. The camera is focused on a horizontal plane AB, (part (*c*)), with the interior pipe wall aligned with the edge of the frame. Part (*b*) of this figure shows the orientation in polar co-ordinates. If the camera were focused only at the geometric plane AB, the view would coincide exactly with the rx plane of the polar co-ordinates. However, as part (*c*) shows, the camera actually 'sees' a certain distance on either side of this plane along the line of sight due to the depth of field of the lens system. Since the lenses present flat surfaces parallel to AB for the camera to view, these planes separated from AB by one-half the depth of field will not coincide with the rx planes at that position. However, because of the extremely small dimensions of the field of view, the actual differences are insignificant and no differentiation need be made. Since the optical system cannot show three-dimensional effects in the motion pictures, the particles within this volume all appear to be on a single rx plane, and in this view there is no accurate means of determining at which rx plane within the volume they are located.

The dimensions shown in figure 3 are for $\times 4{\cdot}3$; the corresponding values for $\times 2$ are 0·205 in. × 0·147 in. × 0·041 in. (axial, radial, line of sight). For $\times 4{\cdot}3$, the 0·069 in. dimension (radial) corresponds to a y^+ of 45 at a $N_R = 20{,}000$, and for $N_R = 50{,}000$, this dimension corresponds to a y^+ of approximately 90.

3.2 *Top view*

As part (*a*), figure 4 shows, the light enters at right angles to the camera line of sight, but in this case the light is directed to the interior wall region at the top centre. This view is essentially rotated 90° from the wall view. The line of sight is now along the r co-ordinate, and the planes perpendicular to the direction of view are θx planes because of the small depth of field, and therefore would be motions parallel to the line of sight in the wall view, just as the motions of the wall view in the rx plane are parallel to the line of sight in this view. Although these viewpoints were used separately, careful analysis of each series of films permitted a three-dimensional picture of the fluid motions to be constructed.

Since the wall of the pipe did not appear in this view, the camera alignment procedure was more elaborate. Details of this can be found in Corino (1965). The dimensions in figure 4 are for $\times 4{\cdot}3$ and correspond to the conditions of figure 3.

3.3. *Away from the wall*

The limited dimensions of the field of view permitted observations to only small y^+ positions when the camera was focused at the wall. In order to examine the fluid motions at greater y^+ values, it was necessary to focus the camera at greater distances from the wall as measured along the AB plane of figure 3. The resulting views were essentially the same as the wall view, but displaced varying distances from the wall. In order to position the camera, a scale device was used. In this case, of course, the focus was at the plane AB.

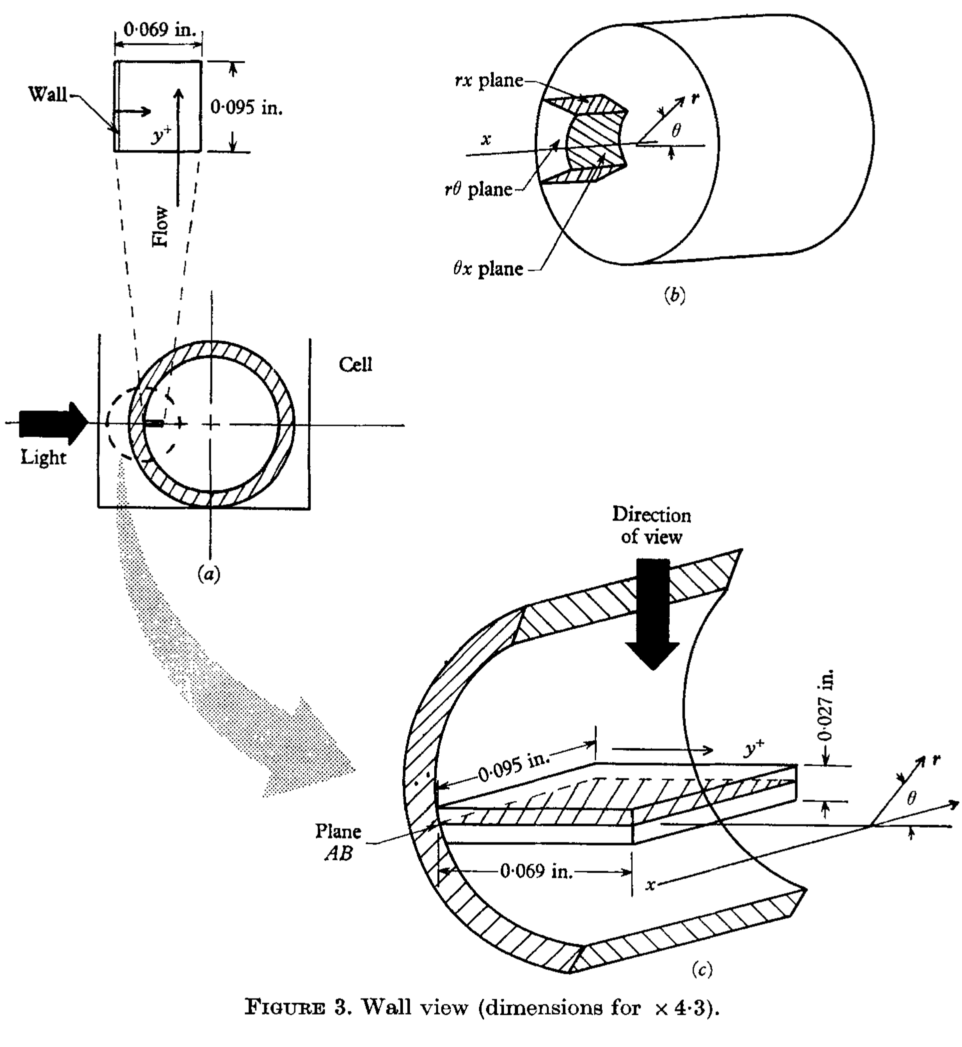


FIGURE 3. Wall view (dimensions for × 4·3).

4. A composite picture

The motion pictures were analysed to obtain a detailed physical description and quantitative measurements of the fluid motions in the wall region. These results were then combined with the general knowledge of turbulent flow to describe the fluid behaviour in this region, and attempt to explain its significance in the generation and maintenance of turbulence. The composite picture to be described is from many films of primarily the wall view with less from the top view. The clearest pictures of the sequence of events was obtained from films of

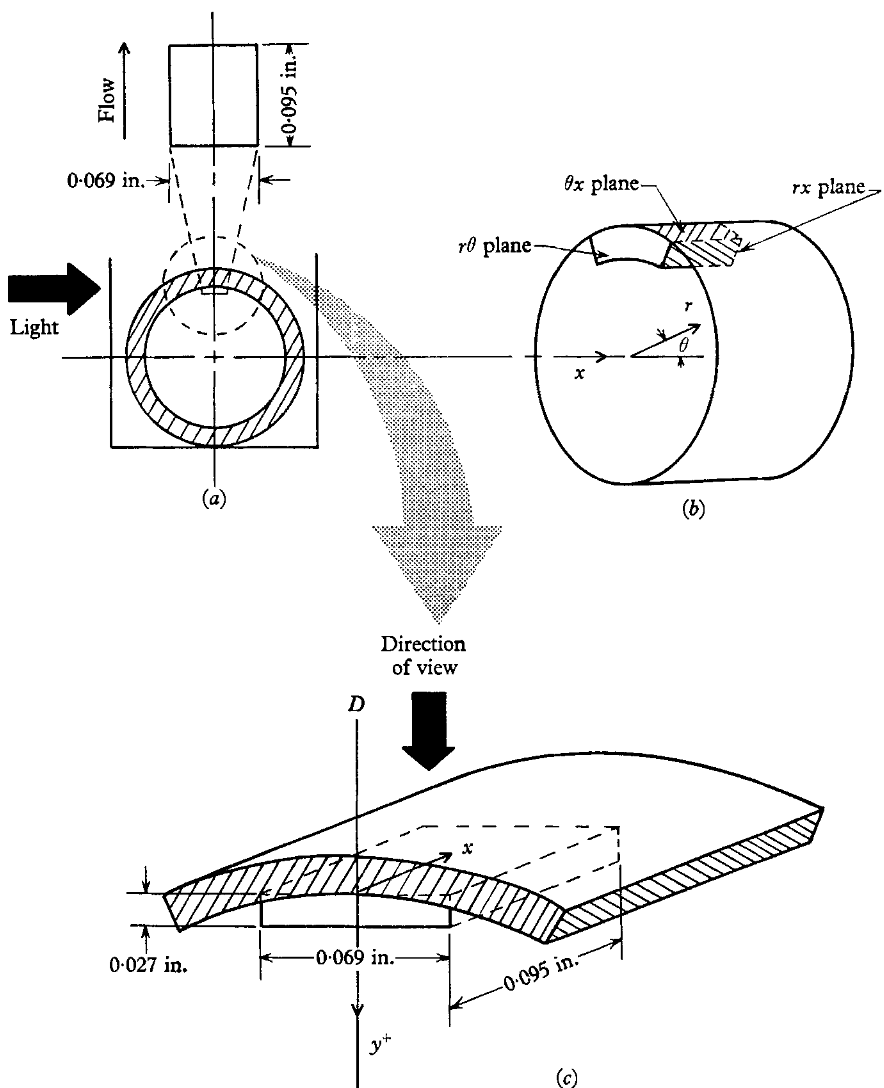


FIGURE 4. Top view.

the flow at about a Reynolds number of 20,000. The motions were complex and the clearest description is obtained by considering each step and camera view separately. While this does result in a clearer, more detailed description of the individual occurrences, it necessarily presents a somewhat lengthy and disjointed picture of the entire process. Thus, this brief, hopefully unencumbered, overall view is used instead. The individual descriptions of each step and view used to develop this composite and the detailed measurements of velocities made from

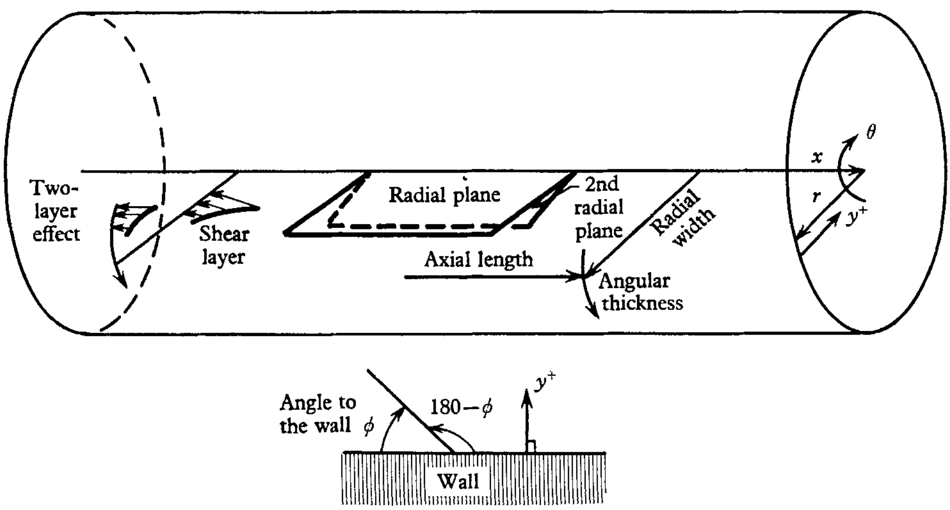


FIGURE 5. Co-ordinate and view description.

the films are available in Corino (1965). There is also available a brief movie showing some details of the experimental facility and certain sequences of the observed events.†

4.1. *The ejection sequence*

The most important and distinguishing characteristic of the wall region ($0 \leqslant y^+ \leqslant 30$) in fully developed turbulent flow was the intermittent ejection of discrete fluid elements outward from the wall. These ejections were local events and occurred randomly in both space and time. As will be seen, they are clearly the counterpart to the ejection or bursts described by Kline *et al.* (1967). The ejection of these velocity elements into regions of much greater velocity must be a part of the turbulence generation mechanism. The eventual interaction of the ejection with the higher speed flow disturbed the entire wall region, even to the wall itself. The actual ejection of fluid was only a part of a sequence of events, which to one degree or another appeared with the ejection in a definite order. Of course, there were variations of the sequence and all of the steps did not appear all of the time or in the exact fashions described, but on the average it proceeded as follows. Figure 5 provides co-ordinates and a view of the field; figure 6 gives a crude sketch of the sequence of events to be described.

† Request 'The Wall Region in Turbulent Flow' from Motion Picture Division, Department of Photography, 156 W. 19th Avenue, The Ohio State University, Columbus, Ohio, 43210. A service charge of $5.00 is made to cover cost.

The first of these events was a *deceleration* of the axial velocity of the fluid within a local region near the wall (figure 6*a*). The limited field of view did not permit an estimate of the axial dimension, but the radial dimension involved was of the order of $0 \leqslant y^+ \leqslant 30$ (see also figure 5). The deceleration was apparently the gradual replacement of fluid possessing about the normal local mean velocity with fluid from upstream that had a velocity of smaller magnitude. The actual extent of the deceleration varied greatly from a barely perceptible difference to cases where the entire field above a particular y^+ value was moving in essentially plug flow at a reduced velocity. The disappearance of the velocity gradient from the region was a striking effect, since normally the region possessed a very steep gradient. The velocities of individual particles, which were representative of the particular region of flow, were measured for the deceleration period and the period preceding it. Deficiencies as great as 50 % of the local mean velocity were observed. The totality of evidence supports the observation that the deceleration period was a decrease in the mean axial velocity within a rather small area of the pipe wall.

While the field was thus decelerated, the next step occurred, which we shall call *acceleration* (figure 6*b*). A mass of fluid from upstream with an axial velocity approximating that of the local mean velocity entered the retarded field and by interaction began to accelerate the fluid. This stream usually entered about a y^+ of 15, and as it crossed the field its effect moved towards the wall. Most often the fluid had a direction nearly parallel to the pipe wall or at a slight angle inward to it. Occasionally it entered with a large radial component of velocity, as much as 20 % of the axial velocity, and moved towards the wall at angles (ϕ) of from 5° to 15°. In both forms, the size of the stream was quite large, with radial widths of the order of the field dimension and axial lengths too great to be measured (see figure 5 for clarification of directions). The fluid within this stream exhibited some degree of turbulence, but limitations of the photographic technique precluded any detailed analysis. It appeared to be a part of a large-scale disturbance carried by the mean flow.

At various times an effect, which we will call *two-layer velocity*, was observed (figure 6*c*). It will be well to digress for a moment and explain this. The observation was that two large masses of particles, each possessing a distinctive velocity, occupied the same radial or y^+ position but did not interact with one another. It should be emphasized that the comparison was made between entire layers and not individual particles. Since the paths of these layers often crossed or were otherwise opposed, the implication from the visual analysis of the films was that they occupied two different radial planes and were separated by some distance along the line of sight (see figure 5).

The two-layer velocity is believed to be associated with the spanwise variation reported by Kline *et al.* In their work on a wide boundary layer (about 10 in. in the spanwise direction), the separation between the high and low velocity regions was about 0·5 in. or so. In our pipe flow, the variation would be distributed about the periphery of the inner wall of the 2 in. pipe. It is not known if pipe and boundary layer flows should have the same spanwise variation, but if it did we could not hope to establish this with our system. The depth of field is the limiting

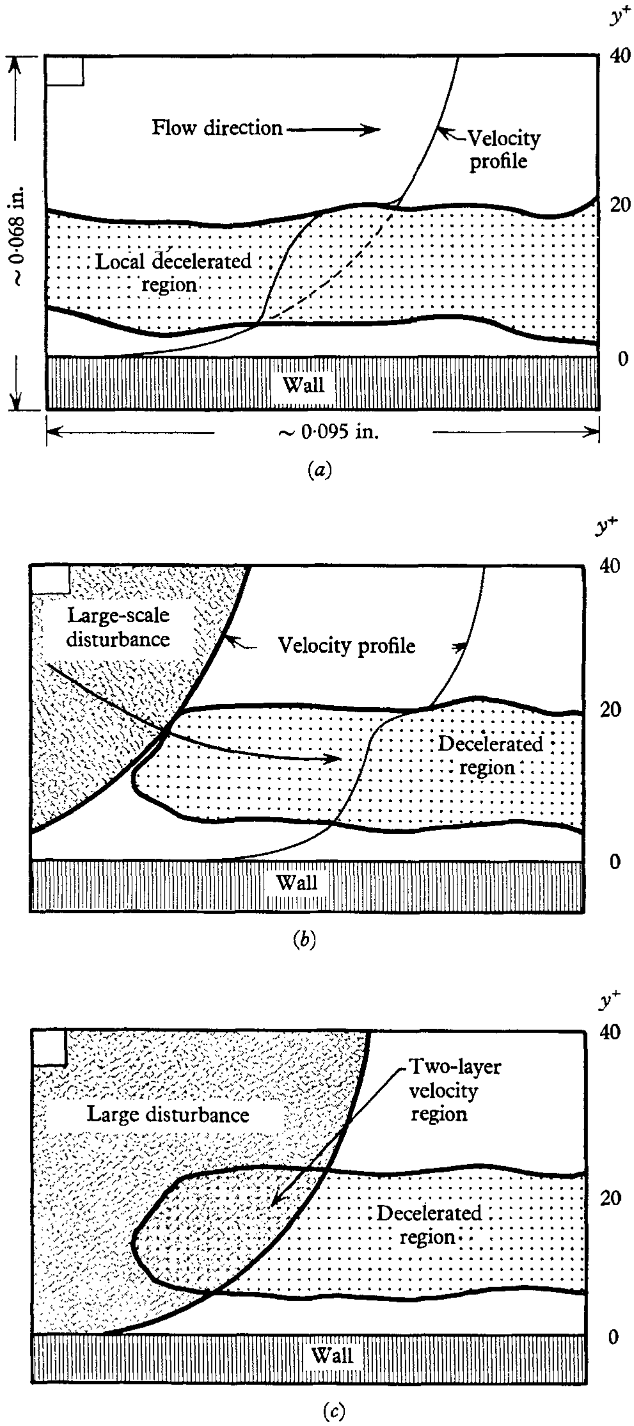
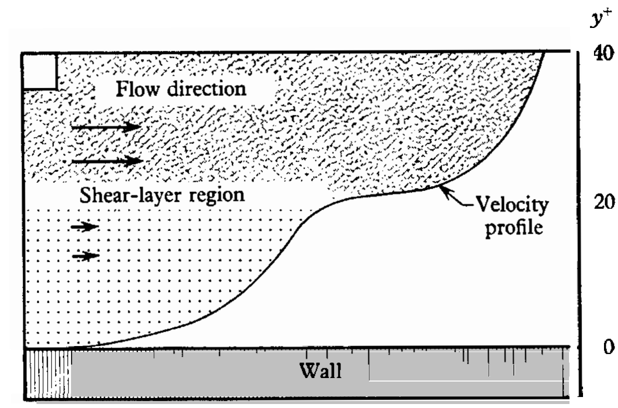
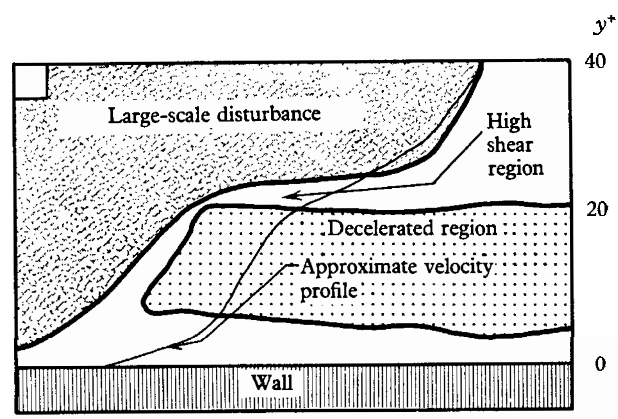


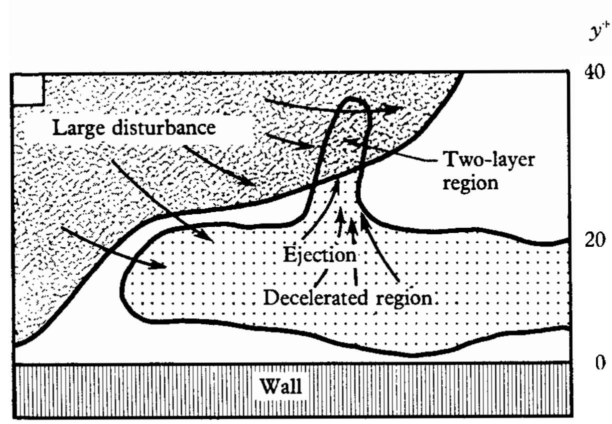
FIGURE 6. Sequence of events: (*a*) deceleration; (*b*) acceleration; (*c*) two-layer velocity (first example); (*d*) shear layer; (*e*) later stage following 2(*b*) (same as 2(*d*)); (*f*) two-layer velocity (second example); (*g*) ejection event; (*h*) two ejections in the field; (*i*) sweep event.



(d)



(e)



(f)

Figure 6 *d–f*
(for legend see p. 13).

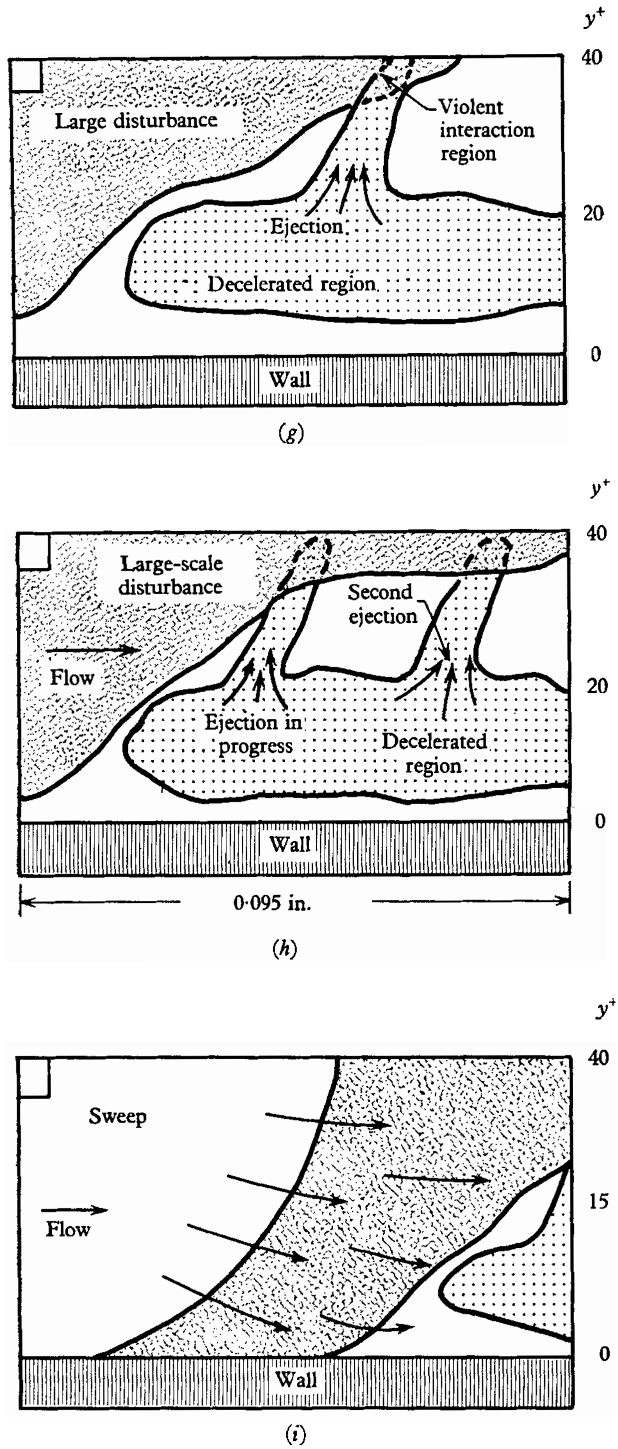


Figure 6 *g–i*
(for legend see p. 13).

dimension for observation of this effect. At $\times 4{\cdot}3$ magnification this depth is 0·027 in., and is clearly less than the dimension of a single spacing interval for boundary-layer flow. One cannot hope to see such a spanwise pattern except when the focus fortuitously coincides with the interface between two streaks of different velocity. With the unsteady nature of the streak structure, this coincidence is highly unlikely to occur very often. Furthermore, the velocity variation over the short depth of field would be quite small if the results of Kline *et al.* were applied to our case.

The two-layer velocity is an indication of a spanwise variation, but of far smaller scale than implied by that observed for the boundary-layer flow. Careful observation of the hydrogen bubble trail pictures of Kline *et al.* does show a less regular but finer scale structure of about one-tenth of the main spacing. It is more likely that we have observed this by our technique. The observation of Nedderman (1961), cited in the introduction, of two bubbles with inverted instantaneous velocities can also be explained by the two-layer velocity effect.

The axial velocities of selected particles representative of each layer were measured, and relative velocities calculated. The ability to make these measurements, and the accuracy of the measurements, were enhanced by the fact that the camera was moved at a particular axial velocity in the flow direction. Thus, in most cases, the slower moving particles had practically a zero or even a negative axial velocity relative to the camera, while the faster ones moved axially past it. This facilitated discrimination between two nearly equal velocities, and permitted the measurement of even small relative motions. The ratio of faster to slower velocities varied from 1·2 to 2·9. The most common ratio, however, was 1·5/1. The higher velocity part of the two-layer velocity effect had a value which approximated that of the local mean velocity in the area of occurrence.

Some distinction should be made between a *shear layer* (figure 6*d*) and the *two-layer velocity* (figure 6*c*, also detail in figure 5). Both, of course, are shear layers, but they occur in different planes. A shear layer occurs as a result of a large $\overline{U}_x$ velocity difference over a small r distance, and appears as a rather sharp interface in a plane perpendicular to the wall. The two-layer velocity occurs as a result of different $\overline{U}_x$ velocities in two closely spaced radial planes.

Let us now return to our main discussion about the stream of fluid at the local mean velocity entering from upstream and interacting with the retarded field. The entry of this stream into the retarded field often resulted in an immediate interaction between it and the particles in the field (figure 6*b*). On other occasions it entered the field but seemed to be on a slightly different radial plane than the field particles, because it did not immediately affect them. This is the first example of the two-layer velocity (figure 6*c*). Gradually, as the flow proceeded across the field, it began to affect the field particles and accelerate them. As it began to interact with them, the two-layer velocity effect began to disappear.

The entering stream usually did an effective job of accelerating and displacing the fluid above a particular y^+ position. Below this position it only very gradually began to affect the retarded fluid. Therefore, at the time of ejection there was often a very sharp interface between the accelerated and retarded fluid. This created a very high *shear layer* (figure 6*e*). On those few occasions when the entering stream of the acceleration step approached with a large velocity in the direction of the wall, and at an angle to it, the particles penetrated into the region of the wall, and many entered the sublayer. Most of these latter lost their identity and were captured by the sublayer fluid and passed out of the field with it. Often, as this mass of fluid was proceeding wallward, there was a simultaneous ejection of the retarded wall region fluid outward. These elements were on a smaller scale than the flow towards the wall. The two opposing flows co-existed, but did not interact, although they were clearly passing one another; thus another example of the two-layer velocity (figure 6*f*). Of course, the fluid may have interacted with the main stream somewhere outside of our field of view. Let us recall, however, that this specific sequence involving the accelerating fluid moving towards the wall occurred only occasionally, and more often the accelerating fluid had a direction nearly parallel to the pipe wall.

The *ejection* itself was the abrupt movement outward from the wall area of fluid originally within this region. This event occurred immediately after the start of the acceleration process. It always originated within the mass of fluid constituting the retarded element. The particles which suddenly eject outward were, prior to this occurrence, observed to be moving much as other particles in the region. Once the steps preceding an ejection had occurred, the ejection itself proceeded very rapidly from the early stages to the fully developed stage. At this stage there was a continuing ejection of fluid outward for varying periods of time and then the ejection gradually ceased (figure 6*g*). Sometimes the ejection would occur just as the accelerating fluid entered the field (after figure 6*b*), while at other times it occurred after the acceleration process had begun (after figure 6*e*), but always before the entire field was completely accelerated. Since the acceleration and ejection occurred in conjunction, the motion pictures were carefully examined for evidence that the accelerating stream was a direct causative factor of the ejection step by some instability mechanism (i.e. a developing oscillation), but no such relation was discovered. At times there was some interaction between the fluid composing the entering stream and the retarded fluid, but most often the interaction occurred only after ejection had begun.

Other than the accelerating stream described above, no fluid from the outside of the region appeared to influence the ejections. It may be stated that the ejection event originated within the wall region, and was not a manifestation of some motion occurring outside of this region. The process was of a local nature and random with respect to time and space. It was of small scale and three-dimensional. Individual ejected fluid elements involved dimensions of the order of 0·03–0·06 in. measured axially (and x^+ of 20 to 40). The angular or θ dimension involved was difficult to measure but was estimated to be of the order of 0·01 to 0·03 in. (a θ^+ of 15 to 20). The estimates of sizes were based on the $\times$ 4·2 movies taken at a Reynolds number of about 20,000, for it was under these conditions the clearest pictures of the events were obtained. These scales are consistent with the maximum sizes estimated by Nedderman and mentioned in the introduction.

On numerous occasions the ejection first appeared at a particular position within the field, and while it was in progress other ejections occurred at adjacent downstream positions (figure 6*h*). At times these ejections appeared to be moving in a connected fashion, i.e. were correlated, but at other times there appeared two or more simultaneous ejections within the same field which were quite unconnected. Recalling that the field of view was approximately 0·095 in. in length one can obtain some idea of the size and local nature of the elements.

The region measured in the radial plane, where most of the ejections originate, was approximately $5 \leqslant y^+ \leqslant 15$ regardless of Reynolds number. There were some ejections which originated outside these limits. There was definite evidence of ejections originating at least as near the wall as a y^+ of 2·5. Below this position there was often a connected movement of particles which occurred simultaneously with the ejection, but rarely did they possess sufficient radial velocity to escape from the region. Their motion usually consisted of a slight outward movement which appeared as an axial flow at a slight angle to the wall.

The events just described can be compared to the most recent observations of Kline *et al.* (1967) that the streak pattern appears to migrate slowly downstream as a whole and drifting slowly outward with oscillations beginning in the region of y^+ of 8–12 and break up in the region of $y^+ > 10$. Their observations of the dye streak (their figure 15) can be explained by our observations. The slow outward movement just cited ($t = 0$). The 'oscillation' corresponds to the beginning of the ejection event. It is the low velocity fluid ejection that causes the dye streak to lift locally (their $t = \delta t$ which corresponds to our figure 6*f*). The 'oscillation' at the $t = 2\delta t$ sketch corresponds closely to our figure 6*h*, where two ejections are occurring. The present magnified view following the entire fluid motion, rather than the streak lines which are difficult to interpret, provides a clearer picture of the process. It is suspected that the dye injection technique is unable to detect those ejections which we observed to occur beyond a y^+ of 10, simply because the dye is unable to drift out beyond this distance. It is disrupted by other ejections and turbulent motions before it can do so. Our results clearly show that the ejection originates in the region of maximum production and not in the region of the wall to a $y^+ < 10$ as suggested by Runstadler *et al.* (1963). Furthermore, even though a dye injected at the wall finds itself eventually outside the viscous sublayer, this does not mean ejection occurs right to the wall. As noted, the closest we observed was at a y^+ of 2·5.

The ejected fluid moved outward from the region of the wall toward the centreline along a slightly curved path directed downstream. The curvature of the path as well as the distance outward which it attained initially depended upon its radial velocity and the position at which the high shear interface occurred. This interface did not always occur at the same position, but usually occurred in the zone $4 \leqslant y^+ \leqslant 32$. The exact position in any particular event depended upon the degree of deceleration and acceleration, and magnitude of the radial velocity component. In a few cases, however, no interface appeared within the field, a distance which ranged from y^+ of 40 to 75. As already noted, this often occurred during the flow towards the wall or when the deceleration took the plug-like flow form. In these instances the ejected element left the field essentially unaffected and with a substantial radial velocity component. There was no way of ascertaining if, in these cases, a shear region formed beyond a y^+ of 75. The path of the fluid before it interacted to any extent with the steep gradient was a slightly curved line at a small angle to the wall ($180\text{-}\phi$), and was directed downstream. The angles of ejection ($180\text{-}\phi$) had a wide distribution from a low of 1·5° to a maximum value of 21°. They had a most common value of 8·5° measured in the radial plane. The ejection angle was independent of Reynolds number. The instantaneous radial velocity components varied; some as high as 30 % of the axial component were observed. Most, however, fell within the range of 10–20 %. These, of course, represented the most energetic ejections. The magnitude of the radial velocity increased with Reynolds number, and this factor made the angle of ejection independent of Reynolds number. The ejection moved not only in the radial plane, but also in the plane parallel to the wall. These movements showed angles (θ) as large as 35° and an average angle of 15° measured from the axis. The instantaneous radial velocities within this plane were of the order of 20–30 % of the axial component. The agreement between the angles of ejection reported by others and those measured in this study are excellent. Runstadler *et al.* (1963) reported a distribution of angles; the maximum angle was 26° and the most favoured trajectory showed a slight dependency on Reynolds number, but fell within the range of 10° to 13°. The present study showed no dependency over the limited range studied. The maximum angle observed was 21°, and the average ejection angle was 8·5°. In addition, the measurements of Fage & Townend (1932) agree with the current observations in both magnitude and in dependency on the plane in which they were observed.

As the ejected fluid moved outward, it was accelerated axially to a small extent. Because of the retarded nature of the region below the interface, this acceleration was quite small and the fluid was still deficient in axial velocity. Upon reaching the steep gradient at the interface it suddenly encountered a fluid of much greater axial velocity, and a violent interaction occurred (figure 6*g*). This interaction created a great deal of turbulent motion and the movements of the fluid elements within it were very intense, abrupt and chaotic. The entire structure had a very small scale. The intensity of this interaction destroyed the identity of the individual elements. The interaction not only occurred between the mean flow and the ejected element, but the continual ejection of fluid into this chaotic mass by the remainder of the original element and others which could occur at approximately the same time caused increased interaction and mixing. The motions might be characterized as very disorganized with the particles having short, abrupt movements and sudden changes of direction and speed. The general movement of the entire region was, of course, downstream, but the chaotic motions spread out in all directions, and the more violent ones reached even to the sublayer and wall. In this manner the inner parts of the sublayer region were disturbed by the ejection. Some elements re-emerge, but many were captured within this region and persisted as less violent disturbances. The observed velocity fluctuations within the sublayer are well documented as previously indicated in the introduction. The depth of penetration was random, but generally greater penetration and intensity occurred at higher Reynolds numbers. The end result, in addition to the creation of the turbulent motion, was that the ejected element was disrupted and accelerated axially at the expense of the mean stream, and was convected downstream. The chaotic motion continued as it proceeded downstream. Since the elements originally possessed an outward directed radial velocity component, the fluid continued to spread outward. The general picture presented here agrees with that given by Kline *et al.* (1967), although exact analytical comparison cannot be made. The studies complement each other. The lower axial velocity of the ejected element is clearly shown in both studies. The actual trajectory of elements is much clearer from the work of Kline *et al.*

To support the conjecture that the ejections are the major contributors to the production of turbulence, the instantaneous values of $u_x u_r$ were calculated for the runs at $N_R \simeq 20{,}000$. The instantaneous values are predominately positive since u_x comes from a retarded flow and thus is negative ($\overline{U}_x > U_x$) and u_r is always negative (inward from the wall). Only 22 observations were available; these were averaged in an accumulative manner; i.e. an ejection originating near the wall contributed to the stress further out. Finally, at this Reynolds number, ejections disturbed the flow on the average 18 % of the time (from figure 8); thus, the calculated value applied only 18 % of the time. The results are shown in figure 7 and account for 70 % of the stress reported by Laufer (1954). A similar estimate at $N_R \simeq 30{,}000$ gave 50 %. In spite of the small sample available and the crudeness of the estimate, the results do indicate that the ejections are very energetic and well correlated so as to be a major contributor to this Reynolds stress and thus the production of turbulent energy. In their recent publication, Kline *et al.* (1967) suggest that this might be true and noted that in some more recent measurements they did observe large values of the instantaneous stress.†

Tritton (1967) recently suggested that the coherent eruption idea implies a negative contribution to the Reynolds stress and thus should be abandoned. This can be corrected by our observations. It is not the motion away from the wall and a faster motion downstream (from the outer regions) that act together, but rather the former with a retarded (slower than the mean) motion downstream. Indeed, the faster motions (acceleration and sweep stages) were usually nearly parallel to the wall and thus would contribute little to the Reynolds stress. On those few occasions that the faster flow moved wallward, this would also be a positive Reynolds stress contribution, and may in part account for the difference between the known total Reynolds stress and that estimated from the ejections. Of considerable importance is our observations that the source of the stress come from the small ejection eddies. The large eddy structure coming from the outer part contributes little. These observations are in accord with the hypothesis of Townsend (1961) of active and inactive parts of the flow and with the recent measurements of Bradshaw (1967).

The position of the zone of interaction changed with the position of the interface. Most commonly the interaction zone occurred over the region $7 \leqslant y^+ \leqslant 30$, although the extremes were from 4 to 32. This can be compared to zone of turbulent activity given as $10 \leqslant y^+ \leqslant 30$ by Kline *et al.* (1967). As noted, once

† Prof. Kline has indicated that in their recent report MD-20, they were able to show quantitatively that essentially all the production does occur during the ejection.

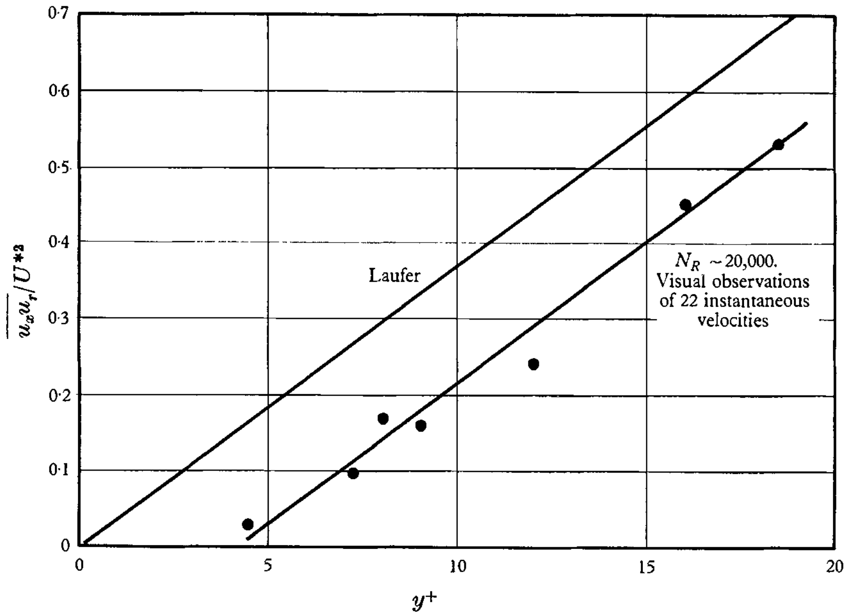


FIGURE 7. Reynolds stress.

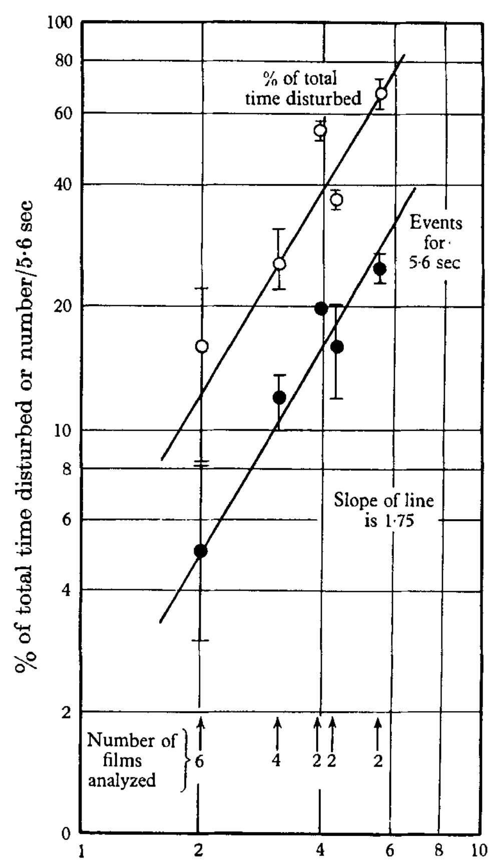


FIGURE 8. Event frequency and disturbed per cent as a function of Reynolds number.

within the interaction zone, the fluid experienced a rapid acceleration downstream. As the distance from the wall was increased, the character of the fluid motions changed. In the wall region and out to just beyond the interaction zone, i.e. y^+ of 50, the motions were of small scale, intense and abrupt. By a y^+ of 70 the greater part of the change to conditions of the outer region had occurred. By a y^+ of 150 the change was completed and thereafter it was of degree rather than character. These outer regions had an increasingly larger scale of disturbance, but the intensity was reduced. The disturbances appeared as large sweeps moving across the field of view at a large angle to the axis. The length was always much longer than the width. The motions were so much larger than the field of view that they were difficult to define. They also passed through the field so swiftly that the nature of their internal structure could not be studied. They appeared to be segments of a large structure which existed in the outer region.

The ejection phase ended with the entry from upstream of a stream of fluid which was directed primarily in an axial direction; this is the *sweep* event (see figure 6*i*). This fluid had an axial velocity that corresponded to that which a normal velocity profile would predict. Usually the ejections had subsided by the time it appeared and it swept the field of elements of retarded flow and re-established a semblance of a normal velocity profile. On some occasions the entering stream did not interact with the particles, but appeared to pass them much in the fashion of the two-layer velocity. After a time, however, the entering stream seemed to encroach upon the field fluid and eventually interacted with it. In both cases the interaction usually produced some chaotic motion. While this action terminated the cycle of events, it did not mean that all disturbances in the wall region disappeared. There remained minor disturbances.

Still photographs of the ejection event have been reproduced from the movie film, but we have found these to be quite inadequate and confusing when compared to the detailed dynamic view obtained in the movies. Several such examples were given by Corino (1965). It is hoped that figure 6 gives the reader a feel for the occurrences and that Corino's thesis and viewing of the movie will provide additional details. Again, the tabulations of the actual measurements of the velocities, sizes, and directions of the various motions can also be found in the thesis by Corino.

4.2. *Reynolds number effect*

At low Reynolds numbers (2300) the flow was laminar and there was a complete absence of any departure from the smooth flow parallel to the wall. At a Reynolds number of 5360, the steeper turbulent velocity was evident and displayed the first evidence of the unsteady nature of the wall region. It appeared as an occasional deceleration–acceleration sequence of the local mean axial velocity. No significant departures from the axial flow were observed, but generally the flow appeared more agitated than previously. Upon increasing the Reynolds number to 11,280, the deceleration–acceleration sequence of the local mean axial velocity was observed to occur with increased frequency, about once per second on the average. The majority of the particles moved axially, but some few had significant departures from the axial in both directions. These constituted the first notable departures from purely axial flow. At this Reynolds number the first evidence of the two-layer velocity effect occurred.

When the films taken at a Reynolds number of 21,000 were studied, the full nature of the wall region was revealed. The entire sequence of events surrounding the ejection process were repeated a number of times in excellent detail. Here for the first time was unmistakable evidence of the ejection of fluid from the wall region outward, and the subsequent interaction with mean flow. Upon increasing Reynolds number in steps to 50,000 the analysis showed that the changes which occurred were not in the basic character of the ejection process, but in the intensity and frequency of occurrence of these events. With each increase in Reynolds number there was an increase in the number and intensity of ejection events, so that by 52,000 the events occurred so often and at such close intervals that even in the periods between events the fluid was highly agitated, and it was extremely difficult to determine where one event ended and the next began. Also, there was an increase in the intensity of the created turbulence, and, therefore, the effect was more clearly felt in the regions very near the wall.

Initially, in order to assign a quantitative value to the relationship between frequency of occurrence and Reynolds number, an attempt was made to count the individual events which occurred during a given time period. This was satisfactory for Reynolds numbers of 20,000 or lower, but above 30,000 the difficulty of separating individual events from each other and the intervening fluctuations became so great that confidence in the counts was greatly reduced. Nevertheless, an estimate was made and the ejections occurred approximately five times more often at Reynolds number of 50,000 than at 20,000. Because of the difficulties encountered in the preceding method of analysis, an alternate method of obtaining essentially the same information was devised. An electric counter was used to count the number of motion picture frames in which the fluid in the wall region was significantly disturbed. From this count and the knowledge of the actual number of frames per second at which the film was exposed, one could determine the percentage of the total photographed interval during which the wall region was significantly disturbed. In this method it was not necessary to separate individual events if they overlapped or if the intervening disturbances were very intense. If they exceeded a minimum intensity, they were included. This is a measure of the fraction of the time the region was disturbed and is not an intensity of turbulence because any time above the arbitrary minimum intensity was counted as being just as important as a very high intensity period. The reproducibility of this method was excellent. Figure 8 shows the results of the two methods and the agreement between them. Each point represents the average of the number of films noted. The limits are also shown. The solid line represents $N_R^{1.75}$ which is equivalent to a U^{*2} dependency. This is to be expected as based on wall similarity ideas; the variation with Reynolds number is a variation only in scale. Typical frequencies would be proportional to U^{*2}/ν or $N_R^{1.75}$. Kline *et al.* (1967) found a U^{*3} dependence, but their technique of measurement was different; their technique gives a frequency of break-up per unit of span, while ours is an average frequency essentially at a point.

$$F/\text{span} = F/\lambda \propto FU^*/\nu,$$

since $\lambda U^*/\nu$ was constant. Now if FU^*/ν is proportional to U^{*3} as they observed, F, the frequency at a point must be proportional to U^{*2}, as we observed. Thus, the observations are in agreement. Black (1966) found the same dependency (U^{*2}) for correlation of wall-pressure gradients at a point at the wall.

The dichotomy in the nature of this basic event is interesting. In the fundamental structure and form the dependency is independent of mean flow parameter, and seems only dependent upon local conditions. Thus, the sequence of events, the ejection angles, the small scale, and the general random behaviour are divorced from mean flow dependency. However, the frequency of occurrence, the ejection velocity, and the position of the different zones show a distinct relation to mean flow parameters. It would appear that the mean flow situation operates to provide conditions locally which are conductive to the occurrence of an event, but that the event depends directly only upon the local conditions.

5. Summary

It is convenient to divide the radial distance from the wall to the centreline of the pipe into three distinct regions, each of which displays fluid motions of a particular character. While the character of the fluid motion is quite distinct, the lines of demarcation between regions are not sharp and a degree of overlapping occurs between adjacent zones. The following summary is based on the observations and measurements of this work and measurements of others all of which have been detailed in the composite picture in the previous section.

5.1 *Sublayer region* ($0 \leqslant y^+ \leqslant 5$)

This may be called the sublayer region, but the adjective 'laminar' is not used because the fluid motions with this region are definitely not laminar. The fluid within it continually exhibits departures from rectilinear flow in the form of excursions of small masses of fluid moving at some angle to the wall. The disturbances are three-dimensional. The amount of fluid involved in any single movement is quite small, indicating a rather small scale of disturbance. These disturbed elements rarely leave the region, although a few with particularly strong deviating velocities do escape outward. The fluid motions within this zone which depart from the mean axial motion are, for the most part, produced and sustained by the turbulence generated in the adjacent one (generation region). The degree of disturbance within the sublayer is dependent upon the degree of turbulence within the generation zone. Since this latter is dependent on the Reynolds number of the flow, a definite dependency on Reynolds number exists for the disturbed motions within the sublayer. This manifests itself in the form of a greater number of deviations from axial flow with increasing Reynolds number. Of course, if the wall region parameters ν and U^* are used to make the intensity dimensionless, it is known that the Reynolds number effect is accounted for. At higher Reynolds numbers, fluid from the generation region repeatedly penetrates deeply into this region, and occasionally some penetrates to the wall. This penetration indicates that a mixing process is occurring not only within the sublayer region, but between this region and fluid from the generation zone.

Such a mixing and agitating process is very important in mass and heat transfer considerations. Since the generation region exhibits a nonregular periodicity in time, the sublayer regions does too. However, the periodicity within the sublayer is much less pronounced due to attenuation and averaging effects.

5.2. *Generation region* ($5 \leqslant y^+ \leqslant 70$)

This is the most important region since within it the major generation and dissipation of turbulence energy occurs. While its limits approximately coincide with the commonly described buffer zone, it cannot in any way be considered as such. Instead of a relatively passive transitional zone, this region is the position of origin of the majority of the fluid ejections, ($5 \leqslant y^+ \leqslant 15$), and also contains the positions where the maximum interaction of these ejections with the higher axial velocity of the mean stream occurs ($7 \leqslant y^+ \leqslant 30$). The ejection process and subsequent interaction at a region of high shear is a mechanism whereby energy is extracted from the mean flow and converted into turbulence energy. The evidence to support this has been presented in the previous section. The character of the ejections is basically dependent on local conditions. The ejections do, however, exhibit dependency on mean flow parameters with regard to the frequency of occurrence and velocity of ejection. The connexion between the mean flow and the local conditions which creates this dependency is not apparent from the data. The nature of the interaction, being of high shear and involving individually small elements of fluid, results in a small scale of turbulence and a very disorganized chaotic motion. A large part of the turbulence energy created here is also dissipated here.

Based on the limited information available, many authors have speculated on what is the cause of the ejection phenomenon. Unfortunately, not enough information is available from this study to completely explain it; however, the observations do have bearing on the suggestions that have appeared in the literature. Space does not allow detailed discussion of all of these, but some general comments are appropriate. First, the various references cited are: Einstein & Li (1955), Malkus (1956), Townsend (1956, 1958, 1961), Grant (1958), Ferrari (1959), Landahl (1967), Bakewell (1966), Kline *et al.* (1967), Wills (1967), Black (1968), Phillips (1967), Willmarth & Tu (1967), Schubert & Corcos (1967), Sternberg (1967).

Some of these invoke the idea of a hydrodynamic instability with subsequent vortex formation which is instrumental in the exchange between the wall layer and the main stream. In our work (Corino 1965), because of the possible similarity between the wall region and the laminar-turbulent transition, we thought that the shear layer might be unstable and give rise to ejections by some instability mechanism. Consequently, the films were carefully studied to see if any oscillatory motion could be detected. As already cited, none was, and furthermore no tight rotation of fluid elements was observed, except on very few occasions. These observations do not rule out a catastrophic non-linear instability, but do make improbable a simple linear instability (oscillation) followed by vortex formation as is visualized for the transition problem. Furthermore, as discussed in the previous sections, the oscillations of the dye streaks observed by Kline *et al.* can be explained by the ejection sequence.† Nevertheless, their conjecture that wall-layer streak breakup (the ejection event) plays an important role in determining the structure of the entire turbulent boundary layer is supported. Indeed, there is broad agreement on the picture of what happens, i.e. shear layer formation, two-layer velocity, ejection, etc.; it is the suggested reason for this that is not confirmed. Black's mechanistic picture requires instability, horseshoe vortex formation, etc.; but, more important, it requires that the ejection fluid (vortex) be at a velocity greater than the mean as given by the law of the wall. This is in direct contrast to our observation that the ejection fluid is from a retarded region.

The deduction of Townsend (1958) and the further measurements of Bakewell (1966) suggest a large eddy structure of elongated streamwise extent that gives rise to a region of strong updraft of the fluid between the eddies. The scale size is consistent with the two-layer velocity observation, but we cannot put quantitative numbers on these observations, as could Willmarth & Wooldridge (1962), Willmarth & Tu (1966), and Mitchell & Hanratty (1966). Townsend (1958) also proposed an outer wake-like layer that was dominated by jets of turbulent fluid from the wall region into the relatively undisturbed outer region. The exact correspondence of events is difficult to establish but clearly the correspondence is there.

Ferrari (1959) and Grant (1958) have attempted to explain similar type occurrences by introducing the effects of pressure fluctuations and gradients, and local instabilities due to vortex stretching. Grant in particular observed jets of fluid emanating from the edges of turbulent wakes and projecting into the main stream. He reasoned that the initial conversion of the mean flow energy to turbulence energy favours certain components, the ones aligned with the direction of stretching of the vortex element. This results in stress being established in the wake which eventually must be relieved. He proposes that the jetting fluid elements represent a secondary flow caused by the stress relieving process.

There has been disagreement on the nature of the sublayer being active or passive (see Kistler 1962). Our film shows the innermost part ($0 \leqslant y^+ \leqslant 2{\cdot}5$) to be essentially passive and the rest ($y^+ \gtrsim 2{\cdot}5$) active. This has the advantage of agreeing with other investigators when their suggestions are interpreted in terms of our observations. Kline *et al.* (1967) cited a communication with Pfenninger, who showed that a small amount of wall suction can markedly decrease turbulence. From this they concluded the region must be active. Their active region would be composed of our thin, passive layer next to the wall and the adjacent active area. Our interpretation or explanation of the experiment would be that any wall suction would counteract the radial ejection velocity (which is approximately 10 % of the local mean velocity and therefore small) and thus suppress turbulent production. Of course, removal of the entire region, both passive and active, would relaminarize the flow, and this is what Kline *et al.* suggested. They discarded the possibility of a large passive region as against a large active one. The removal of a thin passive region was not considered. Our observations

† In retrospect, our observations cannot rule out an oscillation or spiral motion of a scale of the order or larger than our view. The recent observations of Kline *et al.* (report MD-20) are apparently of this nature.

of the thin passive region also accommodate the objection made by Bradshaw (1967), that the disturbances cannot originate in the viscous sublayer ($y^+ \gtrsim 5$). For the most part, the ejections occur outside this range, and thus one would not expect a dependence on wall conditions. It is known empirically that the Von Kármán constant does not depend on the nature of the wall. The work of Mitchell & Hanratty (1966), summarized by Hanratty (1967), does not support the idea of a large passive region, but again does not rule out the thin region observed in our films. Their spectral measurements support the idea, as noted by Hanratty (1967), although this may be simply indicative of our observation that in the immediate vicinity of the wall the fluctuations are of a much smaller scale than in the generation region. The sum total of views, including our films, leads us to suspect that the sublayer region does respond passively to the events occurring in the adjacent active generative region. The picture is complicated by the fact that the thin sublayer is not of a constant set thickness but rather depends on the location of the ejection event ($5 \leqslant y^+ \leqslant 15$), and indeed on all other events in the generation zone. The picture is further complicated by the occurrences at times of disturbances right to the wall as a result of interaction between the ejection and the shear layer in the region of $7 \leqslant y^+ \leqslant 30$. It would appear that a very simple mechanistic picture will not suffice; what is of importance is that interactions do occur between regions and in both directions.

5.3. *Core region* ($y^+ > 70$)

From our work and that of the others previously cited, one can conclude that the eddies in this region have been created in the generation region and have diffused or been convected to this position. The eddy size increases with increasing distance from the generation region. Much of the change in character from the generation region to this region occurs within the approximate limits $50 \leqslant y^+ \leqslant 100$, but the entire zone of $50 \leqslant y^+ \leqslant 150$ may be considered transitional. Beyond approximately $y^+ = 150$ the changes are less marked, and even the growth in eddy size proceeds at a diminished rate. The size and reduced relative motions do not create much turbulence. Nor are these characteristics likely to cause much dissipation, although within the large scale eddies the small scale will produce some.

This entire region contains eddies which originated within the generation region of various upstream positions. It is more dependent upon what occurred upstream than what is occurring in the wall region at the particular time or axial position at which it is observed. This is a result of the fact that the turbulence requires a finite time to diffuse outward, and the velocity profile which causes the core region to move faster axially than the inner regions. The core region, therefore, contains an average sampling of much that has occurred in the inner regions upstream, and as such is a history of these events. This process tends to produce an integral effect on the nature of the motions in this region which eliminates much of the periodicity and local character of the generation zone. It also produces a rather stable character where the fluid motions respond only slowly to local changes which would affect the generation and sublayer regions very quickly. This dependence on preceding events but not on events which are local in space or time could be a factor in the explanation as to how the mean flow affects the local conditions which produce the ejection events.

6. Recapitulation and conclusions

The preceding discussion has demonstrated that the present observations of the nature of the wall region in turbulent pipe flow are compatible with the results reported by numerous other investigators who used quite diverse methods of study. It is particularly important to note that the agreement quite often occurred between measurements that were obtained by very different means. Thus, in considering the scale of disturbance, the observed increase in size with increasing distance from the wall agreed quantitatively with the visual studies of Kline *et al.* and Nedderman, qualitatively with the hot wire measurements of Laufer, and with the indirect measurements of Mitchell & Hanratty. The nature and position of certain distinct zones in the wall region agreed with the visual observations of others, and with the quantitative measurements of Laufer. The position of these regions corresponded approximately to the traditional division of sublayer, transition, and core, but the nature of the regions was observed to be quite different from the traditional view. The fact that no one has before made visual studies of the wall region which would have revealed the details of the region on a par with the present study, precluded any possible comparison in this regard. In some cases, certain unexplained effects observed in other studies could be explained by the more detailed knowledge gained from the present study.

On the basis of this work one may conclude:

(i) In turbulent pipe flow the turbulent motions have a distinctive character which is a function of the distance from the wall. Within the distance of $y^+ \leqslant 5$ the flow is not laminar, but is disturbed by velocity fluctuations of small magnitude, and by the intrusion of bulk elements of fluid from the adjacent region. The region, $5 \leqslant y^+ \leqslant 70$ contains the position of origin of fluid ejections, $5 \leqslant y^+ \leqslant 15$, and the position of interaction of these elements with the main flow, $7 \leqslant y^+ \leqslant 30$, to create turbulence. The region beyond $y^+ > 70$ has reduced intensity of velocity fluctuations, and a larger scale of turbulence than the preceding region.

(ii) The most important feature of the wall region is the ejection of fluid elements which occurs there. These ejections are three-dimensional disturbances which occur locally, and randomly with respect to time and axial position. They have a well-defined character which is independent of mean flow parameters. The intensity and frequency of occurrence are, however, a measurable function of these parameters. The interaction of these elements with the mean flow creates turbulence.

(iii) The composite picture presented defines the function and importance of the observed fluid motions in proper context with the known properties of turbulent flow. To the extent that a comparison is possible, the observed character of the wall region is not contradicted by any existing evidence, and in a number of cases it is supported by results obtained by quite different means.

The National Science Foundation (G-14807) provided considerable support for this project. In addition, one of us (E.R.C.) obtained support from The Ohio State University in the form of a graduate assistantship and fellowship supported by the ESSO Research and Engineering Co. The Dow Chemical Company kindly supplied quite large quantities of trichloroethylene, their Neu-tri product. Harry C. Hershey offered help in reviewing the manuscript, and a recent exchange of views with S. J. Kline shed light on rationalizing the very few apparent, but not real, differences between his work and ours.

REFERENCES

Bakewell, H. P. 1966 Ph.D. Dissertation, Department of Aerospace Engineering, Pennsylvania State University.

Black, T. J. 1966 *Proc. Heat Transfer & Fluid Mech. Inst. Stanford Univ.*

Black, T. J. 1968 *AIAA 6th Aerospace Sciences Meeting*, Paper no. 68–42.

Bradshaw, P. 1967 *J. Fluid Mech.* **30**, 241.

Brodkey, R. S. 1967. *The Phenomena of Fluid Motions.* Reading, Mass.: Addison-Wesley.

Corino, E. R. 1965 Ph.D. Dissertation, The Ohio State University.

Danckwerts, P. V. 1951 *Ind. Engng Chem.* **43**, 1450.

Deissler, R. C. 1955 *NACA* TR 1210.

Deissler, R. C. & Eian, C. S. 1952 *NACA* TN 2629.

Einstein, H. A. & Li, H. 1955 *Heat Transfer & Fluid Mech. Inst. Univ. California, Los Angeles*, Paper 13.

Fage, A. 1963 *Phil. Mag.* **21**, 80.

Fage, A. & Townend, H. C. H. 1932 *Proc. Roy. Soc.* A **135**, 656.

Ferrari, C. 1959 *NASA* RE 2-8-59W.

Grant, H. L. 1958 *J. Fluid. Mech.* **4**, 149.

Hanratty, T. J. 1956 *A.I.Ch.E.J.* **2**, 359.

Hanratty, T. J. 1967 *Phys. Fluids* **10**, S216.

Harriott, P. 1962 *Chem. Engng Sci.* **17**, 149.

Higbie, R, 1935 *Trans. A.I.Ch.E.* **31**, 365.

Hinze, J. O. 1958 *Turbulence* New York: McGraw-Hill.

Kármán, T. von 1939 *Trans. ASME.* **61**, 705.

Klebanoff, P. S. 1954 *NACA* TN 3178.

Kistler, A. L. 1962 *Méchanique de la Turbulence*, Editions du Centre National de la Recherche Scientifique, p. 287.

Kline, S. J., Reynolds, W. C., Schraub, F. A. & Runstadler, P. W. 1967 *J. Fluid Mech.* **30**, 741.

Kline, S. J. & Runstadler, P. W. 1959 *J. Appl. Mech.* **26**, 166.

Landahl, M. T. 1967 *J. Fluid Mech.* **29**, 441.

Laufer, J. 1954 *NACA* TR 1174.

Lin, C. S., Moulton, R. W. & Putnam, G. L. 1953 *Ind. Engng Chem.* **45**, 636.

Ludwieg, H. & Tillman, W. 1949 *Ing.-Arch.* **18**, 288.

Malkus, W. V. R. 1956 *J. Fluid Mech.* **1**, 521.

Mitchell, J. E. & Hanratty, T. J. 1966 *J. Fluid Mech.* **26**, 199.

Nedderman, R. M. 1961 *Chem. Engng Sci.* **16**, 113.

Phillips, O. M. 1967 *J. Fluid Mech.* **27**, 131.

Prandtl, L. 1904 *Proc. 3rd Int. Math. Congr., Heidelberg*, 1928; *NACA* TM 452 (trans.).

Reichardt, H. 1951 *Z. angew. Math. Mech.* **1**, 208.

RUNSTADLER, P. W., KLINE, S. J. & REYNOLDS, W. C. 1963 Stanford University, Department of Mechanics Engineering Dept, Rept. MD-8.

SCHRAUB, F. A. & KLINE, S. J. 1965 Stanford University, Department of Mechanical Engineering, Rept MD-13.

SCHUBERT, G. & CORCUS, G. M. 1967 *J. Fluid Mech.* **29**, 113.

STERNBERG, J. 1967 *Phys. Fluids* **10**, S 146.

TOOR, H. J. & MARCHELLO, L. M. 1958 *A.I.Ch.E.J.* **4**, 97; 1963 *Ind. Engng Chem. Fund* **2**, 8.

TOWNSEND, A. A. 1956 *The Structure of Turbulent Shear Flow*. Cambridge University Press.

TOWNSEND, A. A. 1958 *Boundary Layer Res. Symp., Int. Union Theor. & Appl. Mechs.* Berlin: Springer.

TOWNSEND, A. A. 1961 *J. Fluid Mech.* **11**, 97.

TRITTON, D. J. 1967 *J. Fluid Mech.* **28**, 439.

WILLMARTH, W. N. & TU, B. J. 1967 *Phys. Fluids* **10**, S 134.

WILLMARTH, W. N. & WOOLDRIDGE, C. E. 1962 *J. Fluid Mech.* **14**, 187.

WILLS, J. A. B. 1967 *Nat. Phys. Lab. Aero. Rep.* no. 1224.