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Intermittency measurements in the turbulent boundary layer

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An improved version of Corrsin & Kistler's method has been used to measure intermittency in favourable and adverse pressure gradients, and the characteristic parameters of the intermittency have been related to the form parameter H of the mean velocity profiles.

It is found that with adverse pressure gradients the centre of intermittency moves outward from the surface while the width of the intermittent zone decreases. The converse is true of favourable pressure gradients, and it seems likely that at sufficiently low values of H the flow over the full depth of the layer is only intermittently turbulent.

A new method of intermittency measurement is presented which makes use of a photo-electric probe. Smoke is introduced into the boundary layer and illuminated by a narrow beam of parallel light normal to the surface. The photo-electric probe is focused on the illuminated region and a signal is generated when smoke passes through the focal point of the probe lens. Comparison of this signal with the output from a hot-wire at very nearly the same point shows the identity of smoke and turbulence distributions.

1. Introduction

Intermittency is the name given to the alternation between turbulent and non-turbulent motion that charaterizes certain types of flow: it is commonly denoted by the symbol γ and is defined as the ratio of time turbulent to total time at any point, so that it measures the probability of finding turbulent flow at any instant at the point considered.

Intermittency is observed in two quite different flow situations. First, in the breakdown of a laminar shear flow to turbulence, a process which normally occurs over an appreciable streamwise distance and is characterized by the growth of initially small and randomly distributed patches of turbulence which finally coalesce. Secondly, at the free boundary of a fully developed turbulent shear flow, where the outer edge of the turbulence fluctuates with time so that over an appreciable distance in the cross-stream direction the flow alternates between turbulent and substantially irrotational. It is this second situation with which the present investigation is concerned.

Earlier measurements of the distribution of intermittency in the outer regions

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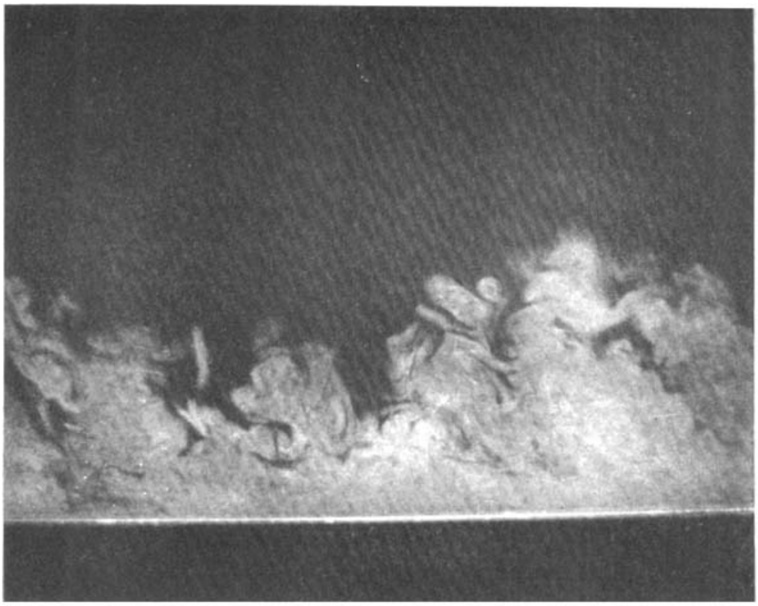
of turbulent boundary layers have been confined to zero pressure gradient (Klebanoff 1954; Corrsin & Kistler 1954) and the object of the present investigation was to obtain more extensive data which could be used to obtain an improved method of calculating turbulent boundary-layer development.

An earlier method (Head 1958), based on the simple hypothesis that the non-dimensional rate of entrainment of fluid into the turbulent boundary layer could be specified as a function of the mean velocity profile, had proved surprisingly successful (Thompson 1964), and it was hoped that the method could be further improved by considering the flux of fully turbulent fluid in the boundary layer rather than the total flux, a knowledge of the intermittency distribution obviously being required to relate the two quantities. It was also hoped that the measurements might ultimately prove useful in contributing to a general theory of entrainment which would replace the present empirical approach to the subject (Spalding 1964). However, quite apart from any contribution they might make towards these rather specialized objectives, the results of the investigation appear to have sufficient general interest to make them worth recording.

In the initial stages of the investigation intermittency measurements were made using the same type of hot-wire apparatus as that used by Corrsin & Kistler (1954). It soon became apparent that with this type of intermittency measuring unit the setting of the discriminator presented very real difficulties and various modifications were incorporated which considerably eased the problem and at the same time improved the potential accuracy of measurement. It also seemed of interest to develop an alternative means of intermittency measurement. This was based on earlier flow visualization studies where smoke was introduced into the boundary layer and illuminated by a plane of light normal to the surface so that a cross-section of the boundary layer was made visible. Figure 1 (plate 1) shows flash photographs of such cross-sections. By focusing a suitable photosensitive device on the illuminated region and passing the output to the same intermittency measuring unit as had been used with the hot-wire, it seemed likely that a similar record would be obtained. In fact the two records would be expected to be identical if the smoke were effectively confined to the turbulent regions. This seemed *a priori* a plausible enough assumption and it was in fact confirmed in detail in the course of the investigation.

Measurements of intermittency were carried out in the normally developing boundary layer with various pressure distributions and in the boundary layer following reattachment. Quite marked differences between the two cases were observed. In the boundary layer developing normally in a favourable pressure gradient it was also noted that there appeared to be a limiting (minimum) value of the form parameter H (the ratio of displacement to momentum thickness), which confirmed the observations of Launder (1964) and Patel (1965) in layers reverting to laminar flow. Extrapolation of the intermittency measurements further suggested that at this (or a very similar) value of H intermittency extended right through the boundary layer.

There are two possibly important limitations of the present investigation: first, the range of boundary-layer Reynolds numbers covered is relatively small, and secondly, the boundary layers, particularly close to separation, were far from



(i) $R_\theta \approx 5000$.

(ii) $R_\theta \approx 1000$.

FIGURE 1. Smoke photographs of the turbulent boundary layer.

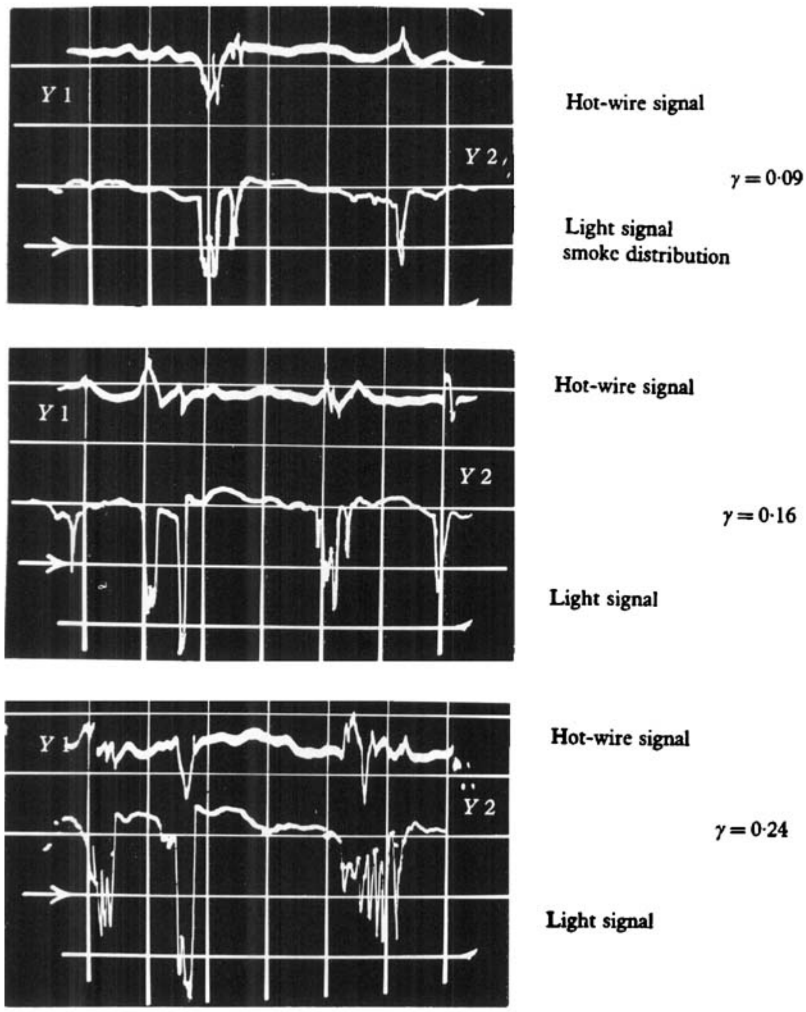


FIGURE 14. Simultaneous oscilloscope traces of hot-wire and light signals at various intermittency values. Distance between hot-wire and focusing point of the photo-probe: 2 mm.

equilibrium. Further experiments are therefore required to establish the effects of Reynolds number and of departures from equilibrium conditions. It would also be of interest to carry out intermittency measurements in more highly favourable pressure gradients to check the suggestion that the process of laminar reversion is accompanied by the spread of intermittency through the entire thickness of the boundary layer.

2. General description of intermittency

As a result of numerous hot-wire investigations it has been firmly established that the turbulence occurring in jets, wakes and boundary layers is instantaneously confined within a more or less clearly defined boundary, commonly termed the turbulence front, which is highly irregular in shape and constantly varying with time. According to Corrsin & Kistler (1954) the turbulence front takes the form of a continuous laminar superlayer, and, while this may in certain respects be an oversimplified description, it emphasizes the sharpness of the division between turbulent and non-turbulent fluid and the fact that the advance of the turbulence front and the entrainment of irrotational fluid take place through the action of viscosity. According to Townsend's picture of the structure of turbulent shear flows (see, for example, Townsend 1956) the continuous deformation of the turbulence front takes place through the action of large and relatively slow-moving eddies and this description, which appears to be generally accepted, is in accordance with visual observations of the smoke-filled boundary layer.

It has been found from experiment that the distribution of intermittency in the y-direction (i.e. normal to the surface in the case of a boundary layer) can be represented with considerable accuracy by the expression

$$\gamma = \frac{1}{\sigma\sqrt{(2\pi)}}\int_y^\infty \exp\left[-\frac{(y-\overline{Y})^2}{2\sigma^2}\right] dy,$$

where $\overline{Y}$ and σ are general intermittency parameters defined as follows: $\overline{Y}$ is the value of y for which $\gamma = 0{\cdot}5$ and is therefore the statistical measure of the mean position of the turbulence front. σ, the standard deviation, is a measure of the width of the intermittency distribution and is defined by

$$\sigma = [\overline{(Y-\overline{Y})^2}]^{\frac{1}{2}} = \left[\overline{Y}^2 + 2\int_0^\infty (y-\overline{Y})\gamma\, dy\right]^{\frac{1}{2}},$$

where Y is the instantaneous position of the turbulence front. From this expression it follows that γ is effectively equal to 1 for $y-\overline{Y} \simeq -2{\cdot}8\sigma$, and zero for $y-\overline{Y} \simeq 2{\cdot}8\sigma$.

3. The measurement of intermittency

Two basically different methods have been used in the past for the measurement of intermittency. The first, the so-called flatness-factor method, is indirect and depends upon the fact that the square of a time-mean quantity is in general different from the time-mean of that quantity squared. Consider a quantity q

which is essentially positive inside the turbulent fluid and zero outside it. Then, if $\bar{\bar{q}}$ is the mean value of q over the time during which the flow is turbulent and $\bar{q}$ is the mean value over all time,

$$\bar{q} = \gamma\bar{\bar{q}}, \quad \text{or} \quad \bar{q}^2 = \gamma^2\bar{\bar{q}}^2.$$

Using the bars with the same significance applied to the quantity squared, we can also write

$$\overline{q^2} = \gamma\overline{\overline{q^2}}.$$

Hence, combining these last two equations, we obtain

$$\gamma = (\overline{\overline{q^2}}/\bar{\bar{q}}^2)/(\overline{q^2}/\bar{q}^2).$$

The ratio $\overline{\overline{q^2}}/\bar{\bar{q}}^2$ is assumed to be invariant throughout the fully turbulent fluid so that it can be measured where the flow is continuously turbulent. A measurement of the ratio $\overline{q^2}/\bar{q}^2$ at any other position will then give the value of the intermittency. The quantity q might represent the concentration of a contaminant introduced into the turbulent flow but it is in fact usually taken as the square of a velocity derivative although, as Corrsin & Kistler have pointed out, this quantity is not strictly zero in the irrotational flow. This method of intermittency

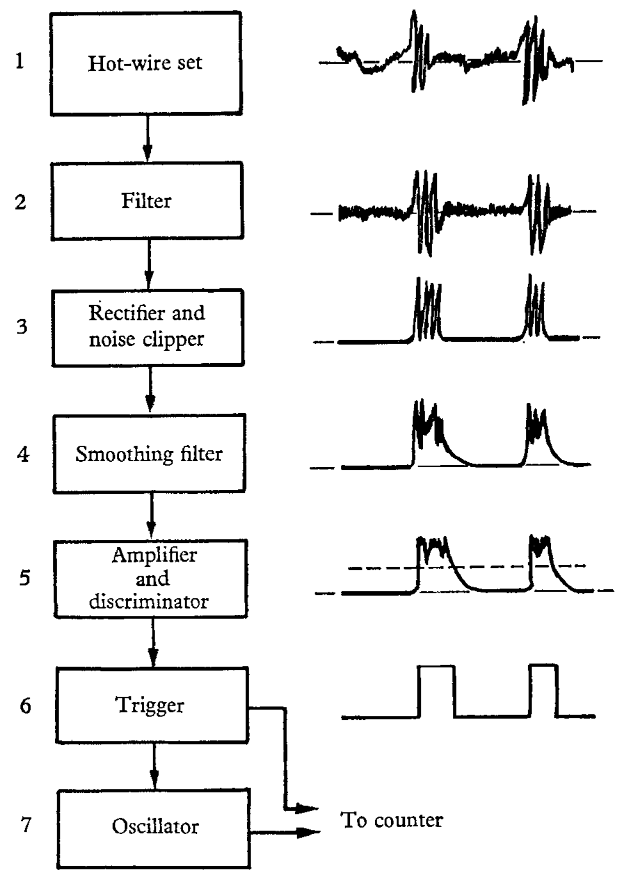


FIGURE 2. Block diagram of intermittency-measuring unit according to Corrsin & Kistler.

measurement was introduced by Townsend (1948) and has also been used by Klebanoff (1954) and Sandborn (1959).

The method described by Corrsin & Kistler (1954) is more direct, the output from the hot-wire being transformed into an on–off signal, 'on' when the flow is turbulent and 'off' when it is not. A block diagram of the apparatus is shown in figure 2, from which it will be seen that the hot-wire signal passes in turn through a filter, a rectifier and noise clipper, a smoothing circuit and an amplifier and discriminator. The output from the discriminator operates a Schmitt trigger circuit, and an oscillator and two counters allow the value of the intermittency to be obtained as the quotient of the readings of the two counters, one of which operates only while the flow is turbulent while the other runs continuously.

The difficulty in using this apparatus was found to lie in choosing the appropriate discriminator setting, only a small change in setting being required to vary the apparent intermittency over a wide range. The method used by Corrsin & Kistler to obtain the correct setting consisted of comparing the original hot-wire signal (or its differentiated form) with the trigger output on a two-beam oscilloscope, varying the setting until the lengths of the bursts as shown by the two traces agreed. Unfortunately, in the present investigation the results obtained by following this procedure, without actually photographing the traces, were not altogether reproducible and some effort was devoted to finding a way around the problem and to improving the general accuracy.

3.1. *Modifications to the intermittency measuring unit*

The sensitivity to discriminator setting just described arises from the shape of the pulse representing the turbulent burst as it leaves the smoothing circuit. This arises in turn from the fact that a condenser is incorporated in the circuit to give a continuous signal during the period of a turbulent burst, i.e. to eliminate the zeros which are necessarily present in the signal as it is first rectified. As an alternative to the use of a capacitor the effect was tried of producing a small phase shift in the signal from the rectifier and adding this to the original rectified signal. By a suitable choice of phase shift the expansion in the length of the pulse could be kept very small and, although the elimination of zeros could not be complete in turbulence of random frequency, it was hoped that the effect of those that remained would prove negligible. In fact, very much more consistent and reproducible results were obtained with this modification.

A useful check on the accuracy of measurement was obtained by the use of a calibration unit controlled by a square-wave generator in the manner independently suggested by Bradbury (1964).

Finally, the impulse counters at output were replaced by electrically damped galvanometers, since it seemed likely that wrong or uncertain results would be obtained when the duration of the turbulent bursts reached the order of magnitude of the counting-impulse duration, which could easily occur at low values of γ. A block diagram of the modified apparatus is shown in figure 3.

Figure 4 shows the effect of discriminator setting on the indicated intermittency values obtained with the original apparatus along with a test curve obtained with the modified unit at a controlled intermittency of 0·5. The turbu-

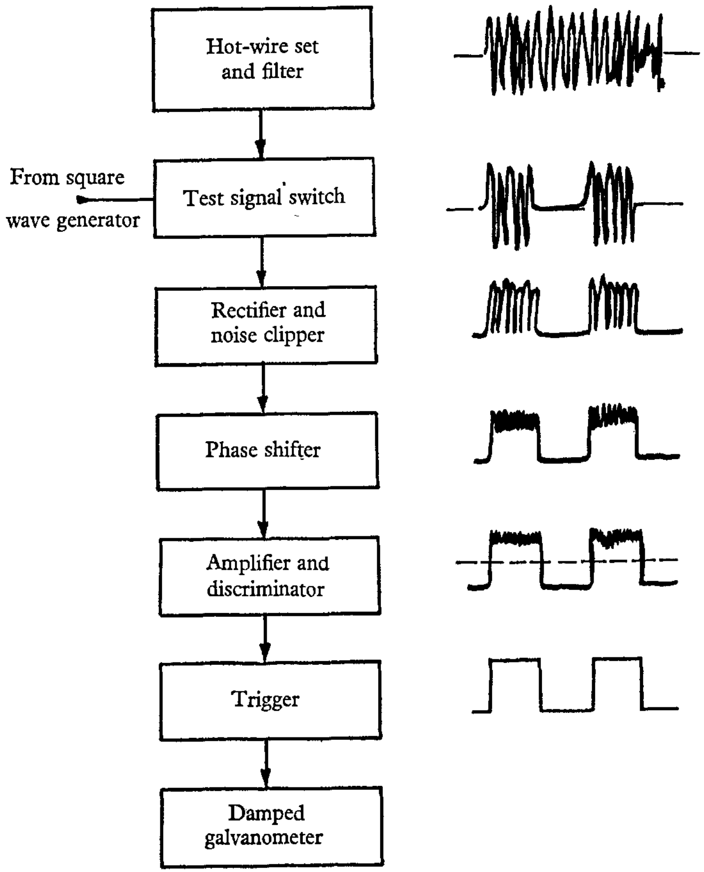


FIGURE 3. Block diagram of modified intermittency-measuring unit.

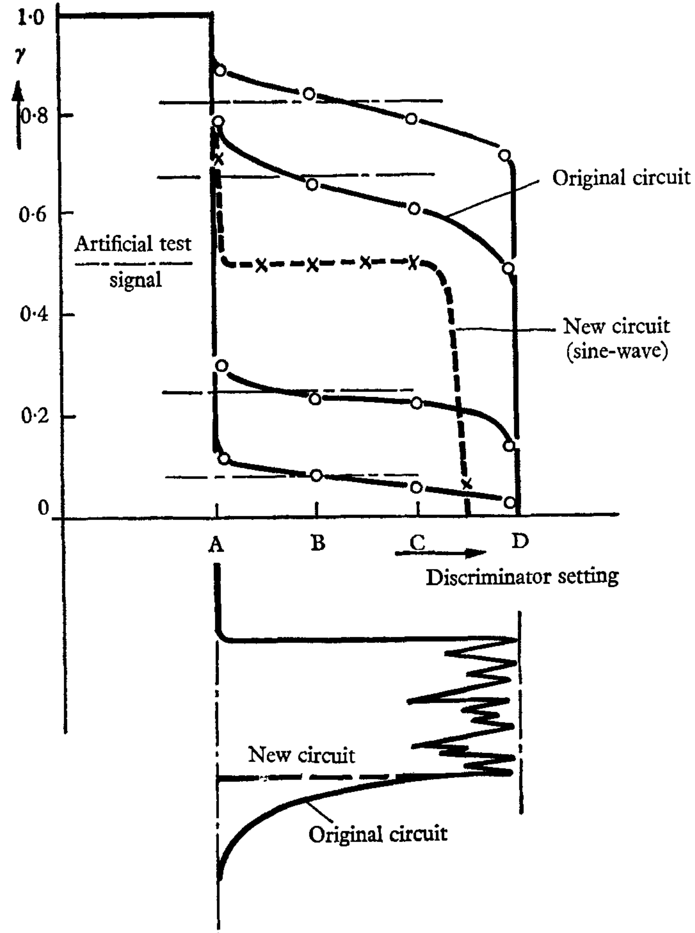


FIGURE 4. Influence of discriminator setting on measured intermittency with original and modified circuits.

lence signal for this test was in fact represented by a sine-wave signal from a frequency generator, but a wide range of frequencies could be covered without any measurable change in output. With an actual hot-wire signal some small dependence on discriminator setting remained, but consistent and repeatable results were obtained when the discriminator was set at its lowest position shortly before the output jumped to unity.

3.2. *Photo-electric method*

As already mentioned, this consisted of focusing a suitable photosensitive device on an illuminated cross-section of the smoke-filled boundary layer and feeding the resulting signal into the intermittency measuring unit just described. The

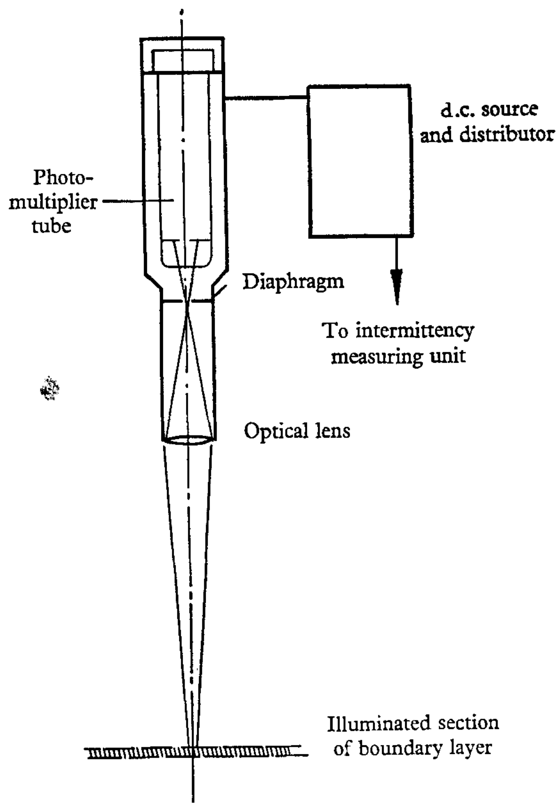


FIGURE 5. Sketch showing principle of the photo-probe.

success of the method as a means of measuring turbulence intermittency obviously depended upon the smoke being effectively confined to the turbulent regions of the flow. It seemed likely that this should be the case, since the smoke particles, if they were sufficiently small, could be ultimately transferred to the outer flow only through molecular action, while being freely dispersed within the turbulent flow by the turbulent motions. The turbulence front could thus be expected effectively to delimit the spread of smoke as of fluctuating vorticity. Comparative measurements of intermittency using the photo-electric method and the conventional hot-wire would show whether or not this assumption were correct and, indeed, a more direct check was found to be possible.

The photo-electric probe developed is shown in figure 5. It consists of an optical lens, a very small annular diaphragm and a photomultiplier tube. The correct setting of the lens is obtained by substituting a light source for the photomultiplier tube and adjusting the focus so that a sharp spot of light is obtained on a screen in the viewing plane. In the present measurements the spot was approximately 0·1 in. in diameter. The finite area viewed by the photomultiplier tube was a possible source of error, but, since the boundary layer was normally between 2 and 3 in. thick, the error was not large.

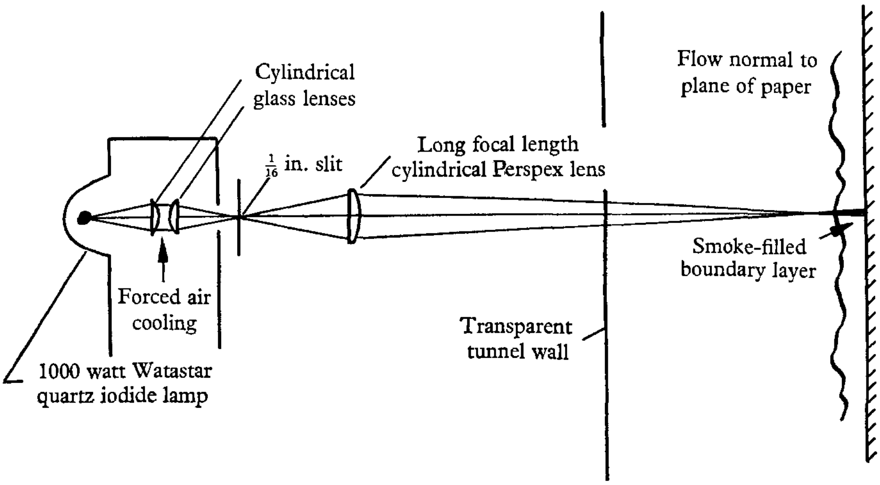


FIGURE 6. Arrangement for illuminating cross-section of boundary layer.

The smoke used was in fact condensed paraffin vapour introduced at the wall some distance upstream of the measuring station. The illumination of a longitudinal section of the boundary layer was accomplished as shown in figure 6, by means of a 1000 watt Watastar light source with a suitable system of cylindrical lenses and a slit which gave a nearly parallel beam of light between $\frac{1}{8}$ and $\frac{1}{4}$ in. deep at the measuring position. This finite depth of the illuminated section was a further source of error, though again not a particularly important one in view of the boundary-layer thickness. A complete plane cross-section of the boundary layer was not of course really necessary for the present experiments, the photo-probe making use of only a small part of the illuminated area; however, the apparatus happened to be available and proved to be quite suitable.

An earlier experiment in which a photo-transistor was used instead of a photomultiplier tube was not successful, possibly because the spectral density of the scattered light was concentrated by Tyndall effect in the short-wave region of the spectrum.

4. Description of experiments

The experiments were carried out in the blower tunnel shown in figure 7. The wall opposite the test wall is flexible, which allows the pressure gradient to be controlled within wide limits. Being of Perspex, it also enables the boundary layer on the test wall to be illuminated from outside the tunnel.

For the hot-wire measurements, a single-wire probe was used coupled with a Pitot tube having a flattened mouth 0·012 in. in depth. The Pitot tube and hot-wire probe were mounted on a single holder in such a way that the hot-wire was fixed at a known distance above the Pitot tube so that the measuring plane of both probes was the same. This is of some importance as it was found that there were substantial variations in boundary-layer thickness in a direction normal to the flow. Since interest was mainly concentrated on the outer region of the boundary layer and the depth of the Pitot tube was small compared with the boundary-layer thickness, no corrections were applied for displacement of the effective centre of the Pitot. The average free-stream velocity during the experiments was 30 ft./sec.

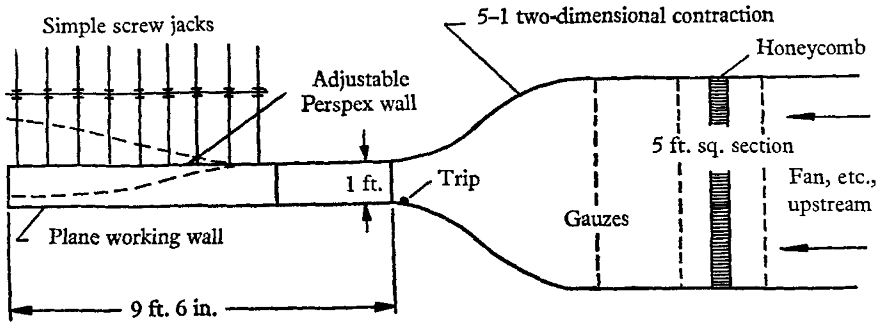


FIGURE 7. Blower tunnel.

To obtain a sufficiently thick boundary layer for accurate measurements, a rod of $\frac{1}{4}$ in. diameter was mounted on the wall near the beginning of the straight part of the test section. No measurements were made closer to the rod than 100 rod diameters downstream. To establish severe adverse pressure gradients without causing flow separation on the opposite flexible wall, two-dimensional obstacles were mounted on the test wall at some distance behind the measuring station. In this way it was possible to produce velocity profiles near to separation without too much flow unsteadiness. These profiles were of course very far from being self preserving, though for moderate positive and negative pressure gradients this condition was probably reasonably closely approached.

Most of the measurements were made using the combination of hot-wire and Pitot tube described above, profiles of intermittency and mean velocity being simultaneously measured. Three separate series of measurements were made with different pressure distributions and the boundary layer developing normally. An additional series of measurements was made in the boundary layer following reattachment behind a two-dimensional obstacle.

The photo-probe became available towards the end of the investigation and comparative measurements of intermittency were made using it and the hot wire in the same boundary layer for different pressure gradients. In addition, to establish the detailed identity of smoke and turbulence distributions simultaneous records were obtained, using a two-beam oscilloscope, of the outputs from the hot-wire and the photo-probe focused on very nearly the same spot.†

5. Results

A digital computer was used to evaluate from the measurements the characteristic boundary-layer parameters δ^*, θ, R_θ and H, and the intermittency parameters $\overline{Y}$ and σ.

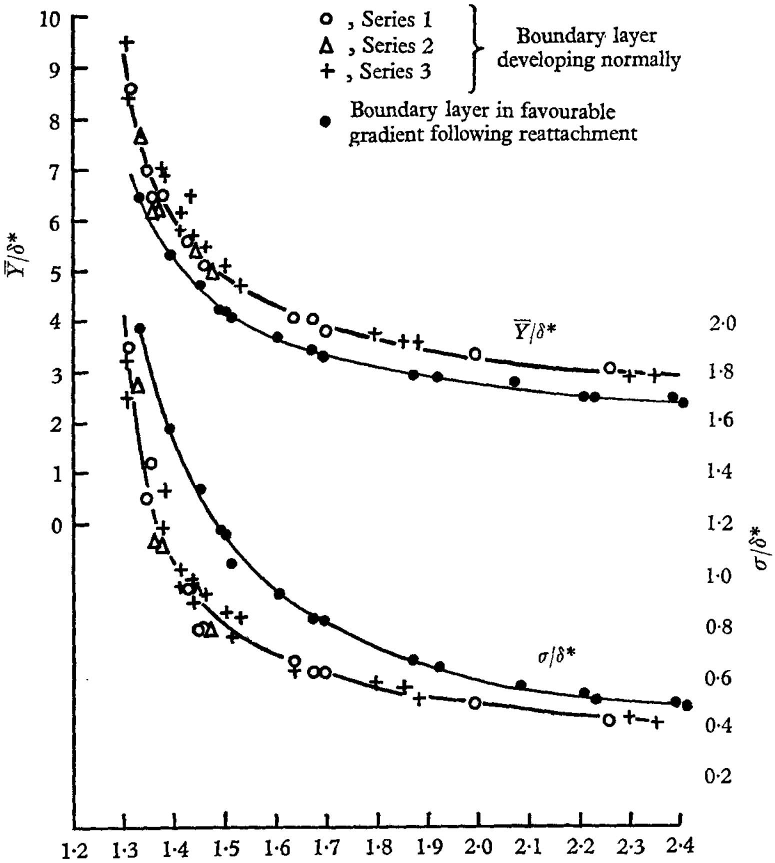


FIGURE 8. $\overline{Y}/\delta^*$ and σ/δ^* plotted against H.

Initially, $\overline{Y}$ and σ were made dimensionless by dividing by the corresponding values of δ^*, and plotted against H as shown in figure 8. Unlike the actual boundary-layer thickness δ, the displacement thickness can be defined with considerable precision and this method of presentation is probably the most accurate. Unfortunately, however, it does not have the same immediate physical significance as corresponding plots of $\overline{Y}/\delta$ and σ/δ, and a large number of measured

† It was necessary for the hot-wire to be a short distance away from the spot on which the photo-probe was focused, otherwise the light reflected from it would have given rise to a continuous signal from the photo-probe.

velocity profiles were examined to obtain a satisfactory relationship between δ/δ^* and H. Cases when the value of δ appeared reasonably well defined are shown plotted in figure 9. The mean curve shown on the figure was used to reduce the values of $\overline{Y}/\delta^*$ and σ/δ^* shown in figure 8 to the corresponding values of $\overline{Y}/\delta$ and σ/δ shown in figure 10. Subsequently, the values of δ/δ^* shown in figure 9 were compared with curves obtained from charts given by Thompson (1965), the

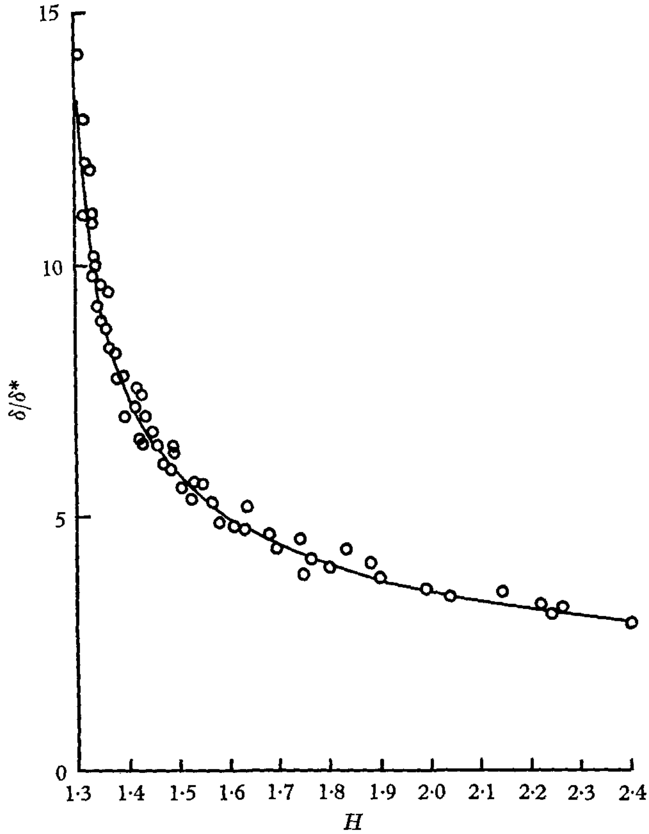


FIGURE 9. δ/δ^* plotted against H.

comparison being shown in figure 11. The Reynolds numbers for the curves correspond approximately to the upper and lower limits of the measurements. Because of the remaining uncertainty in the precise determination of δ, the results are plotted in the form $\sigma/\overline{Y}$ in figure 12.

Figure 13 shows measured mean velocity profiles and corresponding curves of intermittency, with experimental points obtained using the conventional hot-wire and the photo-probe. Figure 14 (plate 2) shows simultaneous oscilloscopic traces obtained from the two devices.

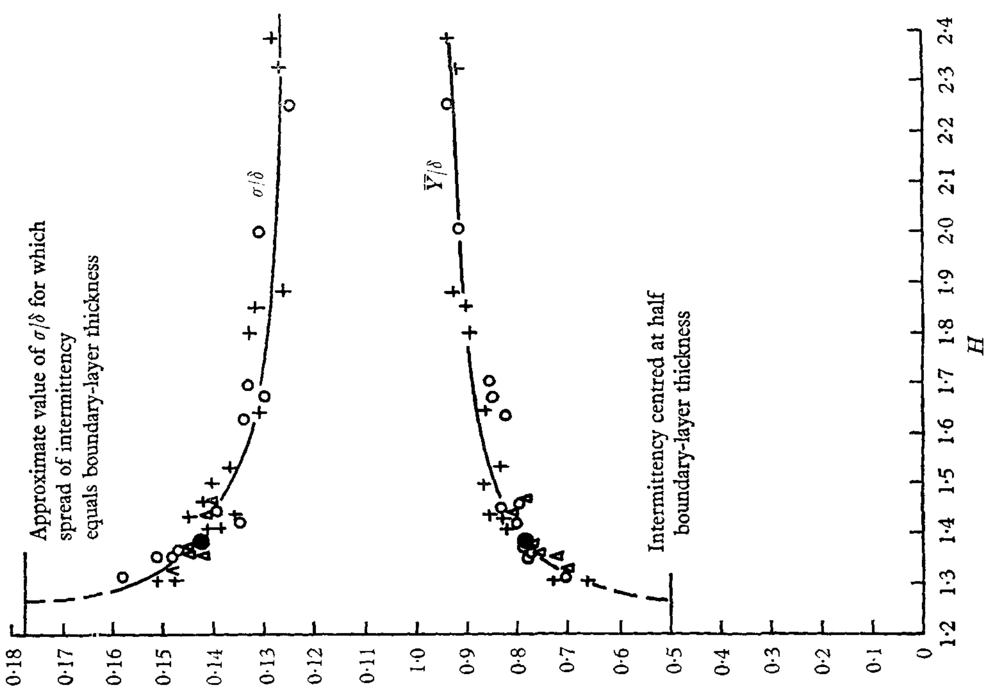


FIGURE 10. $\bar{Y}/\delta$ and σ/δ plotted against H. ●, Values from Klebanoff (1954); other symbols as in figure 8.

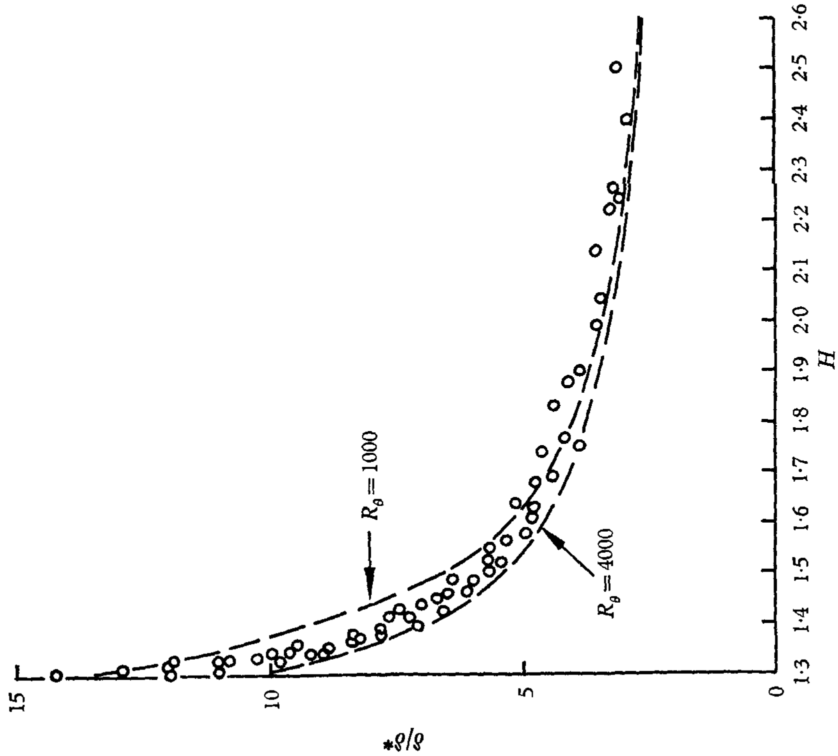


FIGURE 11. Comparison of measurements of δ/δ^* and H with curves obtained from Thompson (1965). – – –, From Thompson's charts.

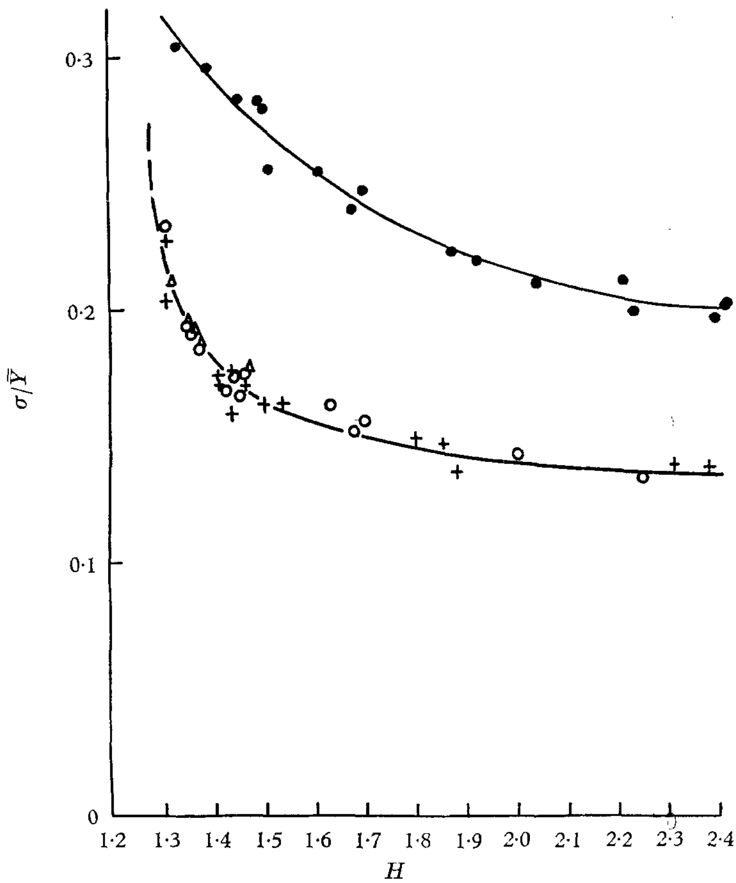


FIGURE 12. $\sigma/\overline{Y}$ plotted against H. Symbols as in figure 8.

6. Discussion

The curves shown in figures 8 and 9 exhibit a trend which evidently cannot extend to very low values of H, and it seems likely that a limiting value should exist between 1·2 and 1·3. In fact the mean lines shown on the figures approximate to straight lines when plotted logarithmically against $\log(H - 1{\cdot}28)$, suggesting a limiting value of 1·28. This result is of some interest, since it ties in with measurements by Launder (1964) and Patel (1965). These experimenters found that, when the turbulent boundary layer is subjected to a sufficiently severe and prolonged favourable pressure gradient, the value of H initially falls, then reaches a minimum (which depends upon the boundary-layer Reynolds number) and finally rises as the flow reverts to the laminar condition. The existence of a minimum value of H, dependent upon boundary-layer Reynolds number (and presumably upon pressure gradient, to a lesser extent), is therefore seen as part of the reverse transition process.

Figures 10 and 12 show clearly that as H is reduced below about 1·5 the spread of the intermittency increases rapidly, so that, at some limiting value of H, again

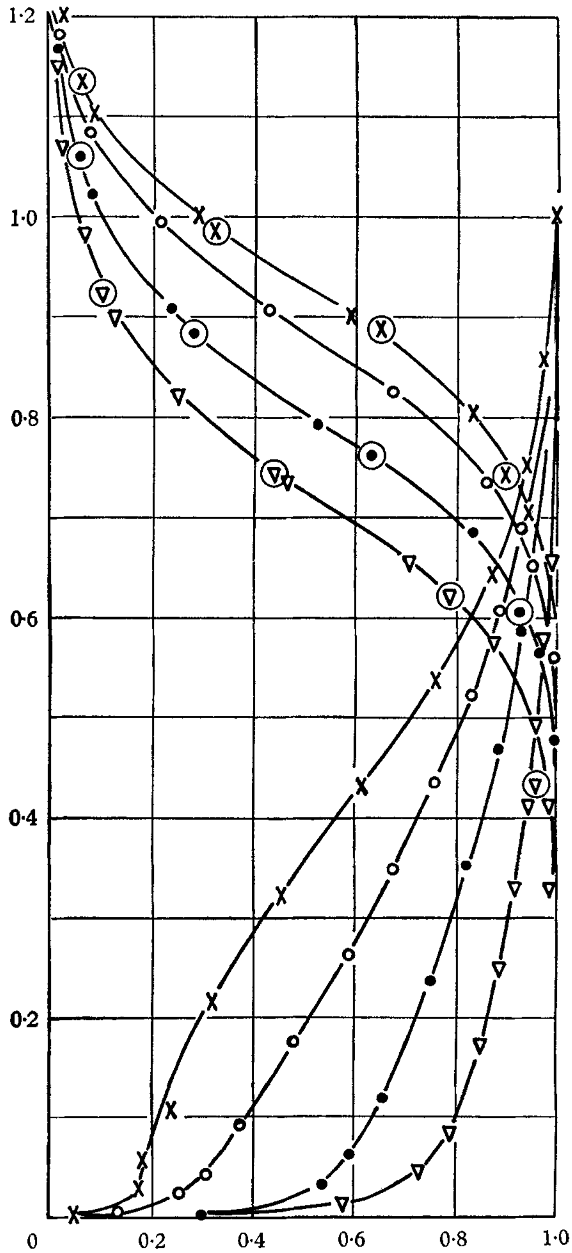


FIGURE 13. Typical profiles of mean velocity and intermittency. ○, Optical measurements. ▽, $H = 1{\cdot}307$; ●, $H = 1{\cdot}426$; ○, $H = 1{\cdot}880$; ×, $H = 2{\cdot}460$.

between 1·2 and 1·3, it appears that the intermittency should extend over the full depth of the boundary layer. From this it may reasonably be inferred that in sufficiently strong favourable pressure gradients, where the flow is reverting to the laminar state, the turbulence is progressively confined to isolated patches separated by regions of non-turbulent flow. Further experiments are required to establish whether this is in fact the case and also to determine whether or not the initial stages of reverse transition are necessarily accompanied by the spread of intermittency right through the boundary layer.

The foregoing tentative conclusions are not dependent on the accuracy with which the curve relating δ/δ^* to H has been determined, and could in fact have been deduced from figure 12 alone. However, the form of the curves in figure 10 does depend fairly critically on the choice of a mean curve for δ/δ^*. It is therefore reassuring that the measurements are in very fair agreement with the curves from Thompson's charts (figure 11), especially when it is recognized that the lowest values of H were associated with the lowest boundary-layer Reynolds numbers, owing to the highly favourable pressure gradient. Within the range of Reynolds numbers covered, no systematic effect of Reynolds numbers could be detected, though a small effect might well have been masked by experimental scatter and the general trend of lower values of H occurring at the lower Reynolds numbers.

The variation of $\bar{Y}/\delta$ and σ/δ at high values of H is not particularly marked and may be due, at least in part, to departure from equilibrium conditions, rapid deceleration of the flow in the wall region forcing the whole of the outer (intermittent) region away from the surface. One conclusion, however, appears inescapable: the structure of the turbulent boundary layer approaching separation does not approximate to that of a free-wake flow, which is characterized by an extremely wide spread of intermittency. The present measurements therefore do not support the physical model which is the basis of Coles' law of the wake.

Turning now to the measurements made in the reattached boundary layer in a favourable pressure gradient (figures 8 and 12) we see a structure rather more closely resembling that of a wake flow. Close to reattachment (where H is in the region of 2·4) the spread of intermittency extends over a somewhat larger part of the layer, and at low values of H it is considerably greater than in the boundary layer developing in the normal way. The intermittency characteristics are indeed very similar to those observed by Corrsin & Kistler (1954) on a rough surface, and suggest a more rapid rate of entrainment than in the normal layer.

The associated profiles of mean velocity and intermittency shown in figure 13 show the trends remarked upon earlier and also the excellent agreement between the intermittency measurements made with the photo-probe and the hot-wire. There is a suggestion in the figure that when γ is close to unity the photo-probe records a slightly lower value than the hot-wire, and it may be that relatively narrow regions of uncontaminated (and hence, by inference, irrotational) flow can be detected and recorded by the photo-probe whereas the hot-wire would only record a velocity fluctuation indistinguishable from the turbulence. It is, in fact, rather remarkable that measured intermittency profiles should be so closely antisymmetric in view of the lack of such symmetry in the characteristic form of the instantaneous boundary of the turbulence. Typically, the tops of the billows of turbulent fluid are quite rounded, while the troughs of irrotational fluid separating them are much sharper and may sometimes extend as fissures well towards the surface.

These observations are based on smoke photographs similar to those in figure 1 (plate 1); and figure 14 (plate 2), which shows simultaneous traces of hot-wire and photo-probe signals, gives ample grounds for believing that such photographs give a true picture of the distribution of turbulent fluid. The very close correspondence of the two signals will be noted, as well as the much more definite character of the photo-probe record, which could possibly be further enhanced by an improved combination of smoke density and lighting. The small fluctuating output from the photo-probe, in what may be assumed to be smoke-free regions, is probably due to scattered light illuminating smoke which is out of the plane of the main beam.

7. Conclusions

It is concluded from the present investigation that:

(i) The intermittency-measuring apparatus of Corrsin & Kistler can be improved by the modifications described in this report.

(ii) Pressure gradient has a marked effect on the distribution of intermittency. In the boundary layer proceeding to separation the intermittent zone decreases in width and moves further from the surface as H increases. The reverse trend is observed with decreasing H in a favourable pressure gradient.

(iii) Reverse transition in a favourable pressure gradient is accompanied by a spread of intermittency through the full extent of the boundary layer. This conclusion is only tentative and further experiment is required.

(iv) Intermittency in the boundary layer following reattachment is very much more marked than in the normally developing layer for the same values of H, and it is suggested that the entrainment is therefore greater. Further measurements are required to relate intermittency, mean velocity profile and rate of entrainment in the boundary layer.

(v) For the boundary layer developing normally and for the range of Reynolds numbers covered in the experiments ($R_\theta \approx 1000$–4000) the value of H appears to be a satisfactory index of the intermittency distribution. No systematic effect of Reynolds numbers was observed but such an effect could have been obscured by experimental scatter.

(vi) A photo-electric probe with suitable illumination of the smoke-filled boundary layer can be used to measure the intermittency of smoke-contaminated fluid.

(vii) With smoke introduced into the boundary layer sufficiently far upstream, smoke-filled and smoke-free regions can be identified with regions of turbulent and non-turbulent flow.

(viii) As a consequence of (vi) and (vii) the photo-electric probe can be used for the measurement of the intermittency of turbulence. This is confirmed by the comparison of intermittency measurements made with the photo-probe and a conventional hot-wire. Small discrepancies observed where the intermittency approaches unity may be due to the fact that the photo-probe can distinguish a narrow region of smoke-free fluid where the hot-wire would record a fluctuation in velocity indistinguishable from turbulence.

The authors are indebted to Mr S. A. M. Thornley for the photographs shown in figure 1 and for his contributions to the technique of boundary-layer flow visualization on which the present photo-probe measurements are based.

Further details of the photo-probe and intermittency-measuring unit may be obtained from the authors.

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