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AN EXPERIMENTAL INVESTIGATION IN A TURBULENT CHANNEL FLOW WITH A THICK VISCOUS SUBLAYER

(Hot-Film Measurements in Oil)

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ABSTRACT

In a turbulent channel-flow hot-film measurements have been made. To achieve a sublayer thickness of approximately 1 cm at $y^+ = 10$, oil was used. The Reynolds numbers used for the investigations were 5,600 and 8,200 based on the channel-width of 22 cm and the channel center-line velocity.

In the vicinity of the wall, $y^+ < 0.1$, the u'-fluctuations were found to be proportional to the wall distance, y^+. The u'-values obtained with a hot-film probe for $y^+ > 0.7$ were all greater than those obtained with a hot-film wall probe, but extrapolation of the data from the movable hot-film probe to the wall gave good agreement with the data from the flush-mounted wall-film probe.

The instantaneous values of the u'-fluctuations in the region $0 < y^+ < 5$ are very similar to the instantaneous values of the wall-gradient, but there is a time shift which is proportional to the wall distance, y^+. Disturbances in the flow in this region were observed to be convected with a constant velocity toward the wall. The mean value of the convection velocity was found to be approximately equal to the friction velocity, u_τ.

The Reynolds stress was found to be intermittent in the vicinity of the wall with high peak to mean ratios.

It was found that the probability density of the instantaneous streamwise velocity is skewed for all y^+ values except $y^+ \approx 13$. For $y^+ < 13$ the most probable instantaneous velocity is less than the mean velocity; for $y^+ > 13$ the opposite was found.

INTRODUCTION

Investigations in turbulent flow with the available equipment and probes are now feasible with a high accuracy. However, problems occur when measurements are attempted in the viscous sublayer. Normally this wall layer is very thin so that a tiny probe is larger or of the same order of magnitude as the sublayer. To make measurements possible in the viscous sublayer the conditions have to be changed. This can be achieved by using a medium other than the customary air or water. With this idea H. Reichardt in the Max-Planck-Institut für Strömungsforschung in Göttingen designed and constructed a channel using oil as the testing fluid. The present investigations were conducted at Reynolds numbers of 5,600 and 8,200 based on the channel width of 22 cm and the channel center-line velocity. Under these conditions the sublayer thickness, $y^+ = yu_\tau/\nu = 10$, corresponded for the lower Reynolds number to a normal wall-distance of 0.775 cm which is 1.4 times the sublayer thickness H. P. Bakewell[1] achieved in his investigations.

THE FACILITY

The experimental investigations were carried out in a fully developed channel-flow with an open surface. Fig. 1 shows a sketch of the channel which consists of a 8.5 m long, 1 m deep and 0.5 m wide tank, filled with oil up to 0.85 m. The tank is divided by a wall (c) into two chambers of nearly the same size. At one end stands the pump (a) and at the opposite end the turning vanes (b). A honeycomb and fine grids (d) provide a symmetrical velocity profile in the test section which is 32 channel widths downstream. Adjacent to the tank is a probe support (e) which can be moved for calibrating the hot-film probes.

The total oil volume in the tank is 3,600 liters (~1000 Gallons). The kinematic viscosity at the operating temperature of 25°C is $6 \cdot 10^{-2}$ cm^2/sec., which is 6 times the kinematic viscosity of water and 0.43 times that of air.

With the maximum center-line velocity of $U_c = 22.5$ cm/sec and the channel width of d = 22 cm, a Reynolds number defined by $Re_U = U_c \cdot d/\nu = 8{,}200$ can be obtained. The lowest Reynolds number obtainable where fully developed channel flow can still be maintained (no intermittency) is 5,600.

Before the oil was pumped into the channel it was cleaned twice by means of filters of the same type usually used for cleaning the fuel of aircraft jet engines. All the particles larger than 0.8 μm in diameter were removed.

The entire facility was installed in a laboratory with a constant temperature of 25°C. Three temperature controlled heaters maintain the temperature of the room constant to within ±0.1°C.

All the measurements were made 10 cm under the free surface.

ELECTRONIC EQUIPMENT

Pressure measurements with high accuracy at low velocities are not easy to carry out. Therefore in this investigation all the data were obtained with two linearized constant temperature anemometers using hot-film probes of approximately 1 mm length and 50 μm diameter and, also, flush-mounted hot-film wall-elements. The linearizers provided a linear relationship between the flow velocity and the output voltage of the anemometers.

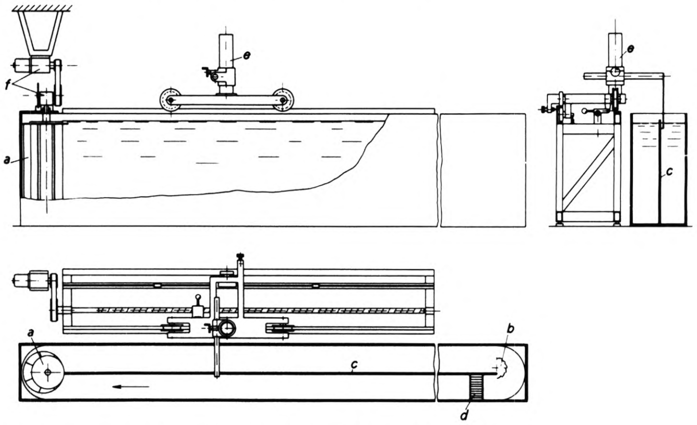

Figure 1. Sketch of Reichardt's oil channel.

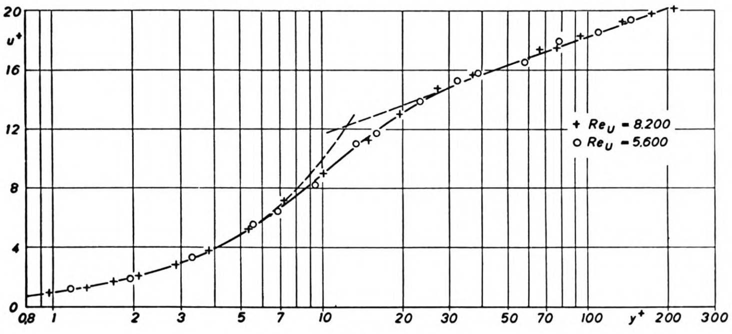

Figure 2. Mean velocity profiles.

The mean velocity profiles shown in Fig. 2 were obtained by averaging over 600 sec the linearized output voltage of a single constant temperature anemometer for the high Reynolds number of 8,200 and for the low one over 1,200 sec. The intensities of the u'-fluctuating velocities were obtained by suppressing the high dc-component, which corresponded to the mean velocity, by a bandpass filter before squaring.

The turbulence signals were recorded on a two channel paper recorder. Great care was necessary in calibrating the probes because there was no other instrument against which the results could be compared. For calibration the hot-film probe was towed through the quiescent oil over a distance of nearly two meters.

NEW EFFECTS IN THE FULLY DEVELOPED CHANNEL FLOW

Fig. 3 shows the distribution of the u'-fluctuations normalized with the local mean velocity in the vicinity of the wall. For both Reynolds numbers the values collapse to one curve. A maximum for $\sqrt{\overline{u'^2}}/\bar{u}$ of approximately 0.37 at a distance $y^+ \approx 4$ and a minimum of 0.24 at the wall is clearly seen in both sets of data. From the shape of the curve between the two extremes it follows that between $y^+ \approx 4$ and $y^+ \approx 0.7$ the u'-fluctuations decrease faster than the mean velocity $\bar{u}$. Below $y^+ \approx 0.7$ the u'-fluctuations decrease with the same order as $\bar{u}$, which results in the finite value of 0.24 at the wall. This maximum was also found by Laufer[7] and Bakewell[2]. The wall values are taken from the readings of the flush mounted hot-film probe.

In Fig. 4, $\sqrt{\overline{u'^2}}$ is again plotted, but now normalized with $u_\tau = \sqrt{\frac{\tau_0}{\rho}}$ instead of $\bar{u}$. Since the relation $y^+ = u^+ = \bar{u}/u_\tau$ holds in the viscous sublayer ($y^+ < 5$), it follows from the definition $(\sqrt{\overline{u'^2}}/\bar{u})_0 = a$ that $\sqrt{\overline{u'^2}}/u_\tau = ay^+$ is valid. The straight line ay^+ (with slope $a = 0.24$) is also plotted in Fig. 4 and is the asymptote for the u'-fluctuations for vanishing distance normal to the wall. Mitchell and Hanratty[8] have also measured this slope and obtained $a = 0.32$, which is the mean slope of the curve near the wall.

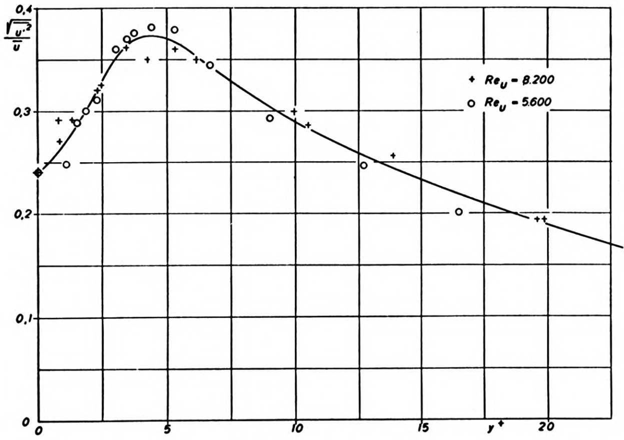

Figure 3. $\sqrt{\overline{u'^2}}/\bar{u}$-distribution near wall.

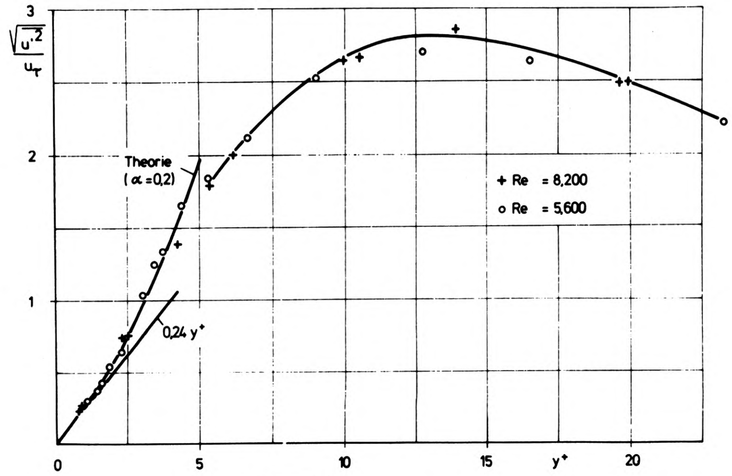

Figure 4. $\sqrt{\overline{u'^2}}/u_\tau$-distribution near wall.

Recently Reichardt and Eckelmann[9] succeeded in describing the nonlinear behavior of $\sqrt{\overline{u'^2}}$ with increasing distance from the wall. A more detailed paper has also been published by H. Reichardt[10]. Neglecting the convection terms in the general equations of motion and introducing the boundary layer hypothesis, it can be shown that the fluctuations of the viscous shearing stress $\tau' = \mu \frac{\partial u'}{\partial y}$ in the viscous sublayer ($y^+ < 5$) are governed by a differential equation of the heat conduction type.

The u'-fluctuations, which are mainly produced in the region $y^+ \approx 13$, travel toward the wall and are damped out. From the theory it can also be derived that the higher frequencies of the u'-fluctuations are attenuated more than the lower ones, so that primarily the low frequency fluctuations are observed at the wall.

This non-linear attenuation can be seen in Figs. 5 and 6 where, for the lower Reynolds number, the signal of the flush mounted hot-film probe together with that of a hot-film probe in the flow are represented. The hot-film was located at the same x- and z-coordinates as the wall probe but at various distances from the wall. Although the u' signal increases with distance from the wall, for purposes of illustration its amplification was adjusted so that both signals became nearly equal in size.

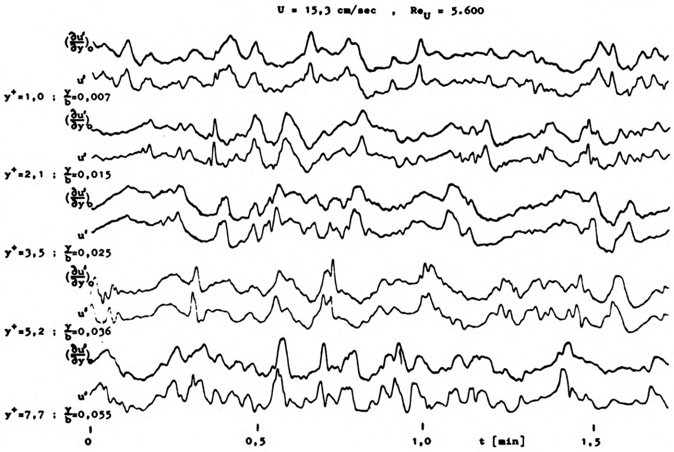

Figure 5. Simultaneous records of instantaneous $(\partial u'/\partial y)_0$ and u' fluctuations at various y^+ positions.

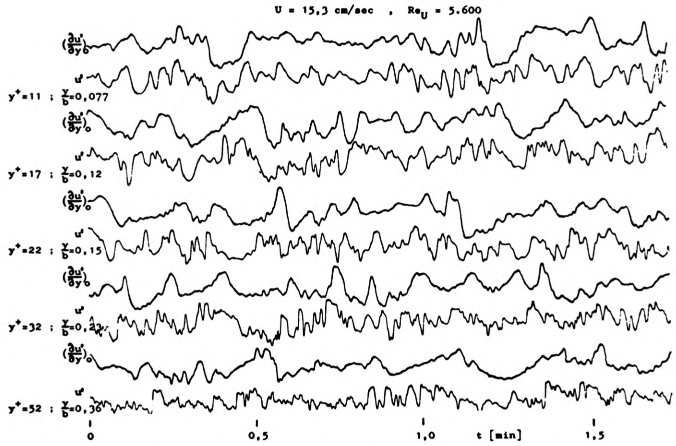

Figure 6. Simultaneous records of instantaneous $(\partial u'/\partial y)_0$ and u' fluctuations at various y^+ positions.

Within the sublayer both signals are very similar. The hot-film probe signal leads the wall signal, however, as can be seen from Fig. 5. The similarity of the signals in the sublayer of a turbulent boundary layer was also discovered by A. K. Gupta[4]. Using the mean gradient at the wall $(\frac{\partial \bar{u}}{\partial y})_0$ for normalizing the time-shift $\overline{\Delta t}$ of the two signals, the values obtained for both Reynolds numbers fit a single curve, when plotted over the wall distance y^+. This is shown in Fig. 7. Within the sublayer the relation between the time-shift and the wall distance is linear. For distances greater than $y^+ = 5$, there occurs a deviation from this linear relation. The velocity which can be derived from the time-shift and the wall distance which is the propagation velocity for the u'-fluctuations, equals the friction velocity u_τ, as seen in Fig. 8. A pro-

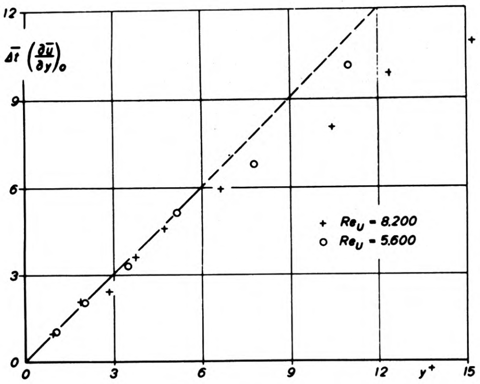

Figure 7. The delay time necessary for u' disturbances to reach the wall.

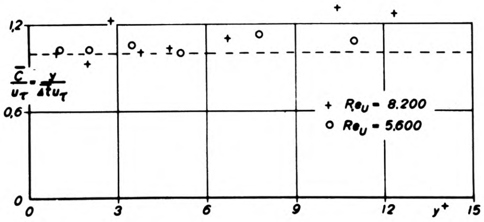

Figure 8. The normalized propagation velocity of the basic flow disturbance.

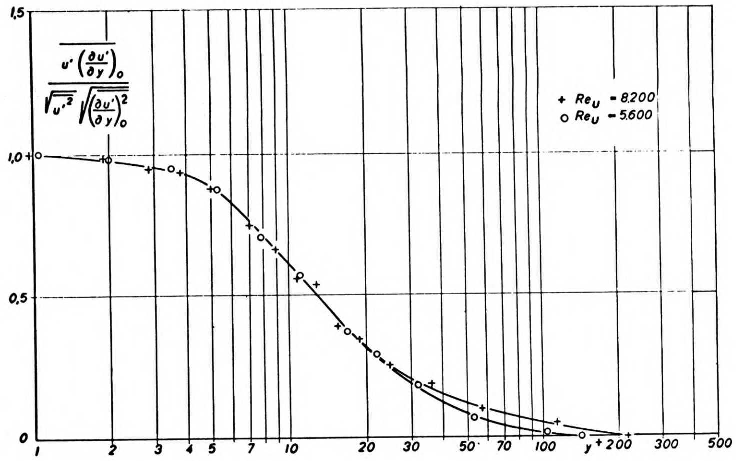

Figure 9. Correlation coefficient of u' and $(\partial u'/\partial y)_o$.

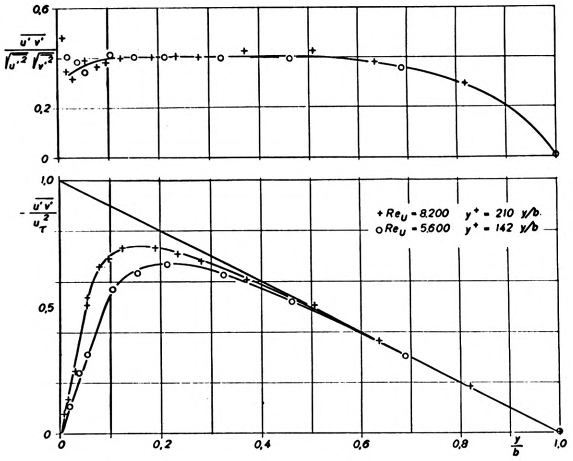

Figure 10. The normalized turbulent shear stress over the channel half width.

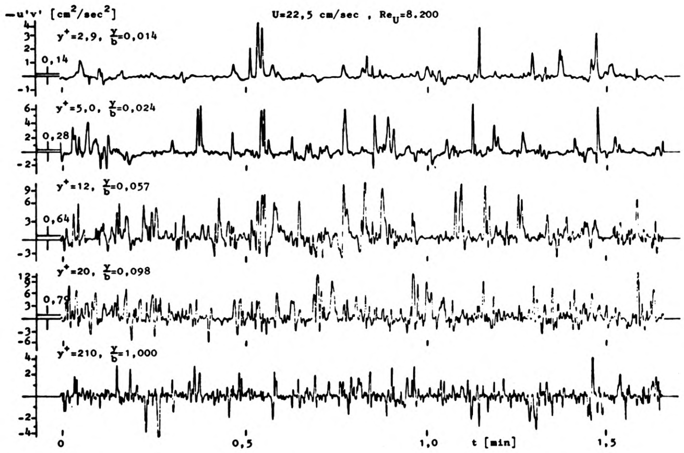

Figure 11. Records of the instantaneous turbulent shear stress at various y^+ positions.

pagation velocity of 0.8 u_τ can also be derived from Reichardt's theory[10] for the sublayer.

The fact that the signal at the hot-film probe u'(y) leads the signal at the wall-probe $(\frac{\partial u'}{\partial y})_o$ is to be expected from the visual data of both Corino and Brodkey[2] and Kline and Runstadler[6]. The observations of Corino and Brodkey suggest that the "sweep" type motion, which is the incoming high momentum fluid that moves toward the wall at a slight angle, would be detected first by a probe at $y^+ > 0$ before being detected at the wall. Kline and Runstadler observed, by means of dye traces, that fluid at $y^+ \leq 0.01$, lifts up while moving downstream. Such a lifting fluid forms an inclined region which first passes the probe at $y^+ > 0$ before affecting the probe at the wall.

The correlation between the wall signal and that of the hot-film probe is shown in Fig. 9. The small deviation from unity within the sublayer is mainly caused by the time-shift of the two signals. The correlation decreases at greater wall distances due to the increasing occurrence of higher frequencies.

Fig. 10 gives the distribution of the turbulent shearing stress $\overline{-u'v'}$ normalized with u_τ^2 from the center-line of the channel to the wall for both Reynolds numbers investigated. The straight line which is also shown corresponds to:

$$\frac{\tau}{\tau_o} = \frac{\tau_{lam}}{\tau_o} + \frac{\tau_{turb}}{\tau_o} = 1 - \frac{y}{b} .$$

In the upper part of Fig. 10, the correlation coefficient, $\overline{\Psi} = \overline{-u'v'} \Big/ \sqrt{\overline{u'^2}\ \overline{v'^2}}$, is plotted. It is constant over nearly half of the channel width. A given value of $\overline{\Psi}$, for example 0.4, can result from two different extremes. First, Ψ(t) can fluctuate with high positive and negative values around the mean-value and second, Ψ(t) can sometimes be zero and sometimes unity. Both extremes exist obviously in the fully developed turbulent channel flow as can be seen in Fig. 11. At the center-line of the channel, $\overline{-u'v'}$ is zero because of symmetry. There occur, however, very high peaks in the instantaneous value of the Reynolds stress. As u' and v' do not vanish in the middle of the channel, Ψ(t) takes high positive and negative values. Going from the center toward the wall, the positive peaks of -u'v' predominate, so that a relatively small value results. Within the log-law region of the turbulent flow the picture is not very different from that represented in the fourth record from the top of Fig. 11 which is also expressed in the constancy of $\overline{\Psi}$ = 0.4 over a wide range of the channel flow field. The picture changes as the wall is approached, however. In the viscous sublayer a different Reynolds stress producing mechanism seems to occur which leads to a highly intermittent structure. Long periods of quiescence are interrupted by relatively high peaks of -u'v'. The maximum of the ratio $-u'v' / \overline{u'v'}$ reaches a value of nearly 30 as can be seen from the first record at the top of Fig. 11. Assuming that in these bursting periods the v'-fluctuations toward the wall are equal to u_τ, as pointed out earlier, an estimation of $-u'v'_{max}$ can be made using the u'-fluctuations from other records similar to those in Fig. 5. The result is, that in the vicinity of the wall, Ψ(t) is unity when the high peaks of -u'v' are occurring.

The investigation of Kim, Kline and Reynolds[5] shows also, for the zone $0 < y^+ < 100$, that essentially all turbulence production occurs during intermittent bursting periods.

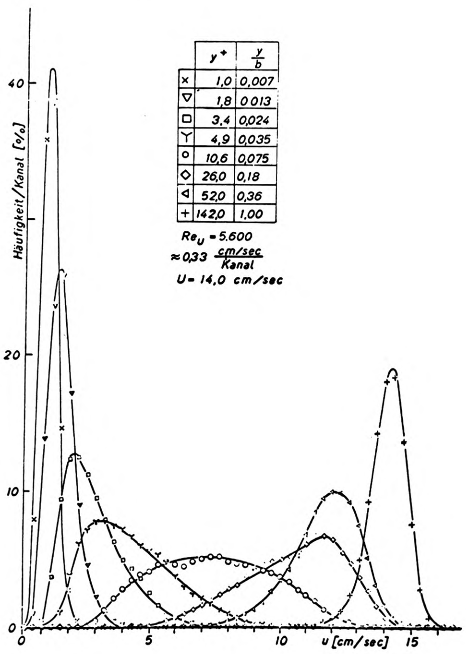

Figure 12. Probability density distribution of the instantaneous streamwise velocity at various y^+ positions.

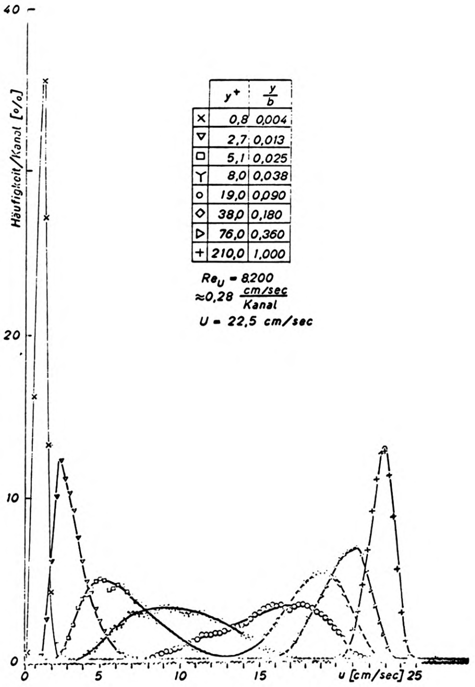

Figure 13. Probability density distribution of the instantaneous streamwise velocity at various y^+ positions.

The amplitude of the u'-fluctuations can also be estimated from the probability density distributions shown in Figs.12 and 13. It was found that the probability density of the instantaneous streamwise velocity is skewed for all y^+ values except $y^+ \approx 13$ (which is not plotted here). For $y^+ < 13$ the most probable instantaneous velocity is less than the mean, whereas for $y^+ > 13$ the opposite was found. This is in good agreement with the observations of Schraub and Kline[11]. They reported, that the low-speed streaks are wider and the high-speed streaks narrower for $y^+ < 10$. Since the location of the streaks is random, one must find, if the average is taken over a long enough time, that the most probable velocity is less than the mean velocity. For $y^+ > 10$ the high-speed streaks are wider and the low-speed streaks narrower yielding the opposite skewness of the probability density distribution. Hence, in the case of Schraub and Kline, a symmetric distribution would be expected for $y^+ = 10$. In the present investigation this was found for $y^+ \approx 13$.

CONCLUSIONS

New effects in the fully developed channel flow could be observed.

In the vicinity of the wall the u'-fluctuations decrease faster than the mean velocity in agreement with the theory of Reichardt. At $y^+ \approx 4$ a maximum was obtained when normalizing the rms value of the u'-fluctuations with the local mean velocity.

The instantaneous u'-fluctuations in the region $0 < y^+ < 5$ were very similar to the instantaneous fluctuations of the velocity gradient at the wall. The u'-fluctuations in the flow, however, lead those at the wall in time. The propagation velocity for the perturbations travelling toward the wall was found to be equal to u_τ.

Highly intermittent instantaneous values of the Reynolds-stress in the vicinity of the wall with peaks of nearly 30 times the mean value were observed.

The probability density of the streamwise velocity was found to be skewed except at the wall distance $y^+ \approx 13$.

SYMBOLS

a	$(\sqrt{\overline{u'^2}}/\bar{u})_o$
b	channel half-width
$\bar{c}$	propagation velocity for u'-fluctuations
d	channel width d = 2b
$(\frac{\partial \bar{u}}{\partial y})_o$	mean gradient at the wall
$(\frac{\partial u'}{\partial y})_o$	gradient fluctuations at the wall
o	wall index
Re_U	$\frac{U_c d}{\nu}$ Reynolds number
$\overline{\Delta t}$	mean time-shift
U_c	centerline velocity
$\bar{u}$	local mean velocity
u'	velocity fluctuations in x-direction
u^+	$\bar{u}/u_\tau$
u_τ	friction velocity
v'	velocity fluctuations in y-direction
x	spatial Cartesian coordinate in mean streamwise direction
y	spatial Cartesian coordinate normal to the wall
y^+	$\frac{y\,u_\tau}{\nu}$
z	spatial Cartesian coordinate in spanwise direction
μ	fluid dynamic viscosity
ν	$\frac{\mu}{\rho}$ fluid kinematic viscosity
ρ	density
τ_o	$\mu(\frac{\partial \bar{u}}{\partial y})_o$ mean shear stress at the wall
τ_{turb}	$-\rho\overline{u'v'}$ turbulent shear stress
τ_{lam}	$\mu\frac{\partial \bar{u}}{\partial y}$ laminar shear stress
Ψ	correlation coefficient of u' and v'

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DISCUSSION

V. GOLDSCHMIDT (Purdue University): I have the impression that the traces you showed for the signals near the wall did not suggest a really noticeable intermittency. Maybe the u'v' did, but the u' did not.

ECKELMANN: Yes, that's right. Although u' and v' do not show intermittency the product, u'v', of both does in the vicinity of the wall. The u' signal has relatively low frequency content and the v' signal has more high frequency content, but the product of both signals results in that highly peaked and intermittent u'v' signal due to the correlation of only about 40 percent between the two.

W. K. BLAKE (Nav. Ship. R & D Center): Yesterday, when Dr. Kline and Dr. Johnson were speaking, there seemed to be some statement about the scaling of burst period on inner or outer variables. Yet 99% of the conversation that has been going on yesterday and today has to do with viscous sublayer type experiments, statistics, and visualizations. Why the apparent emphasis on outer scaling of the burst period when the whole thing seems to be generated in a viscous region?

S. KLINE (Stanford University): I think the answer to that is something like the following: If you have some large disturbances owing to turbulent structure, the large fluctuations hit the wall layers and you get a response. So that it is the frequency of the large outer fluctuations that gives the correlation that Dr. Eckelmann was just talking about and in the Strouhal scaling that Dr. Johnson was talking about. But since it is a certain kind of a layer in terms of the structure of the layer, the space structure with which it responds is in terms of the inner variables. There is a nonlinear calculation made some years ago by Tiederman, who is here, which shows that the most preferred response of the wall layers is to random fluctuations in a transverse wavenumber and I think he got 99. We've been showing 100 on the slides. We don't believe either that the data or the theory is that good, but the agreement is quite clear.

T. HANRATTY (University of Illinois): I should mention another bump that has been observed in the transverse velocity fluctuations. These are the results of measurements made by Fowles at the Massachusetts Institute of Technology. The bump is negative, rather than positive, and it occurs in roughly the same place, somewhere around y^+ of 3 or 4.

B. JOHNSON (U.S. Naval Academy): I have looked at a lot of slides of wiggly lines, but Figures 5 and 6 are the first sets that really impressed me with their significance. You seldom see such a strong and well defined phase lag between the near wall layer and the surface region. This is what Professor Kline and I were talking about in questioning the cascade theory.

KLINE: Landau is the only one I know that will say that the cascade theory is just plain wrong. All I said is that there were some reasons for doubting it.