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WALL TURBULENCE STRUCTURE AND CONVECTION HEAT TRANSFER

Z. ZARIĆ
Boris Kidrič Institute, University of Belgrade, Yugoslavia

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Abstract—Recently accumulated evidence emphasizes the role of coherent, quasi-ordered structures in transport processes of a turbulent shear flow. Statistically, the presence of these structures is manifested as intermittency of the signals of fluctuating quantities leading to departures from gaussianity. This paper presents the results of a conventional statistical analysis of velocity and temperature fluctuations in the wall layers of a channel flow. The results indicate the presence of at least two intermittent phases—inrushes towards the wall and ejections outwards—superimposed on the background turbulence. A conditional sampling and averaging technique, aiming at the detection of the two intermittent phases, is presented. The results demonstrate that the evolution of the probability density distributions in the wall layers could well be explained by the statistical behavior of the intermittent phases.

NOMENCLATURE

e, $= \gamma(\sigma/K)^2$;
f, frequency;
F, flatness factor, $= \overline{u'^4}/K^4$;
F', flatness factor of the time-derivative;
g_{11}, spectral density, $\int_0^\infty g(f)\,df = 1$;
$I(\tau)$, intermittency function;
K, RMS value, $= \sqrt{(\overline{u'^2})}$;
K', RMS value of the time derivative;
K_z, RMS value of the fluctuations of the criterion Z;
$p(u)$, probability density;
$\dot{q}$, heat flux density;
r_{11}, autocorrelation coefficient, $= \overline{u'(\tau)u'(\tau+\tau_s)}/K^2$;
S, skewness factor, $= \overline{u'^3}/K^3$;
S', skewness factor of the time-derivative;
t, instantaneous temperature, $= T+t'$;
T, long-term average temperature;
u, instantaneous velocity, $= U_1+u'$;
U, U_1, mean velocity;
U_*, friction velocity;
y^+, non-dimensional distance from the wall, $= YU_*/\nu$;
Z, conditional sampling criterion.

Greek symbols

γ, intermittency factor, $= \overline{I(\tau)}$;
θ, mean temperature difference, $= T_p - T$;
υ, instantaneous temperature difference, $= T_p - t$;
ν, cinematic viscosity;
σ, RMS value of a phase, equation (15);
τ, time;
τ_s, time-delay;
τ^+, non-dimensional time delay, $= \tau U_*^2/\nu$.

Subscripts

c, quiescent phase;
e, ejection phase;
o, channel axis;
p, wall;
s, inrush phase;
T, temperature.

INTRODUCTION

HEAT transfer by turbulent convection is encountered in a great variety of applications ranging from engineering to life sciences. The problem is still basically unsolved, since the fundamental mechanism of turbulent transfer processes is not known in spite of almost a century of experimental and theoretical research in turbulent flows.

Turbulence is a mechanical system with a great many degrees of freedom. Therefore, although fundamental equations of turbulent flow are known and valid at any instant, the general solution of these equations could not be obtained, not even with the aid of the generations of computers anticipated for the near future. A statistical approach is therefore necessary. Statistical equations are derived from fundamental equations on the basis of a defined averaging procedure. From the time of Reynolds we have had at our disposal a possible approach based on the assumption that a fluctuating quantity, like velocity u, could be represented as a sum of the long-time average value U and the fluctuation around this value, u';

$$u = U + u'. \tag{1}$$

The well-known Reynolds equations, which are at the base of almost all present-day prediction procedures in turbulent flows, are obtained with this assumption and a set of averaging rules. However, Reynolds equations represent an unclosed system in which equations for the statistical moments of the order n always contain unknowns in the form of moments of the order $n+1$. Semiempirical theories of turbulence are concerned with the solution of the closure problem through the relation of moments of the order $n+1$ to moments of the order n on the basis of different hypotheses, founded on experimental evidence. However, these theories could never be general enough. Thus, one is always confronted with some particular flow for which new hypotheses have to be found on the basis of the new experiments. The need for fundamental research in turbulent flows is therefore evident.

A pertinent question arises: is the Reynolds averaging procedure the most appropriate, especially as concerns insight into the basic mechanism of turbulent transfer processes? Somewhat scattered but indicative experimental evidence has been accumulated recently on the basis of which one is inclined to answer negatively. We shall give a short review of this evidence.

One of the most interesting discoveries in turbulence research came from the investigations of Corrsin [1], Townsend [2], Corrsin and Kistler [3] and others of the free boundaries of turbulent flows. It concerns a phenomenon called intermittence, manifesting itself as a sharp, instantaneous, irregular front separating turbulent and non-turbulent regions of the flow. It was found that this phenomenon has a very important role in the processes of turbulent energy generation and turbulent transport. Kovasznay *et al.* [4] has shown that a detailed investigation of intermittence is possible only by separately investigating the turbulent and non-turbulent states of the flow. A technique, called conditional sampling and averaging, is introduced in which a conditional average of a fluctuating quantity $Q(\tau)$ for the turbulent state is defined by:

$$\langle Q \rangle_t = \lim_{\tau_0 \to \infty} \frac{1}{\gamma \tau_0} \int_0^{\tau_0} I(\tau) Q(\tau) \, d\tau \tag{2}$$

where the intermittency function is given by:

$$I(\tau) = \begin{cases} 1 & \text{turbulent} \\ 0 & \text{non-turbulent} \end{cases} \tag{3}$$

and the intermittency factor by:

$$\gamma = \overline{I(\tau)} = \lim_{\tau_0 \to \infty} \frac{1}{\tau_0} \int_0^{\tau_0} I(\tau) \, d\tau. \tag{4}$$

A long-term average velocity U, in the Reynold's sense, is then given by:

$$U = \gamma \langle U \rangle_t + (1-\gamma) \langle U \rangle_{nt}. \tag{5}$$

It is seen that the mean velocity U is a result of two means $\langle U \rangle_t$ and $\langle U \rangle_{nt}$ for different states, related to U by aid of the intermittency factor resulting from the physics of the phenomena. These considerations, for instance, have led Spiegel [5] to propose a "two-fluid" approach to the solution of the turbulence problem, an approach avoiding the Reynolds equations.

Quite recently, some very interesting evidence has accumulated on the nature of large-scale intermittency at the free boundaries of turbulent flows and in mixing layers [6, 7]. It becomes evident that the intermittency in these flow layers is a consequence of the presence of large-scale, strongly coherent structures which have, at least for some period of time, a quasi-ordered and almost deterministic nature. The exact form of these structures and their properties are not known as yet, but it is highly probable that their temporal development and amalgamation, superimposed on the background turbulence of the flow, is responsible for the transport properties of a turbulent shear flow [6, 8].

Intermittency is very distinct close to the free boundaries of a turbulent flow. What about the inner layers of these flows? Recently, investigations by visualization methods have revealed a particular quasi-periodic structure in the wall layers, called "bursting" by Kline and co-workers [9, 10]. It became evident from the works of Corino and Brodkey [11], Grass [12] and Schlanchiauskas [13] that these events of relatively short duration and pronounced turbulence activity, during which most of the turbulence energy is generated, consist of at least two phases: ejections of low-momentum fluid masses from the wall vicinity, and inrushes of high-momentum fluid masses towards the wall. These findings have been supported by the results of investigations using other techniques [14, 15]. The ejections and the inrushes occur intermittently and in interaction with the flow produce high instantaneous values of the sheer stress responsible for the highly non-gaussian probability distribution of this stress. Pronounced departures from gaussianity have been detected also in the statistical characteristics of the parameters at the wall [16–18].

Frenkiel and Klebanoff [19] noted that there is no evidence of intermittency in the velocity signals in the wall layers, at least not the on-off type encountered close to the free boundaries. On the other hand, a certain type of intermittency has been evidenced even in the case of isotropic turbulence where velocity probability density distributions are closely gaussian. Namely, Batchelor and Townsend [20], Kuo and Corrsin [21] and other investigators have found that high frequency velocity fluctuations, or velocity time derivative fluctuations, are of an intermittent character leading to non-gaussian probability distributions. High frequency components are associated with the dissipation, which could be related to the generation of the turbulence energy.

The three mentioned types of intermittency—close to the free boundaries, in the wall layers and in isotropic turbulence—are quite distinct in their respective scales. Nevertheless, all kinds of intermittency result in departures of some of the turbulence parameters from gaussianity. We have therefore suggested [22] that the non-gaussianity of the velocity probability distributions in the wall layers is a consequence of intermittency, which is in agreement with the statement of Betchov [23] that the "spikes observed in the time derivative of turbulent velocity fluctuations constitute the principal non-gaussian contribution" in isotropic turbulence, and that "they are directly related to the irreversible turbulent process". In this sense, the notion of intermittency is a statistical way of expressing the presence of quasi-ordered structures in the flow, distinct in scale from the local background turbulence.

From what has been said, it follows that intermittent phenomena, i.e. the presence of quasi-ordered structures, are largely responsible for the generation of turbulence energy and are at the basis of all turbulent exchange processes, including heat transfer, everywhere in the flow. Fundamental studies of the turbulent exchange processes must therefore concentrate on investigations of such phenomena.

The first part of this paper presents the results of statistical analysis of the velocity and temperature fluctuations in the wall layers on the basis of the conventional, long-term averaging procedure. Although this analysis gives enough indications of the presence of intermittent phenomena in the wall layers, it is not able in principle to analyze these phenomena quantitatively.

The second part of the study presents statistical analysis developed for the investigation of the intermittent phenomena in the wall layers, based on the conditional sampling technique. Different conditional sampling methods have also been used by other investigators of the phenomena in the wall layers [24–27].

EXPERIMENTAL TECHNIQUE

Measurements have been made in air flow at the straight outlet section of a rectangular channel, used previously for other experiments and described elsewhere [22]. A fairly low Reynolds number was chosen in order to thicken the viscous sublayer. Channel walls could be electrically heated, and thus measurements have been made in isothermal as well as in non-isothermal flows. The non-isothermal flow is characterized by a fairly large temperature difference between the temperature of the wall and the temperature at the channel axis of about 50 K. Principal characteristics of the flows are given in Table 1. All measurements have been made close to one of the smooth channel walls with a cross-section of 40 by 300 mm.

Hot wire anemometry is employed as a suitable existing technique for statistical analysis, in spite of a number of disadvantages when used in the wall vicinity. The pronounced non-linearity of the signal at very low velocities appearing in the viscous sublayer requires very careful calibration and digital linearization. The wall effect requires special corrections which are still mainly empirical. At high turbulence intensities in the viscous sublayer the fact that the wire is sensitive to the two velocity vector components normal to the wire has to be taken into account [22]. A single, 5 μm diameter, tungstene wire is employed in order to approach the wall as close as possible. The wire could be switched either to a DISA anemometer, or to a Mueller bridge so that the flow temperature fluctuations also could be detected. More details on the technique are given elsewhere [22, 28].

The digital technique of data acquisition and analysis has been used throughout the study. The digital technique is practically indispensible in statistical analysis and in cases of pronounced non-linearity of the signal. Signals from the anemometer and from the Mueller bridge are registered on an analogue tape using an AMPEX FR-1300 tape recorder operated in the FM mode. The tape is replayed with a 1:32 speed reduction and the signal is fed into the digital computer with a frequency of 250 Hz, via an analogue-to-frequency, frequency-to-digital conversion system. The real time sampling frequency being 8000 Hz, 15-s long signals are registered on a digital tape in the form of a succession of 120 000 instantaneous values. The statistical analysis is performed on a CDC-3600 digital computer.

CONVENTIONAL STATISTICAL ANALYSIS

We have emphasized probability density distribution analysis. Velocity probability densities in isothermal flow are determined on the basis of 120 000 instantaneous values for twenty different non-dimensional distances from the wall, ranging from $y^+ = 1{\cdot}6$ to $y^+ = 211$. Complete probability density distributions have been presented elsewhere [29]. Probability density distributions in the buffer layer only are presented in Fig. 1. Linearization of the signal is done in the computer.

Velocity probability density distributions in the wall layers have been presented by a few authors only [19, 30–32] with Comte-Bellot [33] presenting only measurements of the skewness and the flatness factors. In most of these studies the analogue technique was employed. Our data on the distribution of the first four statistical moments agree reasonably well with the results of other authors. What is more important, the general shape of the complete probability density distributions, in function of the distance from the wall, agrees well with the shape of the distributions presented by Eckelmann [32]. It appears, therefore, that some features of these distributions are general enough for wall turbulence. These include:

(i) Distributions are highly non-gaussian throughout the inner layers. In fact, some of the distributions presented in Fig. 1 are of a shape unlike any known theoretical probability density distribution.

(ii) Skewness and flatness factors have very high values in the viscous sublayer. Asymmetry is such that an appreciable difference exists between the average and the most probable velocity.

Table 1

	U_o (m/s)	U_* (m/s)	T_o (°C)	T_p (°C)	$10^{-4}Re$	$\dot{q}_p$ (W/m²)	$10^3 St$
Isothermal flow	10·2	0·43	40·7	40·7	3·91		
Non-isothermal flow	10·6	0·52	34·7	84·3	4·23	2016	3·75

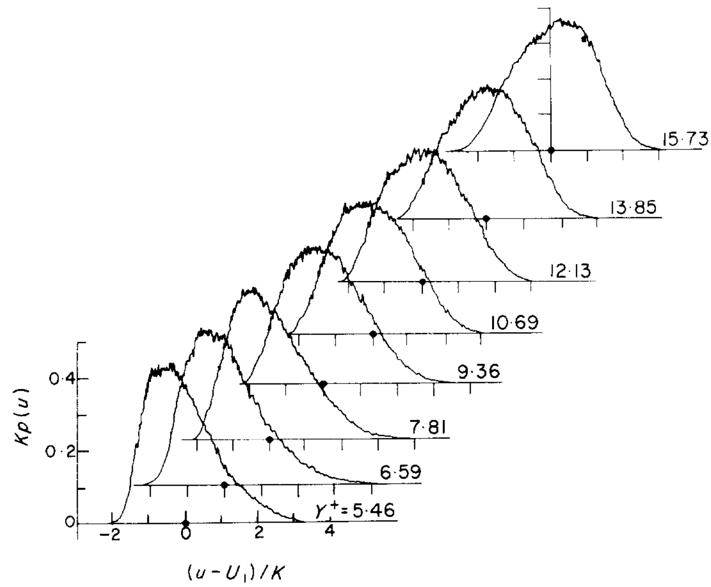

FIG. 1. Velocity probability density distributions in the buffer layer.

(iii) At about $y^+ = 15$ the distributions become symmetrical, with the uneven order moments being equal to zero. Approximately at the same distance from the wall, even order moments are at a minimum, which is appreciably lower than the corresponding gaussian value.

(iv) Further from the wall the distributions are becoming asymmetrical in the opposite sense—towards low velocities, so that the uneven order moments are negative.

Probability density distributions in the wall layers of non-isothermal flows have not been reported in literature. Probability density distributions of velocity and temperature difference ($\upsilon = T_p - T$) fluctuations in non-isothermal flow are presented in Fig. 2 inside the viscous sublayer and in Fig. 3 further from the wall. Corresponding skewness and flatness factors for velocities, S and F, and temperatures, S_T and F_T, are given in Fig. 4. It is seen that the evolution of the forms of velocity probability distributions in non-isothermal flow is similar to that in isothermal flow, departures from non-gaussianity being more pronounced, however, in the latter case. It is also seen that the velocity probability distributions are very similar in shape to the temperature-difference probability distributions.

Since temperature and velocity fluctuations are measured with the same wire but not simultaneously, the influence of temperature fluctuations on velocity fluctuations could not be taken into account. An attempt to correct the data to this effect is made by supposing that the maximum amplitude temperature difference fluctuations, both positive and negative, correspond to the maximum amplitude velocity fluctuations, i.e. that these are closely correlated. As seen from Fig. 5, the corrected velocity probability density distribution becomes almost identical with the temperature-difference probability distribution at $y^+ =$

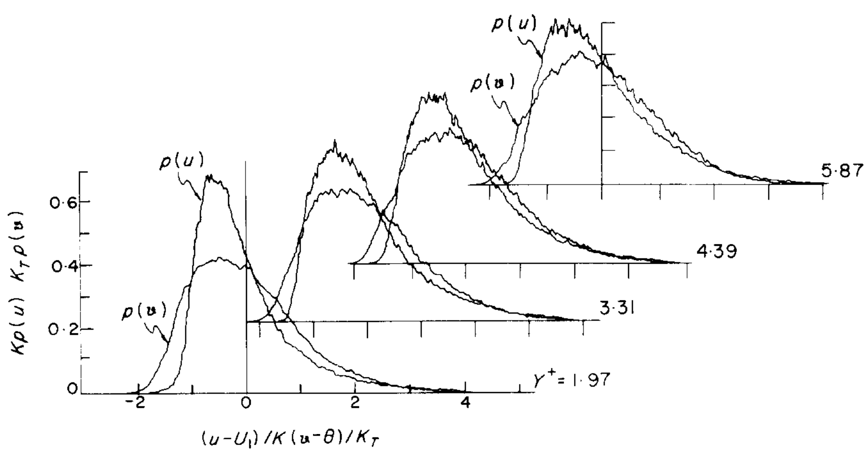

FIG. 2. Velocity ($p(u)$) and temperature difference ($p(\upsilon)$) probability density distributions in the viscous sublayer.

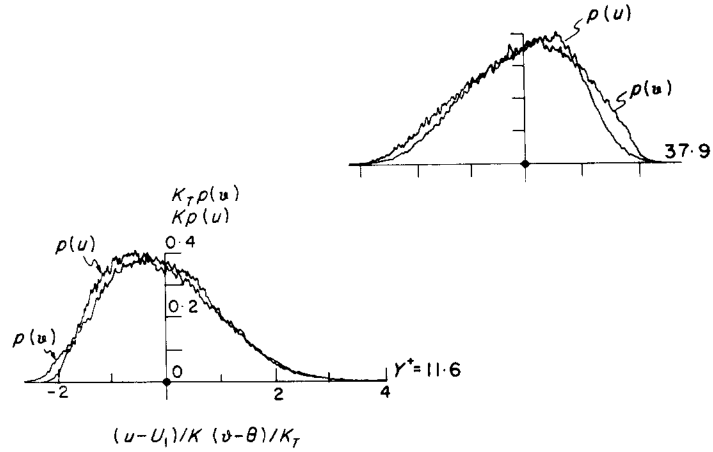

FIG. 3. Velocity ($p(u)$) and temperature difference ($p(\vartheta)$) probability density distributions further from the wall.

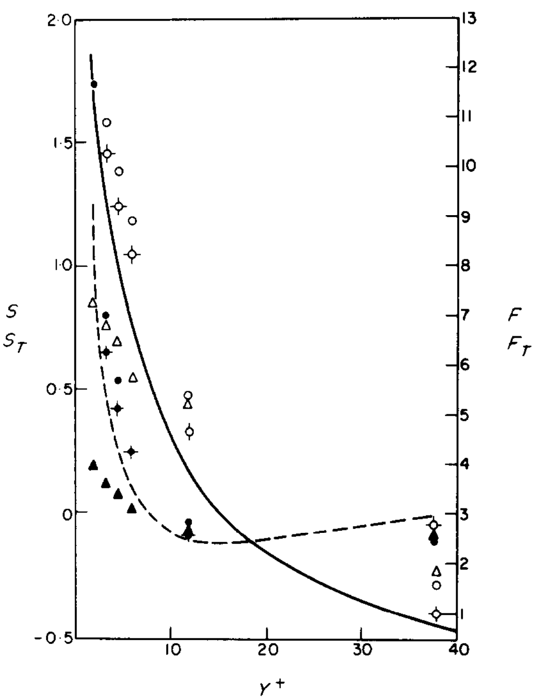

FIG. 4. Skewness (S) and flatness factors (F) in non-isothermal flow. ○, S, without corrections; ⌖, S, with corrections; ●, F, without corrections; ✦, F, with corrections; △, S_T; ▲, F_T. ——, S; – – –, F; isothermal flow.

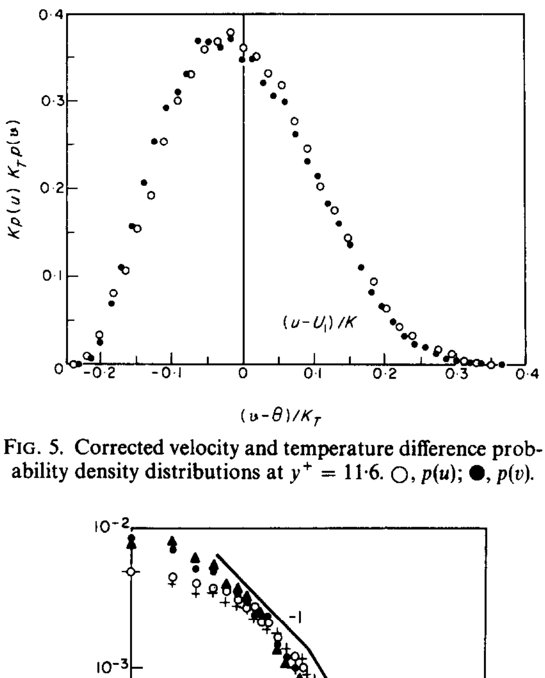

FIG. 5. Corrected velocity and temperature difference probability density distributions at $y^+ = 11{\cdot}6$. ○, $p(u)$; ●, $p(\vartheta)$.

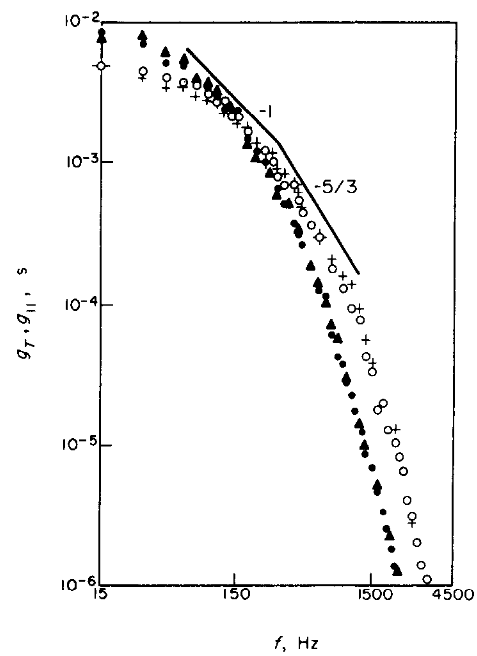

FIG. 6. Velocity and temperature spectral densities. ●, g_T, $y^+ = 5{\cdot}9$; ▲, g_T, $y^+ = 11{\cdot}6$; +, g_{11}, $y^+ = 5{\cdot}9$ non-isothermal flow; ○, g_{11}, $y^+ = 5{\cdot}45$, isothermal flow.

11·6. From Fig. 4 it is seen that with these corrections the corresponding skewness and flatness factors become closer to one another, as well as closer to the corresponding velocity values of isothermal flow. This would support the hypothesis of the high correlation between the velocity and temperature difference in large amplitude fluctuations.

A frequency analysis of the signals was made by using the fast Fourier transform technique. The complete results are given elsewhere [28]. The comparison of velocity and temperature spectra for isothermal and non-isothermal flow for y^+ about 5 is shown in Fig. 6. It is seen that the velocity and temperature spectra coincide in the energy containing range of frequencies.

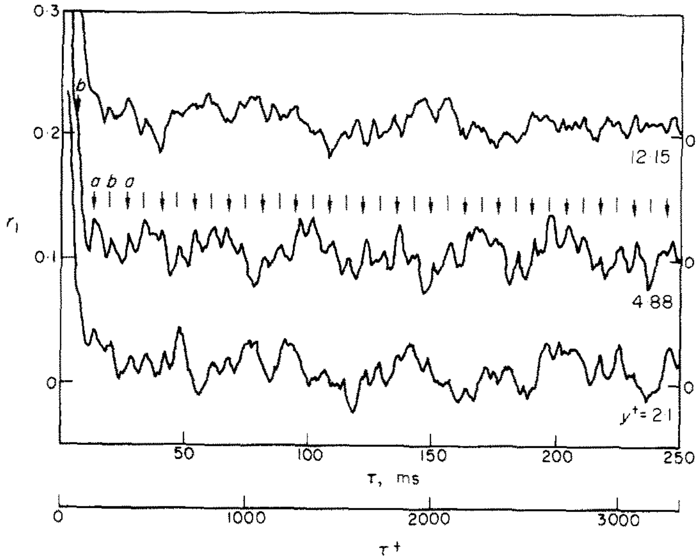

FIG. 7. Autocorrelation functions in the wall layers (isothermal flow).

The velocity autocorrelation (r_{11}) curves close to the wall in isothermal flow are shown in Fig. 7 for very long non-dimensional time delays (τ^+). For such long time delays the quasi-periodicity of the signals close to the wall becomes evident. From the autocorrelation curves a mean period of the quasi-periodic events of $\overline{\tau^+} = 90$ could be obtained, which is in accordance with the findings of Kim *et al.* [10]. From the temperature autocorrelation distributions the same mean period is obtained [28].

Statistical analysis of the time derivatives of velocities ($du/d\tau$) and temperature differences ($d\upsilon/d\tau$) was also performed [28]. Probability density distributions of the velocity time-derivative in isothermal flow are presented in Fig. 8. It is seen that unlike the probability density distributions of the velocity itself (Fig. 1), these distributions are similar in shape throughout the wall layers. Skewness and flatness factors of velocity (S' and F') and temperature difference (S'_T and F'_T) time derivatives are given in Fig. 9. Further from the wall, the results agree well with the measurements in atmospheric turbulence [34]. Very high values of S' and especially F' are detected close to the wall. This indicates a pronounced intermittency of the small-scale fluctuations, as can also be seen from the shape of the probability density distributions in Fig. 8.

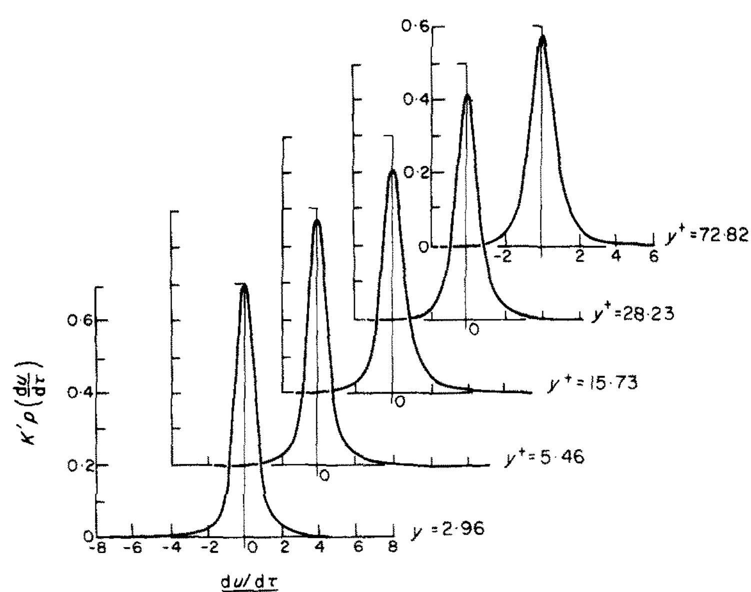

FIG. 8. Probability density distributions of the velocity time-derivative in isothermal flow.

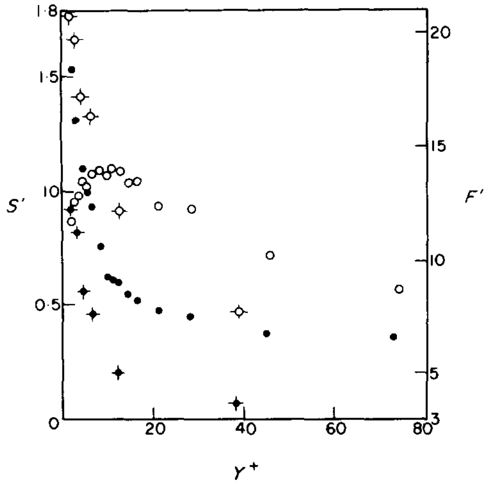

FIG. 9. Skewness and flatness factors of the velocity and temperature difference time derivatives. ○, S'; ✧, F'; ●, S'_T; ✦, F'_T.

The results of conventional statistical analysis indicate the presence of different intermittent phases in the wall layers in a number of ways:

(i) The evolution of the shapes of the velocity probability distributions in the wall layers could be explained by the presence of two different intermittent phases. In agreement with the visualization studies, positive skewness of these distributions close to the wall might well be the consequence of a dominant influence of high-momentum fluid inrushes in this region, while negative skewness of these distributions further from the wall might reflect a dominant influence of low-momentum fluid ejections [29].

(ii) The similarity of the velocity and the temperature difference probability distributions could be taken as further confirmation of the above indications, since large-amplitude positive fluctuations reflect the presence of high-momentum, low-temperature fluid and large-amplitude negative fluctuations the presence of low-momentum, high-temperature fluid.

(iii) Autocorrelation analysis for long time-delays shows the presence of quasi-periodic events with an average period the same for velocity as well as for temperature signals and in agreement with the findings of visualization studies.

(iv) The statistical analysis of the velocity and the temperature time-derivatives gives an indication of a high degree of intermittency of the small scale fluctuations in the wall layer.

However, it is evident that it is impossible to describe quantitatively the observed intermittent, non-gaussian processes by means of the conventional statistical analysis, based on long-term averaging procedure. The development of appropriate methods of statistical analysis of these processes is therefore necessary for the understanding and quantitative description of the wall turbulence phenomena.

CONDITIONAL STATISTICAL ANALYSIS

As already indicated, the conditional sampling and averaging technique has been successfully applied in analysis of the intermittent phenomena at the free boundaries of a turbulent flow. In this technique the most delicate matter is the choice of criteria for making the decision about turbulent or non-turbulent state, necessary for the definition of the intermittency function, equation (3).

The conditional averaging technique has recently been used also in the wall layers [24–26, 35]. In the wall layers, the flow is always turbulent, so that the definition of the intermittency function is even more delicate. On the basis of conclusions drawn from conventional statistical analysis, we are aiming at the distinction of three different phases: two intermittent phases of the inrushes and the ejections and the relatively undisturbed or calm phase. We have therefore defined our intermittency function by:

$$I(\tau) = \begin{cases} 1 & Z > Z_s \quad \text{inrush phase} \\ 0 & Z_s > Z > -Z_e \quad \text{calm phase} \\ -1 & Z < -Z_e \quad \text{ejection phase.} \end{cases} \tag{6}$$

Here criterion Z could be in fact a combination of criteria, and the values of the critical levels Z_s and Z_e could differ from each other.

Analysis of our velocity traces, as well as of the traces of the two velocity components of Wallace *et al.* [27], showed that large amplitude velocity fluctuations are accompanied by large amplitude velocity gradient fluctuations. We have therefore taken as the criterion for switching on the intermittency function $[I(\tau) \neq 0]$:

$$Z_1 = (u - U_m)(\mathrm{d}u/\mathrm{d}\tau) \tag{7}$$

with U_m not necessarily the mean velocity but a value between the mean and the most probable value. As additional criteria, we have also taken:

$$Z_2 = (\mathrm{d}u/\mathrm{d}\tau) \tag{8}$$

$$Z_6 = (u - U_m) \tag{9}$$

to be able to detect intermittent phases in cases when $(u - U_m)$ and $(\mathrm{d}u/\mathrm{d}\tau)$ are of a different sign but have high values. Critical levels of Z_1, Z_2 and Z_6 have to be chosen. In Fig. 10, RMS values of the fluctuations of Z_1 and Z_2, conditionally sampled according to the sign of the $(u - U_m)$, are given in function of the distance from the wall. It is seen that these values vary across the wall layers and that the values for $(u - U_m)$ positive differ from the values for $(u - U_m)$ negative. Critical values of the criteria $(Z_{1s}, Z_{1e}, Z_{2s}, Z_{2e})$ are taken in proportion with the corresponding RMS values from Fig. 10.

Once switched on, it was taken that the intermittency function is not switched off unless the velocity gradient changes its sign and then only if the additional criteria:

$$Z_3 = (u - U_m) \tag{10}$$

$$Z_5 = (u - U_m - bK)(\mathrm{d}\tau) \tag{11}$$

are below chosen critical levels $(Z_{3s}, Z_{3e}, Z_{5s}, Z_{5e})$. It is also avoided that $I(\tau)$ be switched off by small, spurious fluctuations of the velocity gradient, i.e. the value of:

$$Z_4 = |(\mathrm{d}u/\mathrm{d}\tau)| \tag{12}$$

has to be greater than a certain value (Z_{4s}, Z_{4e}).

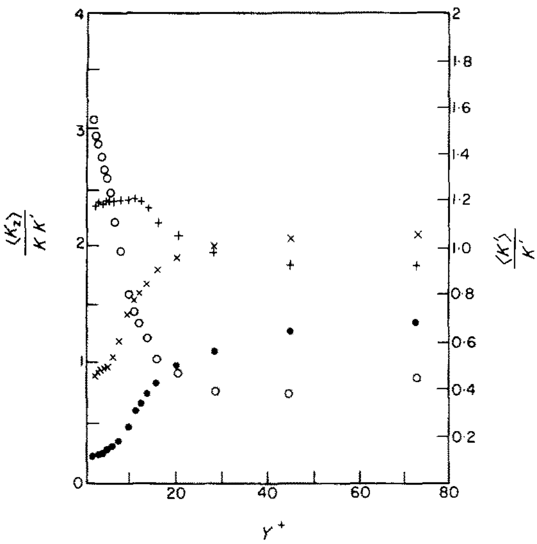

FIG. 10. RMS values of the conditionally sampled fluctuations of Z_1 and $du/d\tau$. ○, $\langle K_z\rangle^+$; ●, $\langle K_z\rangle^-$; +, $\langle K'\rangle^+$; ×, $\langle K'\rangle^-$.

The different criteria used for switching-on and switching-off the intermittency function are illustrated in Fig. 11 in the case of an inrush. With such a number of criteria it was not possible to optimize fully the values of different critical levels (Z_{1s}, Z_{1e}, etc.). After partial optimization, a set of these values was established and the conditional sampling of the velocity and temperature signals was made. Full details are reported elsewhere [28]. The results are given below.

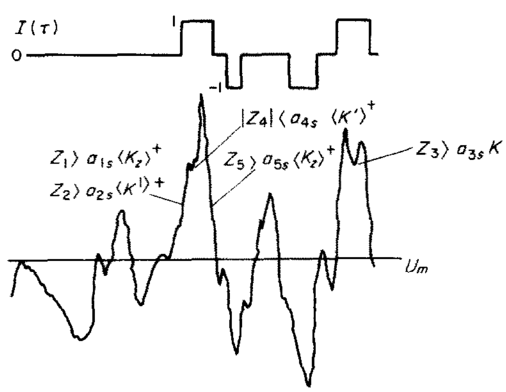

FIG. 11. Scheme of the conditional sampling procedure.

Separation of different phases inside the viscous sublayer are illustrated in Figs. 12 and 13 in the case of velocity and temperature signals, respectively. Curve 1 corresponds to the total signal, and curves 2, 3, and 4 to the inrush, the ejection and the calm phase, respectively. All shown probability density distributions are normalized by the corresponding RMS value of the total signal (K, K_T). Velocity probability density distributions of different phases in the buffer layer, obtained by conditional sampling analysis, are given in Fig. 14. Two important conclusions follow. First, the irregularity of the probability density distributions of the total signal are readily explained by the superposition of three probability density distributions corresponding to the three different phases (compare Figs. 1 and 14). Second, probability density distributions of the calm phase are sensibly gaussian.*

The intermittency factors of different phases:

$$\gamma_i = \langle I(\tau)\rangle_i \tag{13}$$

obtained from conditional analysis are shown in Fig. 15 in function of the distance from the wall. The corresponding contributions to the total variance of the signal (K^2) are given in Fig. 16, with:

$$e_i = \gamma_i(\sigma_i/K)^2 \tag{14}$$

$$\sigma_i^2 = (U_1 - U_i)^2 + \langle u - U_i\rangle^2 \tag{15}$$

and:

$$e_s + e_e + e_c = 1 \tag{16}$$

where U_i are corresponding mean values of different phases. The contribution to the total variance is a measure of the contribution to turbulence energy. From Figs. 15 and 16 it is seen that in the viscous sublayer the intermittent phases which are each present about 15 per cent of the time contribute almost 80 per cent to the total variance of the signal, the inrush phase contributing the most. In the logarithmic region ($Y^+ \geqslant 40$) the calm phase which is present about 50 per cent of the time contributes slightly more than 10 per cent and the ejection phase, present less than 30 per cent of the time, contributes more than 50 per cent to the total variance.

It is seen also that the statistical characteristics of different phases, as determined from the temperature signals, are sensibly the same as those determined from the velocity signal. The large amplitude temperature fluctuations, closely correlated with the large amplitude velocity fluctuations, belong to the intermittent phases and contribute the most to the turbulent exchange of heat.

The analysis of the statistical behavior of the intermittent phases indicates that the fluid masses originating from the logarithmic region, or from zones even farther from the wall, gradually decelerate in the buffer region but penetrate all the way into the viscous sublayer. In the sublayer these inrushes of high momentum fluid provoke, possibly by formation of vortices, ejections of low-momentum fluid from the sublayer into the buffer layer. In the buffer layer these ejections are amplified probably by mutual interactions (amalgamation) and propagate into the regions farther from the wall where, in an as yet undetermined way, they provoke inrushes of fluid masses towards the wall. These two interconnected processes disturb in an intermittent way the background turbulent flow of basically gaussian characteristics and govern turbulent exchange processes in the wall layers. This qualitative description of processes in the wall layers is in agreement with the recent findings of Offen and Kline [37].

*The skewness of the distributions in the viscous sublayer (Fig. 12) is explained by the fact that the wire is measuring fluctuations of both velocity components normal to the wire [36].

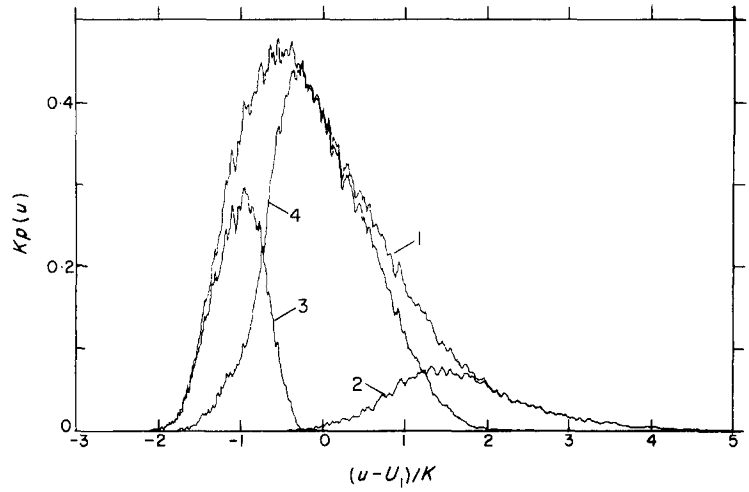

FIG. 12. Separation of the intermittent phases for the velocity signal at $y^+ = 4{\cdot}9$. 1 — total signal; 2 — inrush phase; 3 — ejection phase; 4 — quiescent phase.

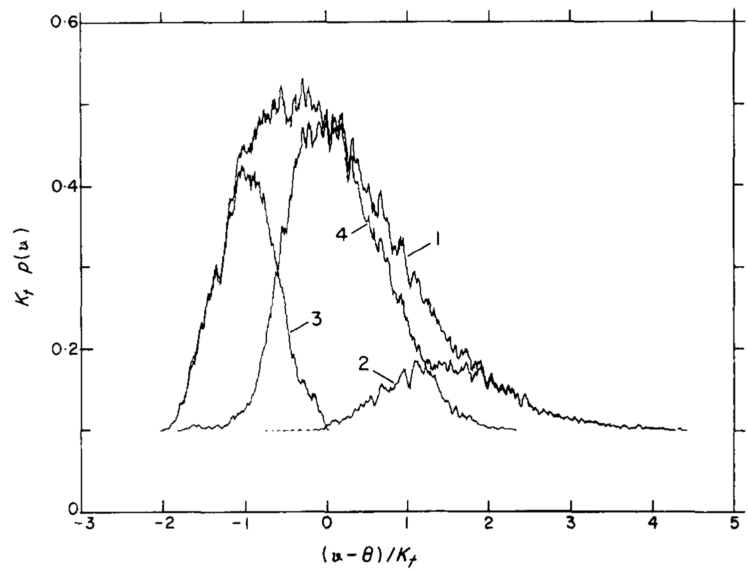

FIG. 13. Separation of the intermittent phases for the temperature signal at $y^+ = 4{\cdot}4$. Same notations as in Fig. 13.

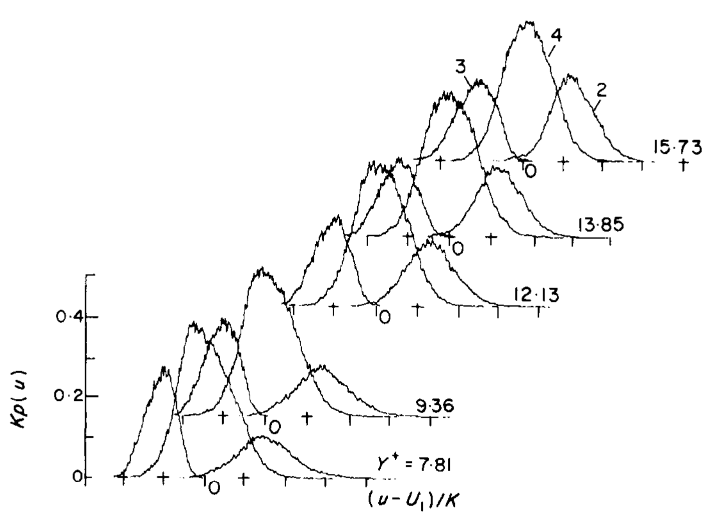

FIG. 14. Probability density distributions of the different phases in the buffer layer (isothermal flow).

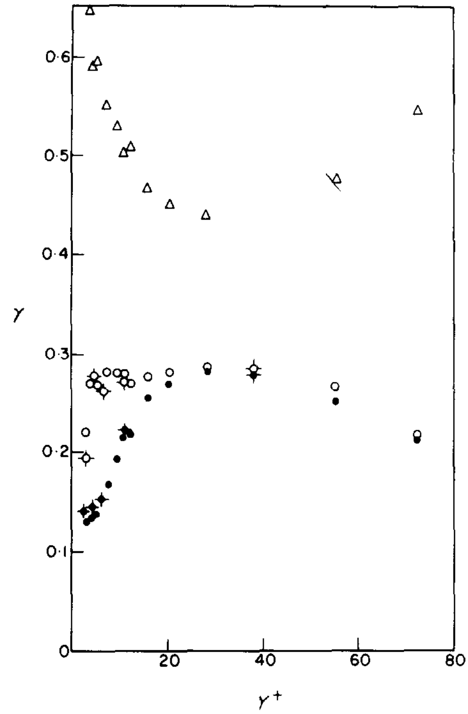

Fig. 15. Intermittency factors of different phases in the wall layers. △, γ_c; ○, γ_e; ●, γ_s; ⌖, γ_{eT}; ✦, γ_{sT}.

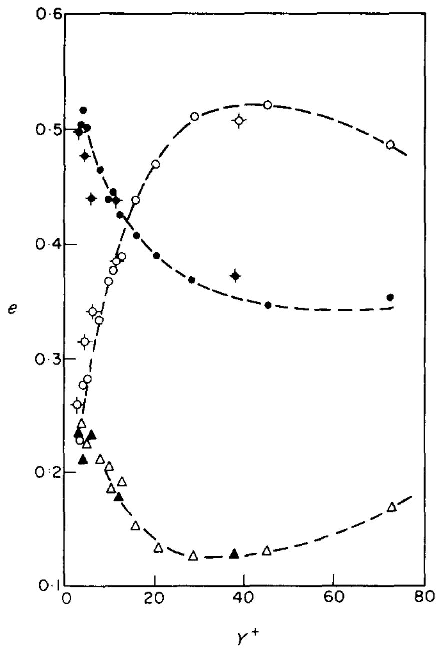

Fig. 16. Contribution of the different phases to the total variance (K^2). △, e_c; ▲, e_{cT}; ●, e_s; ✦, e_{st}; ○, e_e; ⌖, e_{eT}.

Clearly, analysis of the signals detected by a single stationary probe in the flow, or even by a rank of probes, is incapable of offering detailed insight into the physics of the involved phenomena. These signals, when analyzed properly, can only get at the statistical implications of these phenomena. New trends in turbulence research [7], oriented towards what was called by Coles [8] "eddy chasing", i.e. investigations of temporal behavior of quasi-ordered structures—eddies or turbulence spots, are motivated by a need for better insight into the physics of the phenomena. Through such investigations statistical characteristics of different intermittent phases, as detected at a point of the flow, could be determined. It is, however, evident that statistical procedures which do not take into account the presence of the intermittent phases provoked by quasi-ordered structures could only represent a first approximation. Development of statistical theories of turbulence, based on averaging procedures different from those employed by Reynolds, is therefore vital as a basis for more general prediction methods. A "three fluid" model, based on the presence of three different phases, is a possibility.

CONCLUSIONS

The results of the conventional statistical analysis in the wall layers of a channel flow confirm the presence of the two different phases detected by visualization studies, as well as the dominant role of this intermittency in the turbulent exchange processes. However, it is not possible to describe quantitatively the observed intermittent, non-gaussian processes by means of a statistical analysis based on long-term averaging. The development of appropriate methods of statistical analysis is therefore necessary for the understanding of the wall turbulence phenomena.

The paper is further concerned with the development of statistical methods suitable for the quantitative analysis of the intermittent events in the wall layers, as detected by a single probe. Conditional sampling and analysis, developed for the investigation of intermittence of the external flow layers, is employed. However, as the intermittence present in the wall layers is of a different nature, it was necessary to modify the conditions of the sampling procedure. A method is developed, capable of identifying separately the two intermittent phases, as well as of separating them from the rest of the signal.

It is shown that throughout the wall layers the probability density distributions of the total signal are obtained by superposition of three different probability density distributions, two of which correspond to the intermittent phases of ejections and inrushes and the third of which corresponds to the relatively undisturbed, background flow. In this manner, the irregularity of the forms of the probability density distributions of the total signal is easily explained, as well as the evolution of these forms throughout the wall layers. The probability density distributions of the quiescent phase are sensibly gaussian.

A "three-fluid" model based on the existence of three different phases, each with its own statistical characteristics, would be more appropriate for the analysis of turbulence exchange processes in the wall layers. Such a model, however, does not agree with Reynolds' basic hypothesis. It follows that if there is a need to include fluctuating properties of the flow in the analysis, it is necessary to develop new prediction procedures based on the existence of the three different phases.

REFERENCES

1. S. Corrsin, Investigation of flow in an axially symmetrical heated jet of air, NACA WR W-94 (1943).
2. A. A. Townsend, Momentum and energy diffusion in the turbulent wake of a cylinder, *Proc. R. Soc.* **A197**, 124–140 (1949).
3. S. Corrsin and A. L. Kistler, Free stream boundaries of turbulent flows, NACA Rept. 1244 (1955).
4. L. S. G. Kovasznay, V. Kibens and R. F. Blackwelder, Large scale motion in the intermittent region of a turbulent boundary layer, *J. Fluid Mech.* **41**, 283–325 (1970).
5. E. A. Spiegel, Qualitative model of turbulent intermittency, *Physics Fluids* **15**, 1372–1376 (1972).
6. G. L. Brown and A. Roshko, On density effects and large structure in turbulent mixing layers, *J. Fluid Mech.* **64**, 775–816 (1974).
7. J. Laufer, New trends in experimental turbulence research, In publication.
8. D. Coles and S. J. Barker, Some remarks on a synthetic turbulent boundary layer, Workshop on Turbulent Mixing, Purdue University, May (1974).
9. S. J. Kline, W. C. Reynolds, F. A. Schraub and P. W. Runstadler, The structure of turbulent boundary layers, *J. Fluid Mech.* **30**, 741–773 (1967).
10. H. T. Kim, S. J. Kline and W. C. Reynolds, The production of turbulence near a smooth wall in a turbulent boundary layer, *J. Fluid Mech.* **50**, 133–160 (1971).
11. E. R. Corino and R. S. Brodkey, A visual investigation of the wall region in turbulent flow, *J. Fluid Mech.* **37**, 1–30 (1969).
12. A. J. Grass, Structural features of turbulent flow over smooth and rough boundaries, *J. Fluid Mech.* **50**, 233–255 (1971).
13. A. A. Shlanchiauskas, Struktura turbulentnovo perenosa u stenki, *Teplo-i massoperenos* **1**(1) (1972.
14. H. P. Bakewell and J. L. Lumley, Viscous sublayer and adjacent wall region in turbulent pipe flow, *Physics Fluids* **10**, 1880–1889 (1967).
15. A. K. Gupta and R. E. Kaplan, Statistical characteristics of Reynolds stress in a turbulent boundary layer, *Physics Fluids* **15**, 181–185 (1972).
16. A. T. Popovich, Statistical laws and the viscous sublayer in turbulent flow, *I/EC Fundamentals* **8**, 609–614 (1969).
17. P. Duhamel and B. Py, Caractere intermittent de la souscouche visqueuse et interpretation de mesures de densité de probabilité, A.A.A.F., 9ᵉ Collogue d'aérodynamique appliquée (1972).
18. M. K. Lee, L. D. Eckelmann and T. J. Hanratty, Identification of turbulent wall eddies through the phase relation of the components of the fluctuating velocity gradient, To be published.
19. F. N. Frenkiel and R. S. Klebanoff, Probability distribution and correlations in a turbulent boundary layer, *Physics Fluids* **16**, 725–737 (1973).
20. G. K. Batchelor and A. A. Townsend, *Proc. R. Soc.* **A199**, 2381 (1949).
21. A. Y. Kuo and S. Corrsin, Experiments on internal intermittency and fine structure distribution functions in fully turbulent fluid, *J. Fluid Mech.* **50**, 285–319 (1971).
22. Z. Zarić, Wall turbulence studies, in *Advances in Heat Transfer*, Vol. 8, pp. 285–350. Academic Press, New York (1972).
23. R. Betchov, Non-gaussian and irreversible events in isotropic turbulence, To be published.
24. R. F. Blackwelder and R. E. Kaplan, The intermittent structure of the wall region of a turbulent boundary layer, XIII IUTAM Meeting, Moscow (1972).
25. R. S. Brodkey, J. M. Wallace and H. Eckelmann, Some properties of truncated turbulent signals in bounded shear flows, Mitt. Max Planck Inst. No. 113/73 (1973).
26. S. S. Lu and W. W. Willmarth, The structure of the Reynolds stress in a turbulent boundary layer, Techn. Rpt. 021490-2-T, University of Michigan (1972).
27. J. W. Wallace, H. Eckelmann and R. S. Brodkey, The wall region in turbulent shear flow, *J. Fluid Mech.* **54**, 39–48 (1972).
28. Z. Zarić, Etude statistique de la turbulence pariétale, Boris Kidrič Institute, Belgrade (1974).
29. Z. Zarić, Distribution de probabilité des vitesses et des températures pres d'une paroi, *C.R. Hebd. Séanc. Acad. Sci., Paris* **A275**, 459–162 (1972).
30. P. C. Klebanoff, Characteristics of turbulence in a boundary layer with zero pressure gradient, NAGA Rept. 1247 (1955).
31. J. Marcillat, Fonctions de répartition des vitesses turbulentes dans une couche limite, Thesis, Univ. d'Aix-Marseille (1964).
32. H. Eckelmann, An experimental investigation of a turbulent channel flow with a thick viscous sublayer, Mitt. Max-Planck Instit. No. 48 (1970).
33. G. Comte-Bellot, Contribution a l'étude de la turbulence de conduite, Thesis, Univ. Grenoble (1963).
34. C. M. Sheih, H. Tennekes and J. L. Lumley, Airborne hot-wire measurements of the small-scale structure of atmospheric turbulence, *Physics Fluids* **14**, 201–215 (1971).
35. Z. Zarić, Statisticheskii analiz pristennoi' turbulentnosti, *Teplo-i massoperenos* **9**(2), Minsk (1972).
36. Z. Zarić, Distributions de probabilité des signaux provenant d'un dil chaud en écoulement turbulent, *C.R. Hebd. Séanc. Acad. Sci., Paris* **A269**, 986–989 (1969).
37. G. R. Offen and S. J. Kline, Experiments on the velocity characteristics of "bursts" and on the interactions between the inner and outer regions of a turbulent boundary layer, Report MD-31, Thermosciences Division, Standord University (1973).

STRUCTURE DE LA TURBULENCE PARIETALE ET TRANSFERT DE CHALEUR CONVECTIF

Résumé—Les résultats accumulés récemment mettent l'accent sur le rôle des structures cohérentes et quasi-ordonnées dans les processus de transport en écoulement turbulent cisaillé. Du point de vue statistique, la présence de ces structures se manifeste par l'intermittence des signaux des quantités fluctuantes qui conduit à des écarts à la loi normale.

Cet article présente les résultats d'une analyse statistique conventionnelle des fluctuations de vitesse et de température dans les couches pariétales d'un écoulement en conduite. Les résultats font apparaitre l'existence de deux phases intermittentes au moins (irruptions vers la paroi et éjections vers l'extérieur) surimposées à la turbulence de fond. Une technique d'échantillonnage et de moyenne est présentée ayant pour but de déceler les deux phases intermittentes. Les résultats montrent que l'évolution des distributions de densité de probabilité dans les couches pariétales peut être correctement expliquée par le comportement statistique des phases intermittentes.

ÜBER DIE STRUKTUR DER WANDTURBULENZ UND DEN KONVEKTIVEN WÄRMEÜBERGANG

Zusammenfassung—Neue Untersuchungen unterstreichen die Rolle kohärenter, quasi-geordneter Strukturen bei Transportprozessen in turbulenten Scherströmungen. Statistisch zeigt sich die Anwesenheit dieser Strukturen in einem intermittierenden Auftreten der Schwankungsgrößensignale, was zu Abweichungen von der Gauss'schen Normalverteilung führt.

Die vorliegende Arbeit gibt die Ergebnisse einer konventionellen statistischen Analyse der Geschwindigkeits- und Temperaturschwankungen in den Wandschichten einer Kanalströmung wieder. Die Ergebnisse zeigen die Anwesenheit von wenigstens zwei intermittierenden Phasen—Einströmungen zur Wand und Abströmungen von der Wand—die sich aufgrund der Turbulenz überlagern. Ein mögliches Verfahren zur Stichprobenentnahme und Mittelwertbildung für die Bestimmung der beiden intermittierenden Phasen wird vorgestellt. Die Ergebnisse zeigen, daß die Entwicklung der Wahrscheinlichkeitsdichte-Verteilungen in den Wandschichten gut mit Hilfe des statistischen Verhaltens der intermittierenden Phasen erklärt werden kann.

СТРУКТУРА ПРИСТЕННОЙ ТУРБУЛЕНТНОСТИ И КОНВЕКТИВНЫЙ ПЕРЕНОС ТЕПЛА

Аннотация — Ранее накопленные данные свидетельствуют о роли когерентных, квазиупорядоченных структур в процессах переноса при турбулентном сдвиговом течении. Со статистической точки зрения наличие этих структур проявляется в виде перемежаемости сигналов-пульсационных величин, приводящей к отклонению характеристик турбулентности от характеристики гауссовских случайных процессов.

В статье представлены результаты традиционного статистического анализа флуктуаций скорости и температуры в пристенной области течения в канале. Результаты показывают наличие по меньшей мере двух фаз перемежаемости — это выбросы по направлению к стенке и выбросы наружу — налагаемых на фоновую турбулентность. Описывается техника выборки и усреднения, направленная на обнаруживание двух фаз перемежаемости. Показано, что эволюцию плотности распределения вероятности в пристенных слоях можно с успехом объяснить статистическим поведением фаз перемежаемости.