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Turbulence characteristics of a plane diffuser flow with inlet velocity distortion

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Abstract

An experimental study of turbulent characteristics of incompressible flow in a two-dimensional diffuser with inlet velocity distortion is reported. Turbulence level in the boundary layer increases marginally towards the exit of the diffuser and decreases rapidly in the wake region. The region of maximum velocity fluctuation and the maximum Reynolds shear stress shifts away from the wall in the streamwise direction. The energy spectra of the turbulent kinetic energy in the wake region shows a characteristic behaviour indicating possible vortex shedding from the trailing edge of the airfoil.

Key words: Two-dimensional diffuser, inlet velocity distortion, turbulence, boundary layer, wake, energy spectra.

1. Introduction

Diffusers form an important component of many fluid machines. A knowledge of the turbulent structure of flow in a diffuser contributes a great deal to the understanding and improvement in the performance of a fluid machine. While a great deal of information on the performance and prediction of mean flow in a diffuser is available, the data on turbulence measurements are very meagre. The structure of turbulent shear flow in a diffuser was probably first studied by Ruetenik and Corrsin[1] who investigated the turbulence properties of fully developed two-dimensional diffuser flows under equilibrium condition at a semi-divergence angle of 1°. Comparison of their results with those of Laufer[2] for parallel channel flow indicated a large increase in turbulent kinetic energy and average shear stress levels. Okwuobi and Azad[3] also have made detailed studies on the structure of flow in a conical diffuser.

It is rather rare in practice to encounter a uniform inlet flow into a diffuser. Distortion of the entry flow is more of rule than an exception. Such a flow distortion affects the performance of a diffuser considerably. In the present investigation, velocity distortion at inlet to the diffuser was produced by a NACA 0009 airfoil located ahead of the diffuser.

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Investigations were made (i) with uniform core velocity, (ii) with symmetric wake-like distortion and (iii) with varying degree of asymmetry in the wake-like distortion. The present paper reports the results obtained concerning the turbulent structure of the flow in the diffuser. More details are available elsewhere[4].

2. Experimental facility and test procedure

The experimental facility used for this purpose is shown schematically in fig. 1. The test diffuser was designed based on the chart of Reneau *et al*[5] for optimum condition for maximum pressure recovery without appreciable stall.

Distortion in the inlet velocity profile was produced by placing a NACA airfoil of chord length 150 mm ahead of the diffuser spanning the 600 mm height of the test section. The airfoil was placed centrally such that its trailing edge was at the inlet to the diffuser. Non-symmetric distortion was generated by placing the airfoil at an incidence to the flow.

Five components of the Reynolds stress distribution were measured with the airfoil at $\alpha = 0°$ and $\alpha = 4°$ and without the airfoil, using an x-wire. At any station, two traverses were made, one with the wire in the x-y plane for deriving the values of u', v' and $-\overline{uv}$ and the other with the wire in the x-z plane to give the values of u', w' and $-\overline{uw}$. In addition to the good agreement between the values of u' independently obtained by traversing in the two planes, additional check for u' was made with a single wire. The location of the six measurements

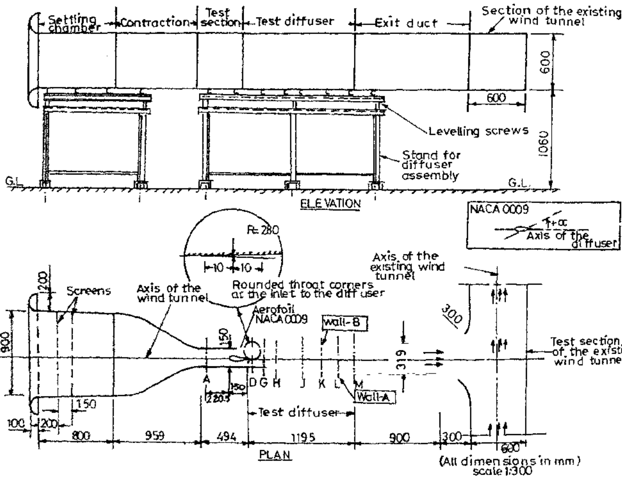

FIG. 1. Sketch of the wind tunnel.

Table I
Location of measurement stations

Measurement station	D	E	G	I	K	M
Distance X in mm	9	61	210.5	406	786	1136
X/c	0.06	0.406	1.403	2.706	5.24	7.57

stations is indicated in Table I. Auto-correlation measurements were also made at two stations for $\alpha = 0°$ and $\alpha = -4°$ from which integral time scales and one-dimensional energy spectra were calculated.

Turbulence quantities were measured with standard DISA hot-wire equipment, *viz.*, 55D01 anemometers, 55D15 linearizers, 55D30 and 55D31 digital voltmeters, 55D35 r.m.s. voltmeters, 55D25 auxiliary unit, 55D70 analogue correlator, 55A35 channel selector, 55D26 signal conditioner, 55D75 time delay unit, 55B01 sweep drive unit, 55A38 x-wire probe, 55A22 single wire probe and HP 70358 x-y recorder. Frequency counter function generator and oscilloscope were used for calibration. A DISA 55A12 micromanipulator was used to weld 5 μ-dia and 1.2-mm long platinum-coated tungsten wire to the hot-wire probes.

The exponent in the hot-wire equation used in the present experiment was chosen as 0.46. In the case of x-wires, the sensitivities of the two wires were found to be almost equal in all cases, the largest difference being of the order of 0.47% of mean voltage. Corrections at high turbulence intensities require information on higher order correlations. Since complete information on higher order correlations was not available, no corrections were applied. The largest intensity of turbulence measured in the wake region was of the order of 20% near the trailing edge of the airfoil. Irwin[6] has shown that even for turbulence intensities of the order of 20%, the correction necessary is of the order of 5%. Based on the turbulence measurements of Spangenberg *et al*[7] which were more or less similar to the present situation, the maximum error in the present case may be estimated to be of the order of 20% in the regions close to the wall.

3. Results and discussion

3.1 *Turbulence characteristics*

The turbulence quantities measured at station M near the diffuser exit are shown in fig. 2, as a typical example of the type of distribution in an adverse pressure gradient. The individual r.m.s. values u′, v′ and w′ fluctuations are plotted in fig. 3. Both these figures refer to the case when $\alpha = 0°$. Figure 3 shows that the total turbulent intensity in the wall layer region increases in the streamwise direction which has also been observed earlier by Spangenberg *et al*[7]. A similar type of behaviour was also observed for $\alpha = 4°$ and for the case when the inlet profile was free of any distortion. It is well known that a diffuser being a retarded flow region, acts as an amplifier of velocity fluctuations in the wall layer. It is also observed that in general, the relation $u' > w' > v'$ is valid in the wall layer. It can also be seen that for stations

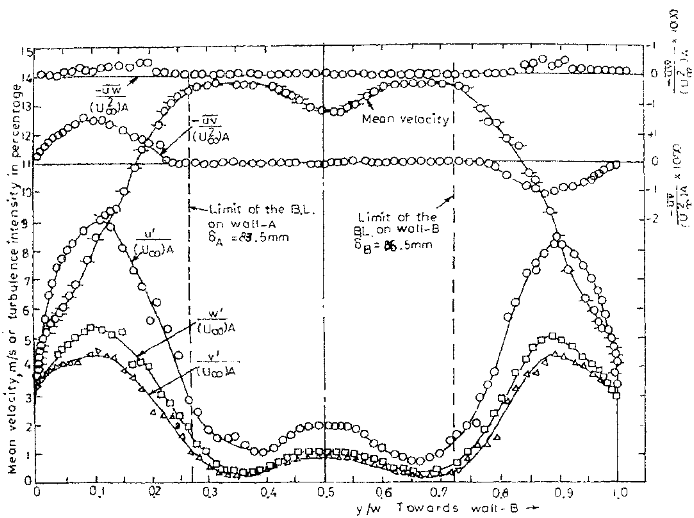

FIG. 2. Distribution of turbulence quantities at station M, $\alpha = 0°$.

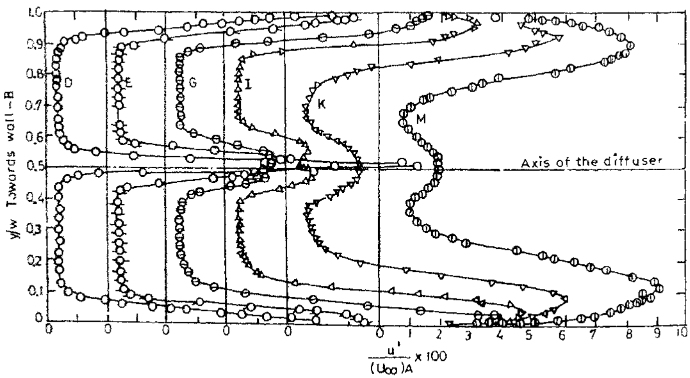

FIG. 3a. Distribution of u', $\alpha = 0°$.

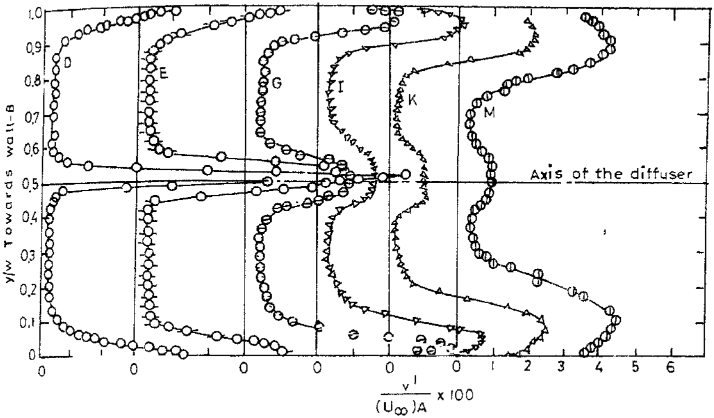

FIG. 3b Distribution of v′, $\alpha = 0°$.

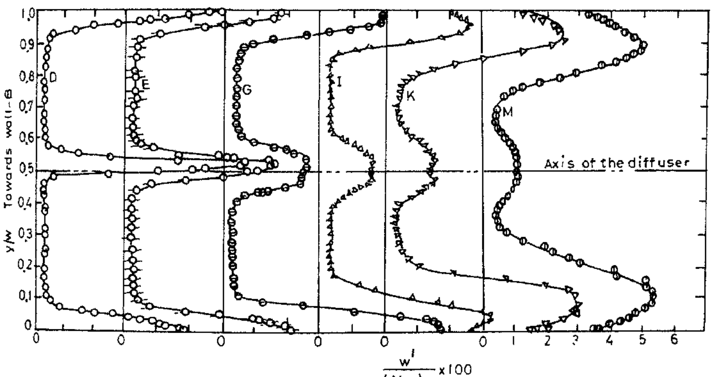

FIG. 3c. Distribution of w′, $\alpha = 0°$.

very close to the diffuser inlet, the peaks of u′, v′ and w′ values are very close to the wall as in a conventional boundary layer, but this peak moves away from the wall with distance downstream. This is a phenomenon typical of retarded flows.

Figure 4 shows the distribution of $\overline{uv}$ and $\overline{uw}$shear stresses for $\alpha = 0°$. The shear stress component $\overline{uw}$ is almost zero everywhere in the diffuser except for a very small region close to the diffuser inlet and in the wake of the airfoil. A similar behaviour was also observed for the case without airfoil indicating that the flow through the diffuser can possibly be treated as two-dimensional. For the case when $\alpha = 4°$, a slight departure from two-dimensionality was observed near the walls — A and B towards the exit of the diffuser. Just as in the case of the normal stress components, the shear stress component $\overline{uv}$ in the wall layer has its maximum value close to the wall initially which, however, shifts away from the wall downstream. The peaks in all the cases investigated occur more or less at the same position relative to the wall.

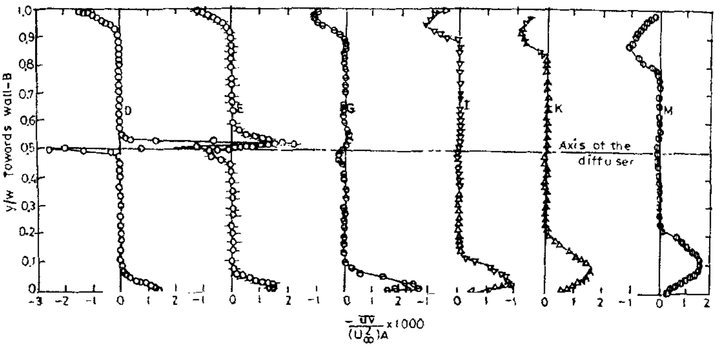

FIG. 4a. Distribution of $\overline{uv}$, $\alpha = 0°$.

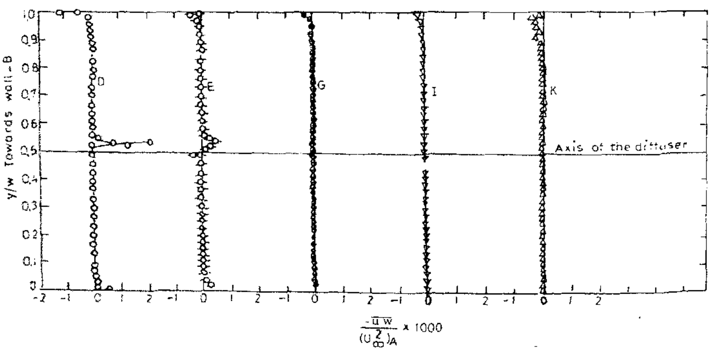

FIG. 4b. Distribution of $\overline{uw}$, $\alpha = 0°$.

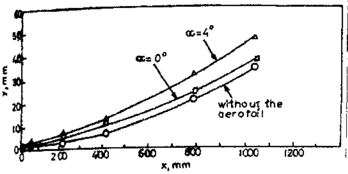

FIG. 5. Line of maximum u′ in the boundary layer near wall-A.

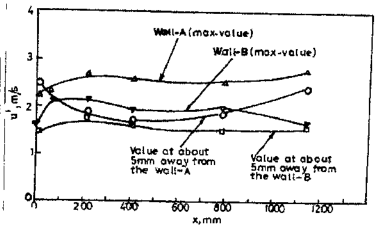

FIG. 6. Comparison of maximum u′ in the boundary layer on wall-A with that on wall-B, $\alpha = 4°$.

Figure 5 shows the locus of the positions of maximum absolute intensity of turbulence in the wall region on wall-A, with the airfoil at $\alpha = 0°$ and $4°$ and without the airfoil. The locus of the positions of $\overline{uv}_{max}$ almost closely coincides with the above lines (not included in the figure). The shift away from the wall progressively increases with distortion in the inlet velocity profile. It should also be noted that a positive value of α represents the tilting of the wake axis towards wall-A. Figure 6 shows a comparison between the maximum values of u′ in the wall layers on both walls-A and B for $\alpha = 4°$. This figure also presents values of u′ at a distance of 5 mm from both the walls. This figure clearly shows that when α is positive and the wake axis is tilted forward wall-A, the turbulence intensities near wall-A are much larger than those near wall-B. It should also be pointed out that the wall shear stress on wall-A was observed to be much less than that on corresponding positions on wall-B. All these results corroborate an earlier conjecture of Stratford[8] based on tuft studies that the level of turbulence in a boundary layer increases as it approaches incipient separation.

High Reynolds stress regions are also regions of high production of turbulent kinetic energy, since these two are inseparable events[9,10]. The region of maximum production in a boundary layer is close to the edge of the viscous sublayer. For zero pressure gradient flows, this also happens to be the region of maximum u′ — fluctuations. However, the situation is different in adverse pressure gradient flows. The mean velocity and the absolute value of the turbulent intensity decrease towards wall-A, but at different rates so that the intensity relative to the local mean velocity generally increases towards the wall. These relative intensities near wall-A are shown in fig. 7(a) for stations G and K at $\alpha = 0°$, $4°$ and for the case without the airfoil. Figure 7(b) shows the intensities normalised with the reference velocity U_∞ at station A. It is clear from these figures that even though the location of the absolute maximum of intensity shifts away from the wall, it is still the most active in adverse pressure gradient flows.

There is evidence in literature on conical diffusers for the existence of two peaks in the production of turbulent kinetic energy one near the wall and the other in a region of maximum fluctuation[3]. It is quite likely that even in the present case, the production of turbulent kinetic energy would exhibit two peaks, even though this term has not been estimated. There is certainly no evidence to the contrary.

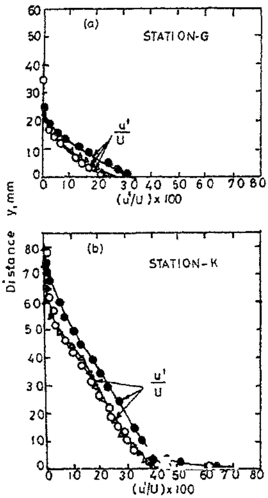

FIG. 7a. Intensity of u' relative to the local velocity U.

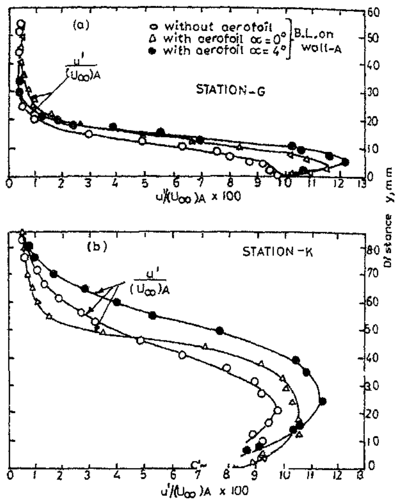

FIG. 7b. Intensity of u' relative to the reference free stream velocity U_∞ at station A.

At entry to the diffuser, the level of turbulence intensity in the wake was higher than in the wall region at $\alpha = 0°$, but decreased rapidly downstream. For example, the maximum value of intensity u' reduced from 12.4% at station D to about 2% at station M. Similarly, the maximum of v' decreased from 11.5% to 0.9% and that of w' from 6.8% to 1%. In general, the relation $u' > v' > w'$ was satisfied throughout the wake region. This is in contrast to the wall layer relation $u' > w' > v'$. The presence of the wall inhibits v', whereas in the wake no such inhibition is present. When the angle of incidence was changed to 4°, u'_{max} was found to vary between 12.7% and 3.8%, v'_{max} between 10.1% and 1.95% and w'_{max} between 8.3% and 2%. The relation $u' > v' > w'$ was, however, still maintained.

Figure 8 shows the variation of U and $\overline{uv}$ in the wake region at station D for $\alpha = 0°$. It is seen from the figure that $\overline{uv}$ changes sign at the location where U has an extremum. This shift increased to 1 mm at station G and 1.8 mm at station K, decreasing to 1.2 mm at station M. However, compared to the actual dimension of the wake, these shifts are very small. It is also very difficult to judge from experimental data where $dU/dy = 0$. Hence, no question of negative energy production arises here. Even in flow situations where the shift is marked[6,11], it is well known that the contribution of normal stress to energy production more than compensates the negative energy production due to shear stresses.

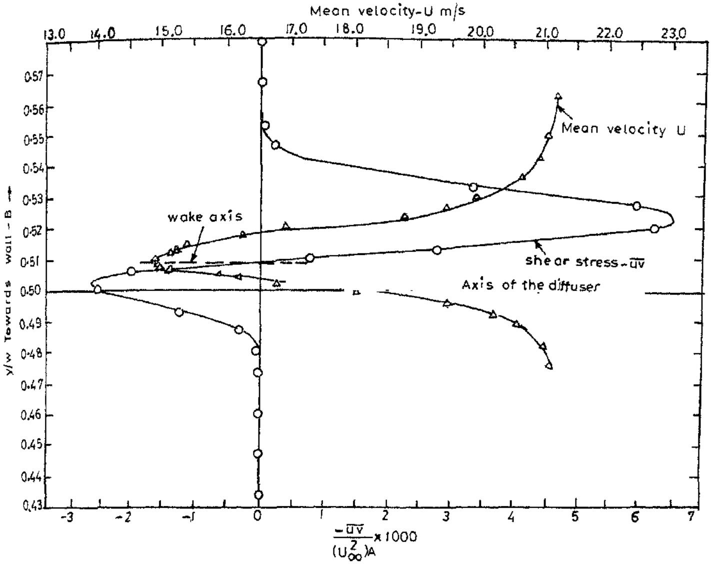

Fig. 8. Distribution of $\overline{uv}$ and U near the axis of the wake, station D, $\alpha = 0°$.

3.2 *Integral time scales*

The integral time scales T_u, T_v and T_w were obtained by calculating the area under the respective auto-correlation curves. The integration was carried up to the first point at which the auto-correlation changed sign, since this portion represents the most significant part of an auto-correlation curve [12]. The results showed that the time scale T_v increases relative to T_u in the streamwise direction in the wall layer of wall-A. The same behaviour was also noticed in the case of T_w. However, at any station, there was no appreciable change in time scales as the airfoil incidence was changed.

Along the axis of the wake where the maximum velocity defect occurs, the time scales remained more or less unaffected by changes in inlet velocity distortion. However, away from the axis and towards the edge of the wake, the time scales changed with airfoil incidence close to the diffuser inlet, but became marginal along the downstream. Apparently, the inlet velocity distortion has no appreciable effect on the time scales near the diffuser exit. The time scales T_v and T_w were found to be larger in the wake region relative to their values in the wall region.

3.3 Energy spectra

The one-dimensional energy spectrum is obtained as a Fourier cosine transform of the measured auto-correlation curve. It has to satisfy the normalization condition

$$\int_o^\infty \frac{E_u(K_1)}{u'^2}\, dK_1 = 1$$

and similar conditions for the v' - and w' - components. The wave number K_1 is related to frequency through $K_1 = 2\pi f / U$.

The measured auto-correlations were digitised manually into 256 equal parts, which were then interpolated to give 512 equal parts. The frequency spectra were obtained by numerical integration of the equations

$$\frac{E_u(f)}{u'^2} = 4\int_0^\infty R_u(\tau)\cos 2\pi f\tau\, d\tau, \text{ etc.}$$

with frequency intervals of 10 Hz up to 5000 Hz. While recording the auto-correlation itself, frequencies between 2 and 20000 Hz were utilised.

Figure 9 shows the spectra of the three-velocity components at station G in the wall layers of both walls-A and -B and at distances of 0.2 δ and 0.6 δ from the wall, for $\alpha = 0°$. The v'- and w'−spectra are almost the same for all conditions, but the u'−spectra show some variation at low wave-numbers at 0.6 δ.

Figure 10 shows the three spectra at 0.2 δ from wall-A for $\alpha = 0$ at stations G and K. For purposes of comparison, the (−5/3)−slope line is also shown. It is, of course, difficult to recognise any major region where this slope can be observed in the spectra. But, at any station in the low wave-number, the energy levels of u', v' and w' are such that $u' > w' > v'$, the w' and u' values being almost the same. This is a consequence of the fact that generally in all layers, $u'^2 > w'^2 > v'^2$. Spectral measurements obtained for $\alpha = -4°$ exhibited similar characteristics as with $\alpha = 0°$.

Figure 11 shows the spectra again at stations G and K, but on the wake axis and at $\alpha = 0°$. All spectra indicate a distinct maximum, indicating some kind of periodicity in the flow. One possible reason is the trailing vortex behind the airfoil which appears to persist even at station K. Similar results have also been reported by Palmer and Keffer[13] in the wakes behind a pair of cylinders. Ramaprian[12] also reported such peaks in the v'−and w'−spectra in the equilibrium axis symmetric wall jets.

4. Conclusions

It is seen from the results presented here that entry flow distortion has a significant effect on the turbulence characteristics. The relationship $u' > w' > v'$ is generally valid in the boundary

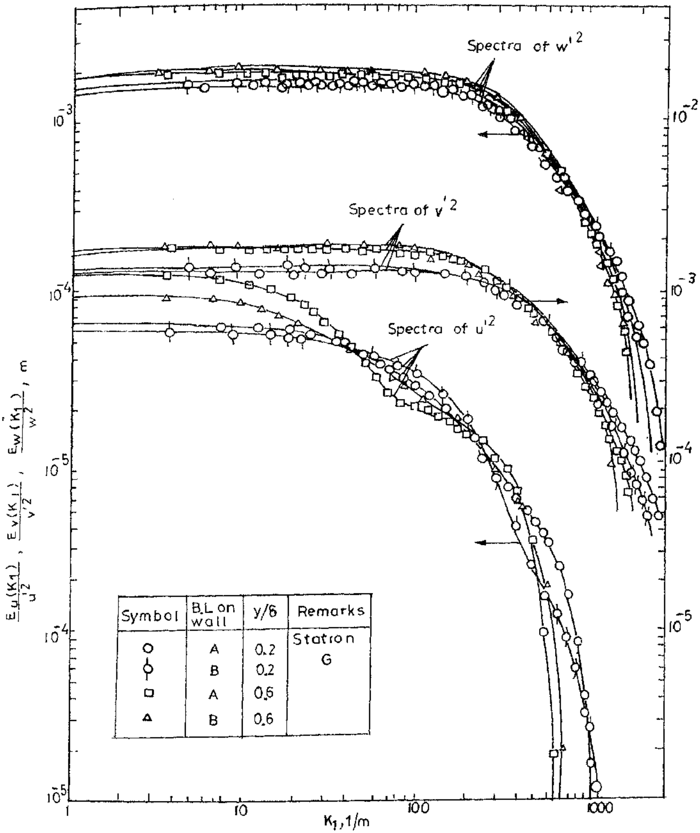

FIG. 9. Comparison of energy spectra in the boundary layer near walls-A and B, $\alpha = 0°$.

layer region. The location of the maximum r.m.s. fluctuations and the shear stress $\overline{uv}$ shif away from the wall in the streamwise direction. However, the intensity of turbulence relati\ to the local mean velocity attains a maximum value near the wall, gradually reducing awa from it.

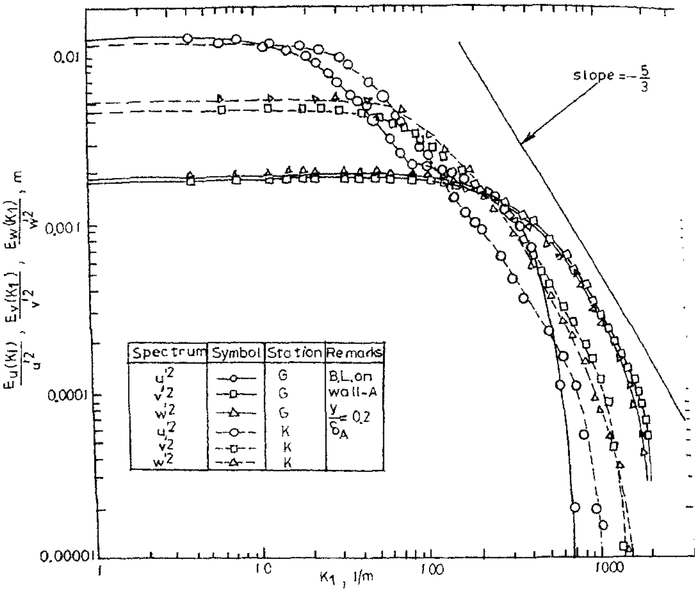

FIG. 10. Spectra of u'^2, v'^2 and w'^2 in the boundary layer, $\alpha = 0°$.

In the boundary layer region, the lifetime of v′−fluctuation relative to the lifetime of u′−fluctuation increases appreciably towards the exit of the diffuser. Along the axis of the wake, the lifetime of v′ and w′ fluctuations relative to the lifetime of u′−fluctuation increases towards the exit of the diffuser and in general in the wake region this period is higher than that in the boundary layer region. In the wake region, the maximum of r.m.s. fluctuation reduces appreciably towards the exit of the diffuser while in the boundary layer region there is a marginal increase. The relationship $u' > v' > w'$ is generally valid for the wake region. The distribution of wave number spectra in the wake region exhibits a distinct behaviour with prominent peaks. This indicates the possibility of vortices shed by airfoil possibly on account of unsteady separated flow.

Nomenclature

A	reference station A or wall-A	c	chord length of the airfoil
B	reference station B or wall-B	E_u (f)	one-dimensional frequency spectra

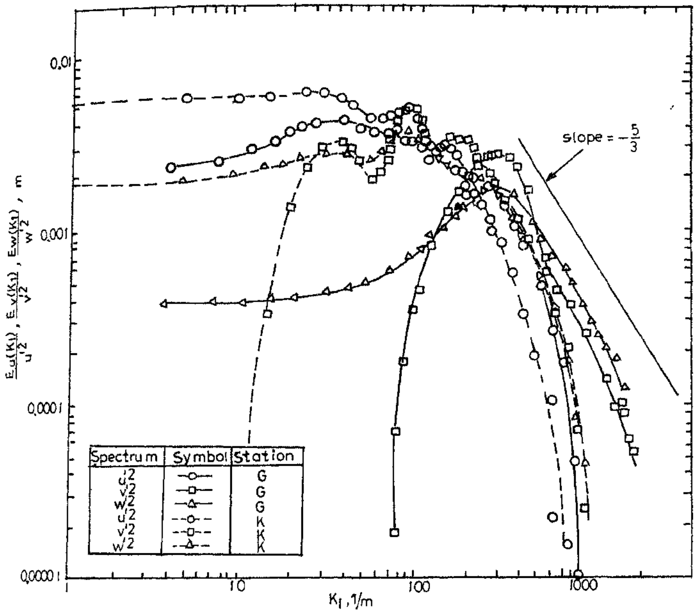

FIG. 11. Spectra of u'^2, v'^2 and w'^2 along the axis of the wake, $\alpha = 0°$.

$E_u(K_1)$	one-dimensional wave number spectra	u', v', w'	r.m.s. values of u, v and w ($= \sqrt{\overline{u}^2}, \sqrt{\overline{v}^2}, \sqrt{\overline{w}^2}$)
f	frequency in Hz	$\overline{uv}$, $\overline{uw}$	Reynolds shear stresses
K_1	wave number ($= 2\pi f/U$)	W	local width of the diffuser
$\overline{q}^2$	twice the turbulent kinetic energy ($= u'^2 + v'^2 + w'^2$)	X	distance measured from the trailing edge of the airfoil along the axis of the diffuser
$R_u(\tau)$	auto-correlation coefficient	y	distance from the wall measured normal to the axis of the diffuser
T_u, T_v, T_w	integral time scales of u, v and w fluctuations	α	angle of incidence of the airfoil
U	streamwise component of mean velocity	δ	boundary layer thickness
$(U_\infty)_A$	mean free stream velocity at the reference station A	τ	delay time in auto-correlation function
u,v,w	velocity fluctuations in x,y and z directions		

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References

1. RUETENIK, J.R. AND CORRSIN, S. — Equilibrium turbulent flow in a slightly divergent channel, *50 Jahre Grenzschicht forschung*. Ed. Gortler, H. and Tollmien W., Braunschweig, Freidr, Vieweg and Schn, 1955, p. 446.
2. LAUFER, J. — Some recent measurements in a two-dimensional turbulent channel, *J. Aero Sci*, 1950, **17**, 277.
3. OKWUOBI, P.A.C. AND AZAD, R.S. — Turbulence in a conical diffuser with fully developed flow at entry, *J. Fluid Mech.* 1973, **57**, 603.
4. CHITAMBARAN, V.K. — Some studies on the structure of incompressible flow in a two-dimensional diffuser with inlet velocity distortion, Ph. D. Thesis, Indian Institute of Technology, Madras 600 036, 1978.
5. RENEAU, L.R. JOHNSTON, J.P. AND KLINE, S.J. — Performance and design of straight, two-dimensional diffusers, *J. Basic Engng. Trans. ASME*, 1967, **89**, 141.
6. IRWIN, H.P.A. — Measurements in a self-preserving plane wall jet in a positive pressure gradient, *J. Fluid Mech.* 1973, **61**, 33.
7. SPANGENBERG, W.G., AND MEASE, N.E. — Measurement in turbulent boundary layer maintained in a nearly separated condition, in *Fluid mechanics of internal flow* by Sovran, G. (Ed)., Elsevier Publishing Co. 1967, p. 110.
8. STRATFORD, B.S. — Prediction of separation of the turbulent boundary layers, *J. Fluid Mech.* 1959, **5**, 1.
9. MOLLO-CHRISTENSEN, E. — Physics of turbulent flow, *J. AIAA*, 1971, **9**, 1217.
10. WILLMARTH, W.W. — Structure of turbulence in boundary layers, *Adv. Appl. Mech*, 1975, **15**, 159.
11. BANDOPADHYAY, P. — Some studies on a developing three-dimensional incompressible turbulent wall jet, Ph.D. Thesis, Indian Institute of Technology, Madras 600 036, 1974.
12. RAMAPRIAN, B.R. — Turbulence measurements in an equilibrium axisymmetric wall jet, *J. Fluid Mech*, 1975, **71**, 317.
13. PALMER, M.D. AND KEFFER, J.F. — An experimental investigation of an asymmetrical turbulent wake, *J. Fluid Mech*, 1972, **53**, 593.