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INVESTIGATION OF A COMPOUND WALL JET IN THE VICINITY OF JET EXIT

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ABSTRACT

Wind tunnel tests are conducted to study the effect of upper surface blowing on aerodynamic characteristics. A wall jet is issued tangent to a flat plate that forms the upper surface of an airfoil at zero angle of attack. The leading edge of the airfoil is NACA 0015. The effect of chordwise blowing on the aerodynamic load is studied through investigation of the pressure distribution on the flat surface. The pressure coefficient shows two consecutive sharp peaks resulting in two adverse pressure gradients. Higher peaks are obtained for the higher jet/free stream velocity ratios. This feature indicates the complicated structure of the vortex flow in the transition region along the flat plate surface.

In addition to the investigation of the aerodynamic load, the effect of upper surface blowing on the mean velocity, turbulence and Reynolds shear stress of the flow field is illustrated. It is found that the chordwise mean velocity profiles are similar in the free mixing region. As the jet/free stream velocity ratio becomes more than unity, jet blowing activates the mean upward lateral velocity which increases with increasing jet velocity. The inflection points of mean velocity profiles are accompanied by peaks of turbulence and Reynolds shear stress. Likewise, both normal and turbulent shear stress profiles exhibit the similarity episode.

INTRODUCTION

There has been a great deal of interest lately on the short-takeoff and landing aircraft in military operations. The ability to takeoff and land in short distances gives V/STOL aircraft a special advantage over other types of military aircraft. Obviously the Navy is the most interested division in this particular type due to ground-roll limitations for take-off and landing on board aircraft carriers. Based on the success of the British VTOL "Harrier" fighter in the Faulklands war, noted for its rapid thrust vectoring, allowing it to accelerate and decelerate very rapidly, the U.S. Marine Corps increased its fleet of V/STOL jet fighter and attack bomber aircraft to 332 in 1986. In January 1986 the U.S. and the U.K. signed an agreement for a joint program to investigate configurations and airframe and propulsive systems for supersonic, tactical, single-seat short takeoff and vertical landing (STOVL) aircraft.

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In order to perform the V/STOL process, high lift is required within short flight distances. Therefore the aircraft would have to fly at high angles of attack. Separation of flows over the upper surfaces of the wings is a phenomenon associated with high-angle-of-attack flights. Controlling of the boundary-layer is being proposed as a possible approach to prevent this phenomenon. In this context it is suggested that a sheet of fluid be blown through narrow tangential slots to re-energize the boundary layer and hence delay separation. This seems to be the most practical way of controlling separation in aircraft since the required compressed air can be supplied by the engines of the aircraft. Additionally blowing, in contrast to suction, maintains the slots clear of atmospheric dirt and ice. Other applications of the upper-surface blowing technique include the prevention of separation on leading edge and trailing-edge flaps, helicopter rotor blades, blades of turbomachinery that have bluff trailing edges, and prevention of separation in diffusers.

Tangential blowing on a circular cylinder was introduced primarily for the generation of lift. Lockwood [1] at NASA investigated the generation of lift by blowing tangentially from a number of slots around a cylinder. This was intended for the purpose of utilizing the fuselages of hypersonic aircraft to generate lift by tangential blowing in order to reduce landing speeds. Cheeseman [2] and Dunham [3] explored the possibilities of utilizing a blown circular cylinder for generating lift for VTOL aircraft instead of the normal flapping airfoil blades. As a consequence of these and other investigations of similar nature, it is possible to deduce that a lift of 20 times the jet momentum can be delivered by utilizing two or more slots that are optimally positioned around a cylinder. An advantage of this method over conventional methods of lift generation is that the drag coefficient decreases as the lift increases such that it becomes a forward thrust at large blowing rates.

A number of basic investigations were conducted by Eskinazi and Kruka [4], Kruka and Eskinazi [5], Patel and Newman [6], Goradia and Colwell [7], and Kacker and Whitelaw [8] on plane turbulent compound wall jets. It may be concluded from their findings that the velocity profile in the boundary layer and free-mixing regions are similar if considered separately. Goradia and Colwell [7], and Erian and Eskinazi [9] found that, even with pressure gradients, similarity of velocity profiles exists if each distinct region is considered separately.

Papailiou [10] investigated the structure of a two-dimensional turbulent wall jet in a moving stream in the presence of an adverse pressure gradient. A wall-jet was injected beneath the boundary layer that was formed along the wall of a duct-diffuser passage. The development of the mean and fluctuating turbulent velocity fields of the jet, under the influence of the pressure gradient, was investigated. A strong oscillating separation dominated the flow in the diffuser in the absence of the wall-jets. The application of the wall-jets delayed or completely eliminated the separation.

A research aircraft, Quiet Short-Haul Research Aircraft (QSRA), incorporating upper-surface blowing is being developed by a joint Navy/NASA program to study the application of advanced propulsive-lift technology to the environment of the naval aircraft carrier (Queen and Cochrane [11]). As a matter of fact, the STOL performance of the QSRA led the US Navy to consider it for use in an investigation of operating large propulsive-lift STOL aircraft from aircraft carriers. Likewise in Japan, where there are many airports that cannot accept large aircraft, a short-takeoff and landing capability is most desirable for domestic aviation. The National Aerospace Laboratory (NAL) of Japan started work on the upper-surface blowing (USB) STOL aircraft program in 1977. Hiroyuki Yamato and others [12] reported that NAL determined that the USB system is the most feasible technique for STOL performance.

In the present study, attention is focused on the investigation of the compound wall jet in the vicinity of the jet exit. In addition to the investigation of aerodynamic loads, the paper reports on interesting observations and describes detailed measurements of the mean velocity, turbulence and Reynolds shear stress of a two-dimensional plane turbulent jet in a moving stream.

APPARATUS AND EXPERIMENTAL PROCEDURE

The test model consists of a flat plate that makes part of the upper surface of an airfoil. The leading edge of this airfoil is chosen to be NACA 0015. The upper flat plate extends to go beneath the upper part of the nose forming the jet afflux slot as demonstrated in Fig. 1. The test model is made of 2 mm-thick aluminum sheet. Suitable supports are placed at the sides of the model to maintain a stiff jet boundary. The span, chord length and maximum thickness of the test model are 50 cm, 25 cm and 3.5 cm, respectively. Chordwise blowing is issued from a jet slot of 3 mm thickness. The test model is installed vertically in the wind tunnel test section which is 2 m long and has a cross-sectional area of 0.5m x 0.7 m. A chamber is placed right above the model as illustrated in Fig. 2. The jet air is supplied to the chamber from an 11.1 kW variable-output fan. The wind tunnel used is a non-return open type with a maximum speed of 50 m/s. The pressure distribution is measured through pressure tappings located chordwise along the midspan of the upper flat plate.

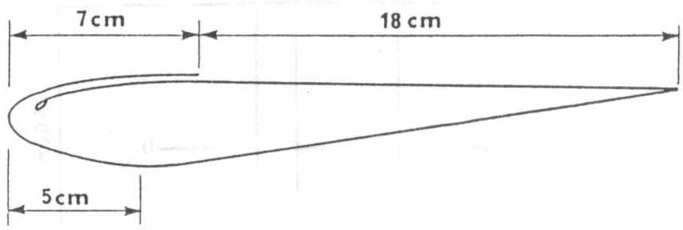

Fig. 1 Test model section

A DISA type 56C16 constant temperature anemometer unit integrated with an X-Array Probe 55p64 was used to measure the mean velocity components and turbulence at different sections. The hot wire probe could be traversed at the center of the upper flat plate surface; along the chordwise direction of this surface, and perpendicular to this direction. A probe protection shield was used to prevent unintentional mechanical damage to the probes. The shield was mounted on the probe support.

The following measurements were recorded and plotted at different sections downstream the jet exit:

1. Mean velocity U along the mid-chordwise direction of the flat plate, and the associated turbulence u' along the same direction.
2. Mean velocity V normal to the surface of the flat plate, and the associated turbulence v' along the same direction.
3. Reynolds shear stress u'v' related to the above directions.

These parameters were measured at zero angle of attack for several jet/free stream velocity ratios at Re of 2.45×10^5 corresponding to a free stream velocity of 12.5 m/s and a characteristic length of 0.25 m representing the total chord of the test model.

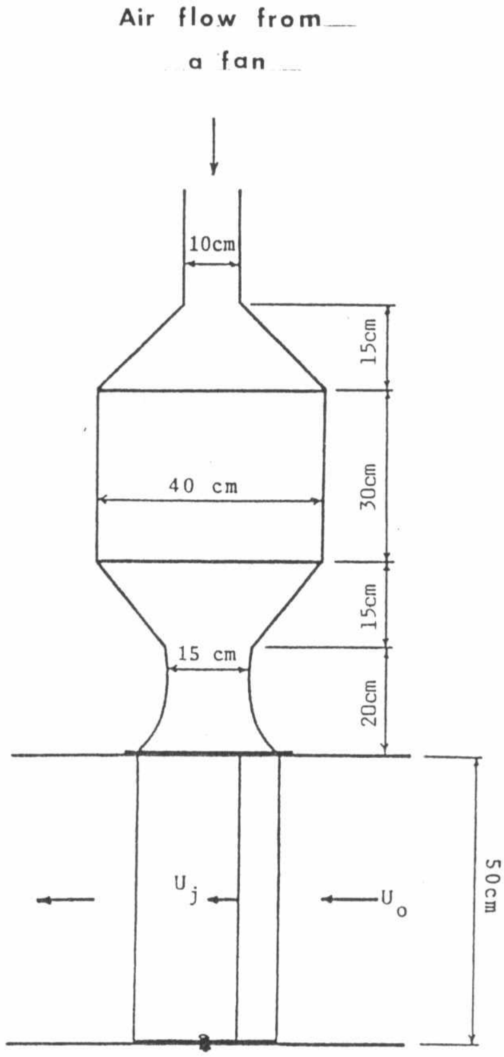

Fig. 2 The experimental setup

RESULTS AND DISCUSSION

a) Pressure Measurements

Figure 3 shows the static pressure distribution on the flat plate at zero angle of attack for different values of jet velocity/free stream velocity U_j/U_o. The pressure measurements were taken at Re=2.43 x 10^5 for jet/ free stream velocity ratios of 0.272, 2.374, 3.106 and 4.391. At the low jet/ free stream velocity ratio of 0.272, it is noticed that the pressure on the flat plate at the jet exit undergoes a slight drop followed by a considerable rise, indicating the process of separated-flow reattachment. Increasing U_j / U_o shows a distinguished feature in the pressure distribution curves. Sharp fluctuations are noticed in the region from x/t = 0 to 17. They are composed of two consecutive peaks due to two adverse pressure gradients. Higher peaks are obtained for higher jet/ free stream velocity ratios and vice versa, as depicted in the figure at U_j/U_o = 2.374, 3.106 and 4.391. It seems that these peaks occur at the same locations for all values of jet/ free-velocity ratios. This feature indicates the complicated structure of the vortex flow field alongside the surface of the flat plate in the region up to x/t = 17. Downstream this region, the distributions of pressure coefficients have lower values as the jet/ free stream velocity ratio is increased.

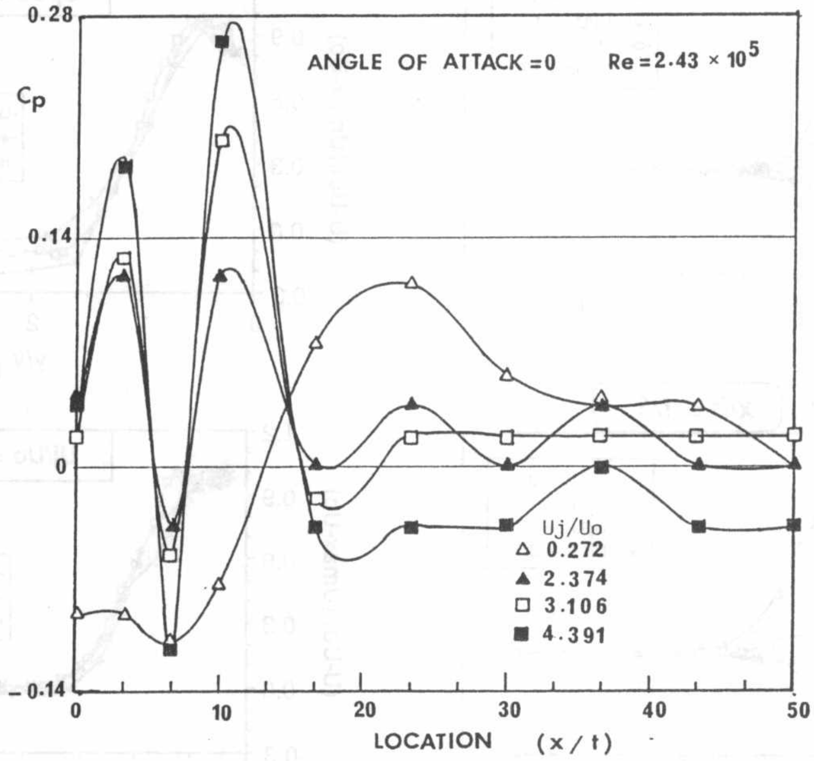

Fig.3 - Static pressure distributions

b) Mean Velocity Profiles

Figures 4 (a,b and c) show the variation of chordwise mean velocity as normalized by the free stream velocity, U/U_o, with the lateral distance y as normalized by the height t of the slot, where t = 3 mm. The jet/ free stream ratios U_j / U_o assume the values 0, 1, 2 and 3.7. These figures represent chordwise mean velocity profiles at different measurement stations that are located by chordwise distance *x* from the exit of the jet as normalized by b=0.18 m, which is the chord length of the flat plate. These profiles illustrate peaks for jet-free stream ratios of 2 and 3.7. Magnitudes of these peaks decline and the effective region of the jet becomes wider as the location of the profile is moved away from the exit of the jet. It seems that, for stations x/b=1/3 and 2/3, the chordwise mean velocity distributions have approximately the same profiles for the lower jet/ free stream ratios from zero to one. On the other hand, station x/b=1/6, which is close to the jet exit, exhibits distinct profiles for the jet/ free stream ratios of zero and one(Fig. 4a).

The velocity profiles are replotted in Fig. 4d and 4e in dimensionless form with $(U - U_o) / (U_{max} - U_o)$ against $y/y_{1/2}$. Here U_{max} is the peak velocity of the profile and $y_{1/2}$ is the lateral distance in the free-mixing region at which the chordwise mean velocity equals $(U_{max} + U_o)/2$. These dimensionless parameters are illustrated for jet/ free steam ratios of 2 and 3.7 at the three stations, x/b=1/6, 1/3 and 2/3. It appears that the profiles are similar in the free-mixing region. If the above profiles are replotted at any of the three stations but for jet/ free stream ratios of 2 and 3.7, the similarity criterion in the free-mixing zone is ensured also with respect to jet power. The similarity, however, seems to disappear in the boundary-layer region (See Fig. 4f).

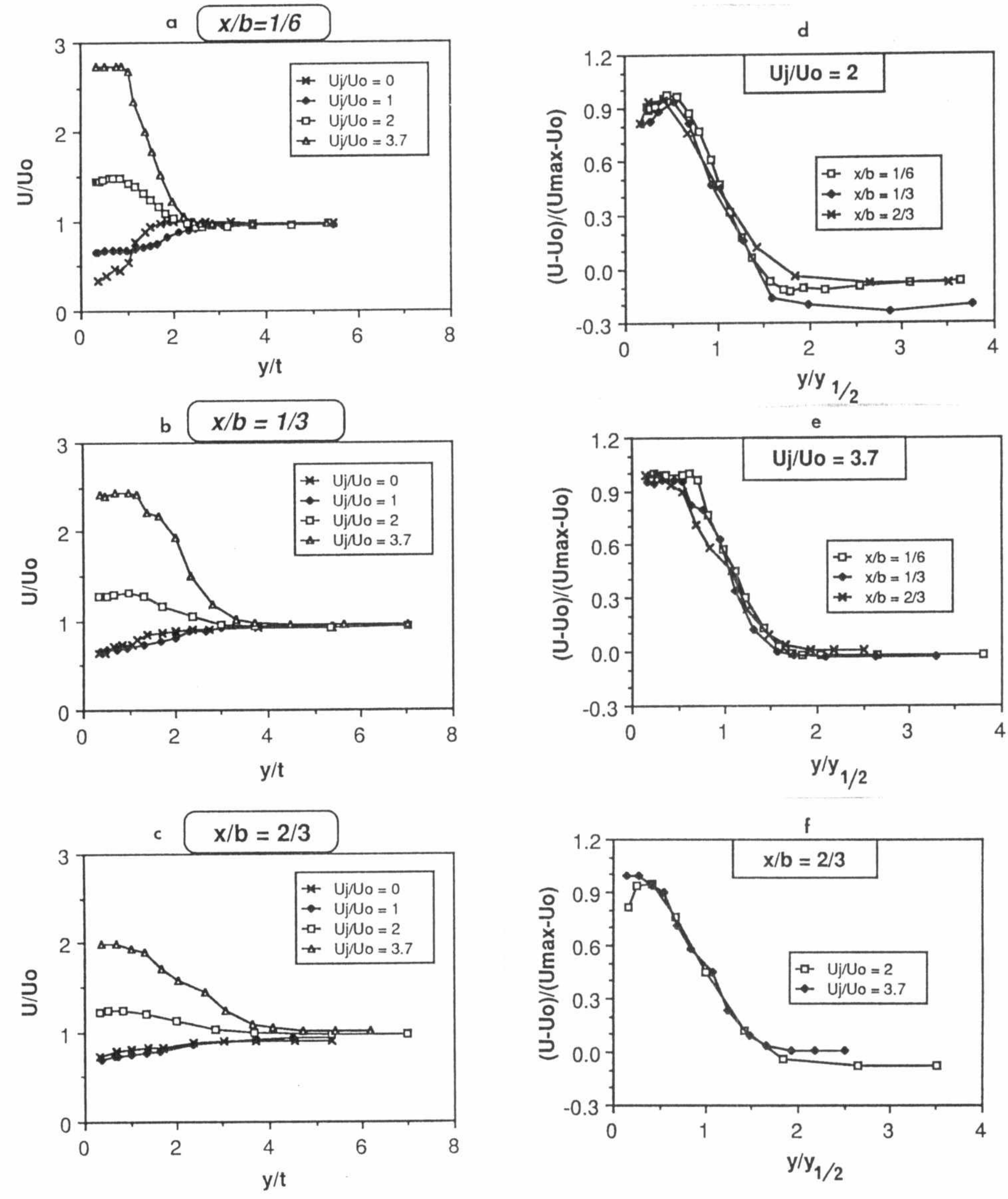

Fig. 4 Profiles of chordwise mean velocity.

Figures 5 (a, b and c) present the variation of lateral mean velocity as normalized by the free stream velocity, V/U_o, with the normalized lateral distance y/t. When the jet velocity equals the free stream velocity, it is observed that the lateral mean velocity practically vanishes. On the other hand, if the jet velocity becomes higher than the main flow velocity, the flow field is seen to move the lateral mean velocity upward, as indicated by the negative sign in the figures. This upward mean flow increases with increasing jet velocity, as demonstrated by the lateral mean velocity profiles for U_j/U_o =2 and 3.7 at the three stations. For the experiment with no jet flow, the lateral mean

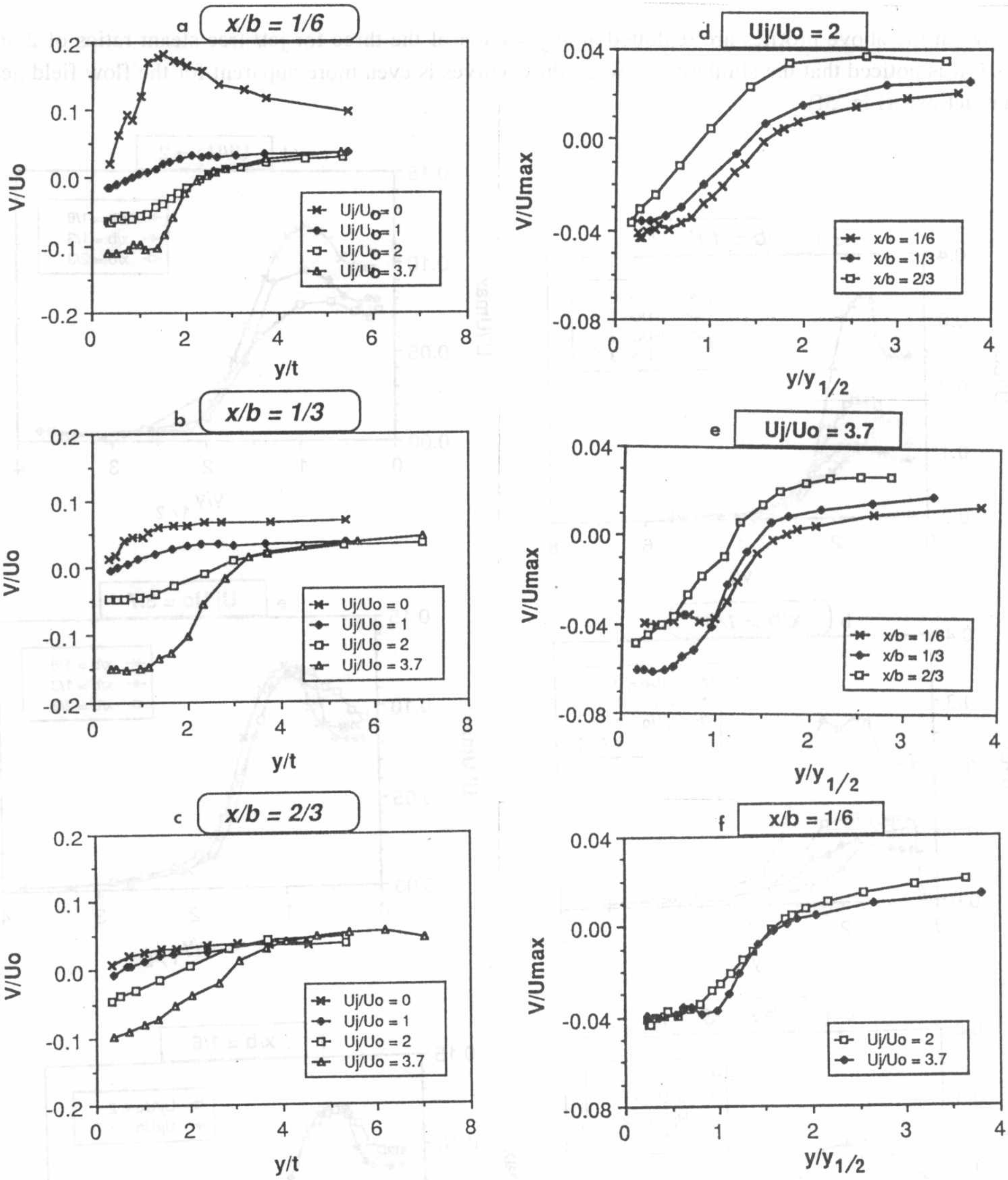

Fig. 5 Profiles for lateral mean velocity.

velocity profiles indicate that the mean velocity of the flow field is downward. These latter velocity components decrease as the downstream distance increases, indicating the reattachment of the flow field that springs from the step of the jet exit. The lateral mean velocity profiles are replotted in Fig. 5d and 5e in dimensionless form with V/U_{max} versus $y/y_{1/2}$ for jet/ free stream ratios of 2 and 3.7 at the three stations 1/6, 1/3 and 2/3. It is obvious that these lateral mean velocity profiles are not similar with this non-dimensionality. Additionally it is noticed that as the downstream distance of the station increases, the profiles exhibit higher V/U_{max} values, while the upward velocity at the same station is lower.

When the above profiles are replotted at any section of the three for jet/ free steam ratios of 2 and 3.7, it is noticed that the similarity between these curves is even more apparent for the flow field near the jet exit (Fig. 5f).

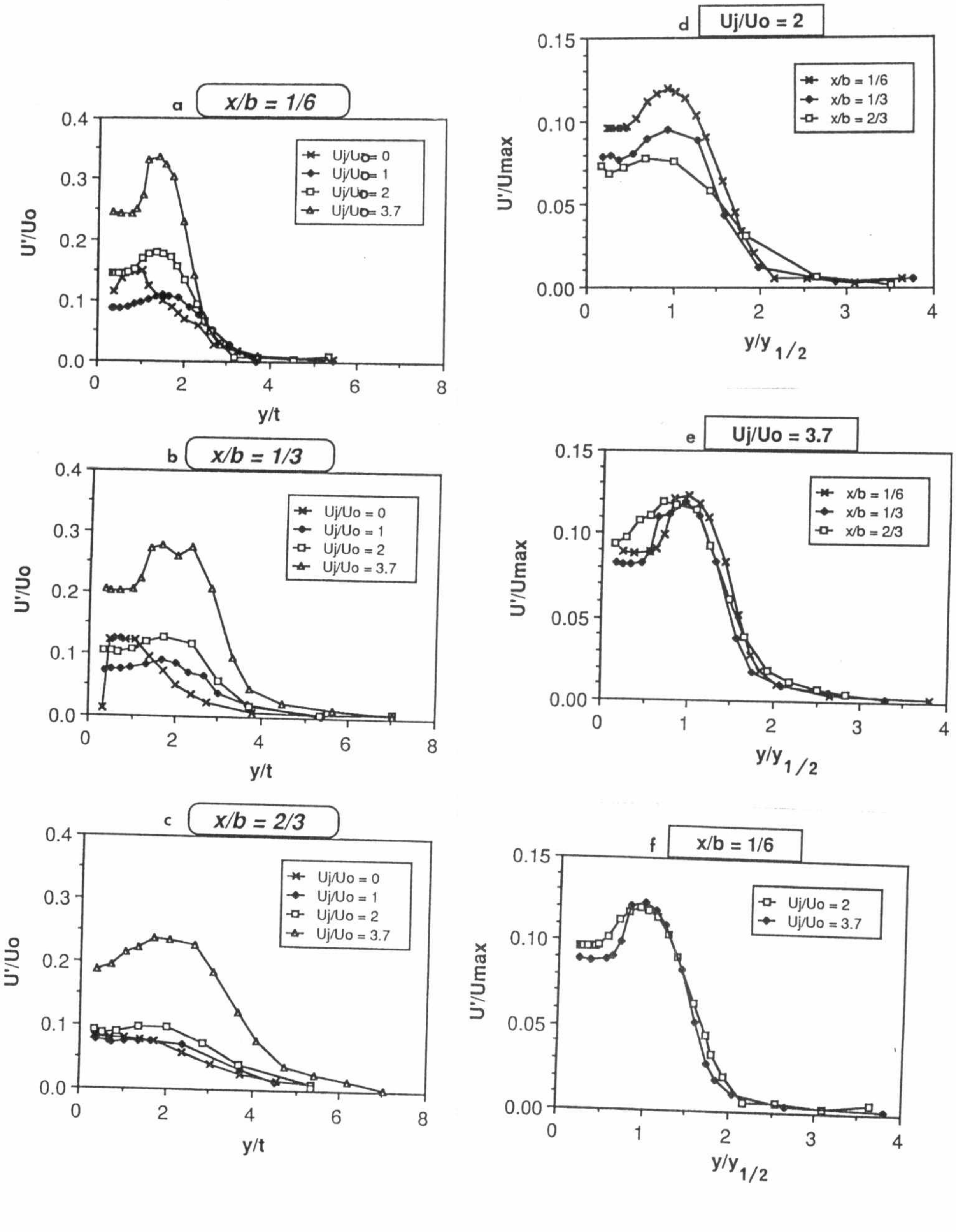

Fig. 6 Chordwise turbulence distributions.

c) Turbulence Measurements

The results of turbulence measurements in the chordwise direction are shown in Fig. 6 (a, b and c). The turbulence component u' is normalized by the free stream velocity U_o and plotted versus the normalized lateral distance y/t at the three stations for several jet/ free stream ratios. The figures indicate that turbulence profiles possess peaks that decay with increasing distance of station from jet exit. In addition, the rate of increase of turbulence intensities is higher for U_j / U_o between 2 and 3.7

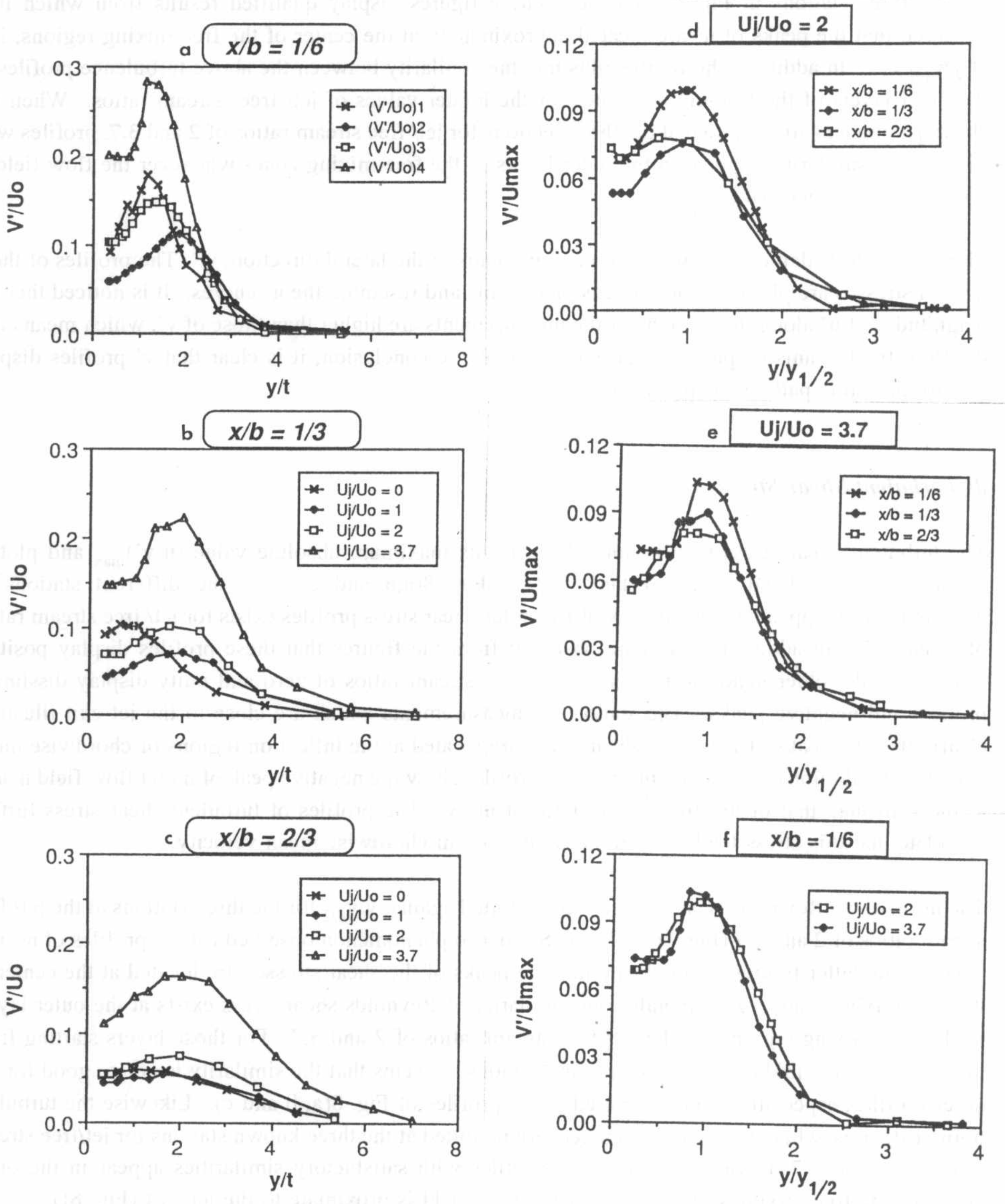

Fig. 7 Lateral turbulence distributions.

than that for U_j / U_o between 1 and 2. Likewise these profiles reveal that, up to a lateral distance y/t of 1.5, the jet/ free stream ratio of unity results in lower turbulence intensities than that of the flow field without a jet. This curious phenomenon is attributed to the relative weak shear in the free-layer region for the ratio of unity. Therefore less turbulence is produced there so that less turbulence energy can be transported towards the wall by diffusion.

These turbulence intensities in the chordwise direction are normalized by U_{max} and plotted versus $y/y_{1/2}$ for the three stations in Fig. 6d and 6e. These figures display qualified results from which it is observed that the peaks of u' are located approximately at the center of the free-mixing regions, i.e., at $y/y_{1/2} = 1$. In addition, the figures illustrate the similarity between the above turbulence profiles in the outer layers of the free-mixing zones for the higher values of jet/ free- stream ratios. When the above parameters are replotted at the three sections for jet/ free stream ratios of 2 and 3.7, profiles with satisfactory similarities appear in the outer layers of the free-mixing zones whenever the flow field is proximate to the jet exit (Fig. 6f).

Figures 7 (a to f) depict the turbulence measurements in the lateral direction, v'. The profiles of these normal stresses are plotted in nondimensional forms and resemble the u' curves. It is noticed that the magnitudes of u' along the sections of the measurements are higher than those of v', which means that the flow field is anisotropic. In addition to the above conclusion, it is clear that v'-profiles display exactly the same patterns as the u' profiles.

d) Turbulent Shear Stress

The turbulent shear stress u'v' is normalized by its maximum absolute value $(u'v')_{max}$ and plotted against the normalized lateral distance y/t in Fig. 8(a,b and c). At the different stations of measurement, it appears that similarity of Reynolds shear stress profiles exists for jet/ free stream ratios of 2 and 3.7. In addition, it may be observed from the figures that these profiles display positive peaks. On the other hand the remaining jet/ free stream ratios of zero and unity display dissimilar profiles and negative peaks. The stations of measurements which are close to the jet exit illustrate clearly that the peaks of Reynolds shear stress are located at the inflection regions of chordwise mean velocity distributions. This explains why the profiles show the negative peak of no jet flow field nearer to the wall than that of jet/ free stream ratio of unity. The profiles of turbulent shear stress further elucidate that this stress tends to zero at the maximum chordwise mean velocity.

The normalized Reynolds shear stresses are replotted against $y/y_{1/2}$ for the three stations at the jet/ free stream ratios of 2 and 3.7 (Fig. 8d and 8e). Similar to phenomenon observed for the profiles of normal stresses, the latter figures also indicate that the peaks of the shear stresses are located at the center of the free-mixing zones. Additionally, the similarity of Reynolds shear stress exists at the outer layers of the free-mixing regions for the jet/ free stream ratios of 2 and 3.7. For those layers starting from the wall up to the middle of the free-mixing regions, it seems that the similarity is not so good for the latter profiles, especially when compared to the profiles of Fig. 8(a, b and c). Likewise the turbulent normal stresses, when the above parameters are replotted at the three known stations for jet/free stream ratios of 2 and 3.7, Reynolds shear stress profiles with satisfactory similarities appear in the outer layers of the free mixing zones whenever the flow field is proximate to the jet exit (Fig. 8f).

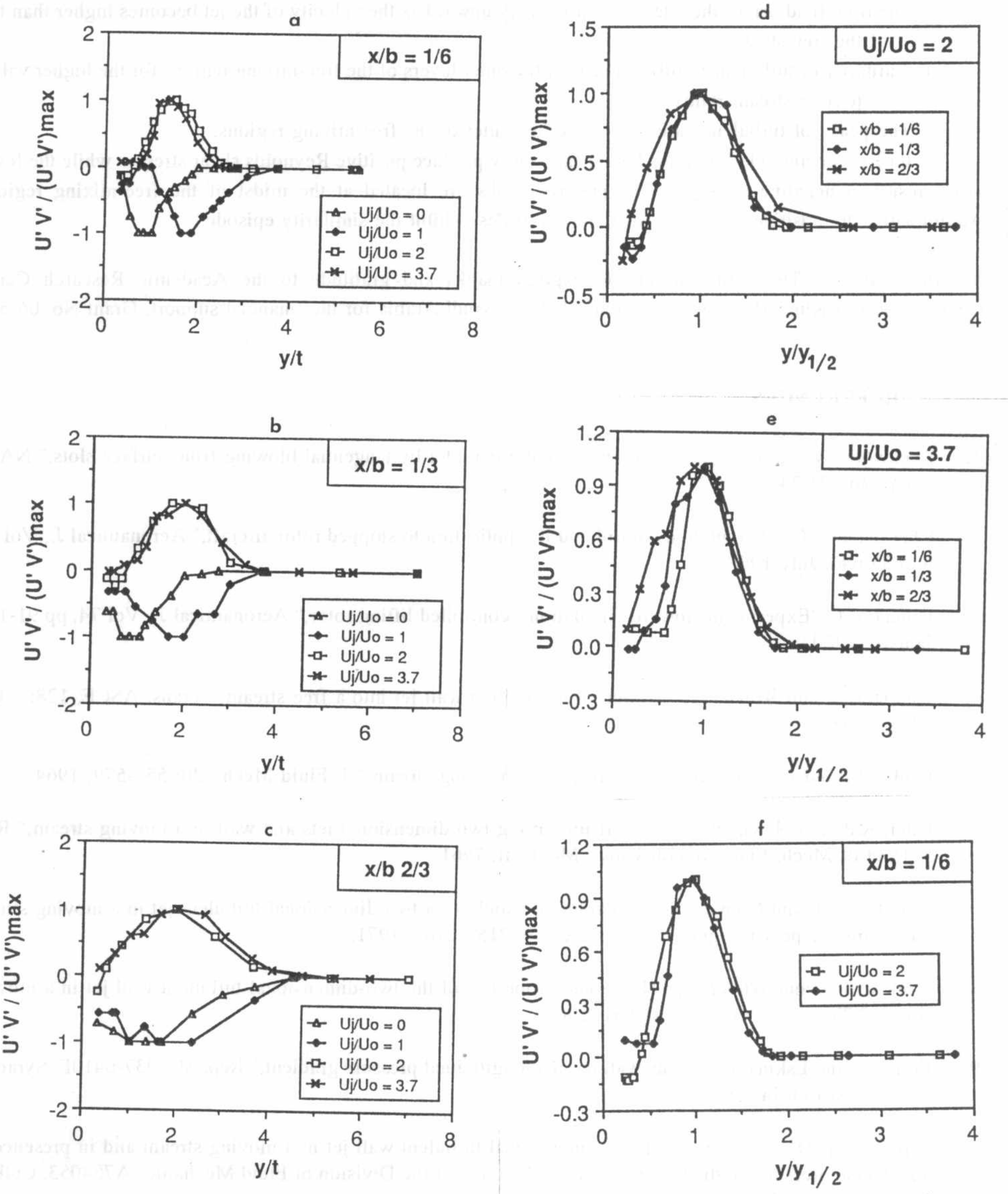

Fig. 8 Variation of Reynolds shear stress.

CONCLUSIONS

The present work has provided considerable insight into the phenomenon of upper surface blowing on the aerodynamic characteristics of plane turbulent compound wall jets in the vicinity of jet exit. To cite a few of the interesting observations,

1. For high jet/free stream velocity ratios, the pressure distribution exhibits two sharp peaks near the jet exit.
2. Chordwise mean velocity profiles are similar in the free-mixing region.
3. The flow field drives the lateral mean velocity upward as the velocity of the jet becomes higher than that of the free stream.
4. Similarity of turbulence profiles exists in the outer layers of the free-mixing regions for the higher values of jet/free stream ratios.
5. The peaks of turbulence are located at the center of the free-mixing regions.
6. Jet/free stream velocity ratios higher than unity produce positive Reynolds shear stresses while the lower ratios result in negative stresses. The positive peaks are located at the midst of the free-mixing regions. Additionally, the positive turbulent shear stress profiles exhibit the similarity episode.

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