International Journal of Computer Applications (0975 – 8887)
National Conference on Innovations and Recent Trends in Engineering and Technology (NCIRET-2014)

Turbulent Boundary Layer Study past Porous Obstacles

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ABSTRACT

The concept of the boundary layer was proposed by Ludwig Prandtl in 1904. This concept has allowed prediction of skin friction drag, heat transfer from the wall and separation of the boundary layer, which in turn enables proper design of airplanes, ships, other vehicles and equipment through/around which fluid flow takes place. The centenary of the proposal by Prandtl is being celebrated in various ways. This article is an attempt to study the behavior of turbulent boundary layer and standing eddy region past porous obstacles having different shape and different porosities.

Keywords

Turbulent Boundary layer; porous fences; standing eddy region

1. INTRODUCTION

Flow of fluids with low viscosity values and thus very high Reynolds Numbers occur in many technical applications. In the analysis of ideal fluid problems it has been found that the pattern of fluid motion is governed primarily by the geometry of the boundary between which or around which the fluid moves. As the flow pass the streamline body, the influence of viscosity at high Reynolds number is confined to a very thin layer in the immediate neighborhood of the solid wall. If the condition of no slip were not to be satisfied in the case of the real fluid there could be no appreciable difference between the fields of flow of the real fluid as compared to an ideal fluid. In the thin layers the velocity of the fluid increases from zero at the wall no slip to its full value, which leads to external frictionless flow. This thin layer is called the boundary layer or frictional layer. (13)

In the last few decades the concept of boundary layer in general and turbulent boundary layer had been particularly applied in, various fields including aeronautics, guided missiles, naval architecture, marine engineering, hydraulics, meteorology, oceanography, chemical engineering, sanitary engineering ,atomic reactors, astrophysics are the flow of liquids and gases in the human body. The research work on turbulent boundary layers is being done continuously.

The major aspects to researches are

a) Study of turbulent boundary layer when subjected to varying pressure gradients.

b) The study of fluid removed or injected from or into the flow.

c) Various obstacles are placed in the boundary layers.

d) The wall roughness changes along the plate.

e) Relative motion of one part of the wall in relation of fixed part when host of other changes are imposed on the boundary layer.

For turbulent boundary layer even small roughness has a pronounced effect upon the layer. As the Reynolds number varies and as the wall roughness is changed the skin friction or wall shear coefficient of a turbulent boundary layer also changes. In recent years a number of wind tunnel experiments have been performed on obstacles, mostly for the purpose of determining forces on structures. (13)

A turbulent boundary layer disturbed in some form or other, e.g. By surface irregularities or by change of surface terrain is to be found in many engineering problems, particularly in building research, Windbreak design , agricultural engineers dealings with shelter belts, hydraulic engineers involved in the design of spurs and aerodynamicists dealing with tall buildings exposed to atmospheric boundary layer flow are interested in the separation of boundary layer caused by an obstruction, reattachment of the boundary layer to the wall downstream and its subsequent redevelopment .(7)

2. PREVIOUS STUDY

A significant amount of information has been gathered on several of coherent structures in a turbulent boundary layer. Due to high shear or high Reynolds number turbulence is generated leading to the formation of eddies. Large eddies break to smaller and still smaller eddy until they are finally dissipated through viscous shear. Some of the researcher works related to disturbed turbulent boundary layer is given here as under.

Sang-joon-lee, studied experimentally flow characteristics of turbulent wake behind porous fences. The velocity fields were measured using the two-frame PTV method in a circulating water channel. The fence models used in this study have geometric porosity (η) of 0%, 20%, 40% and 65%, respectively. Each fence model was located in uniform flow whose boundary layer thickness (d) at the fence location was about 0.1 of the fence height (H). Among the porous fences used in this study, the porous fence with porosity $\eta = 20\%$ shows the maximum reduction of mean stream wise velocity, but it has the highest vertical mean velocity at about $x/H = 1$ location and large turbulence intensity in the near wake region. However, the porous fence with $\eta = 40\%$ has good flow characteristics for abating wind erosion with small turbulent fluctuations and a relatively large reduction in mean velocity. Except for the solid fence ($\eta = 0\%$), two shear layers develop from the porous fences. As the fence porosity (η) increases, the height of the shear layer and the streamline curvature decrease. When the porosity (η) is greater than 40%, there is no re-circulation flow behind the fence due to the strong bleed flow, the Reynolds shear stress is nearly negligible in the entire near-wake region and relatively small turbulent kinetic energies are concentrated in the region just behind the fence ($x/H = 0.5$). When the fence porosity is less than 20%, the Reynolds shear stress and turbulent kinetic energy are strong over the fence and in the shear layer near the reattachment region. (17)

Dong and Wang studied the effect of porous fences in wind erosion. Porous fence is a kind of artificial windbreak that has many practical applications. The threshold wind velocities at different distances downwind from porous fences were measured and the corresponding characteristics of particle movement observed to assess their shelter effect. It is found that the fence's porosity is the key factor that determines the resulting shelter effect. The area near a fence can be typically classified into five regions, each with a different mode of particle movement. Dense fences, and especially solid fences, favor the accumulation of sand upwind of the fences. Fences with porosities of 0.3–0.6 (depending on the fence height) provide the maximum It is confirmed that the fence porosities of 0.3–0.4 that have been proposed for practical application in previous research are the most effective for abating wind erosion.(4)

Muck and Bradshaw, studied the response of a well-developed turbulent boundary layer to suddenly applied convex surface curvature, using conditional-sampling techniques so that the turbulent and non-turbulent regions of the flow can be clearly distinguished. They found that the effects of convex (stabilizing) and concave (destabilizing) curvature on boundary layers, and presumably on other shear layers, are totally different, even qualitatively: mild convex curvature, with a radius of curvature of the order of 100 times the boundary-layer thickness, tends to attenuate the pre-existing turbulence, apparently without producing large changes in statistical-average eddy shape, while concave curvature results in the quasi-in viscid generation of longitudinal ('Taylor-Görtler') vortices, together with significant changes in the turbulence structure induced directly by the curvature and indirectly by the vortices. From the point of view of calculation methods, the implication is that, although stabilizing and destabilizing curvature are connected by a common dimensional analysis, the differences are such that the one cannot be regarded as a useful guide to the treatment of the other. Specifically, rates of change of turbulence-structure parameters with curvature parameter are likely to be nearly discontinuous at zero curvature, and in particular the time of response of a turbulent boundary layer to convex curvature, implying mere attenuation, is very much less than the time of response to concave curvature, implying reorganization of the eddy structure.(10)

Perea took measurements in the wakes of two dimensional solid and porous fences immersed in the boundary layer. The porosity (ratio of open to total area) of the perforated fences ranged from 0.0 to 0.5 .It is seen that the porosity and not the form of construction of the fence that determines the structure of the wake flow. As the porosity increases, the recirculating bubble detaches from the fence and moves downstream, becoming smaller, above porosity of 0.3 the bubble could not be detected. The wake velocities increase with increasing porosity. In contrast to this, the turbulence intensity decreases with increasing porosity but a solid fence provides a flow of very low turbulence in the near wake region.(11)

In the far wake region it is shown that the mean velocity defects and excess turbulent stress profiles could e represented by functional forms and both these quantities decay downstream as inversely proportional to x. It is difficult to say which porosity provides the best shelter but a solid fence is best for protecting the near waked zone, while a fence with porosity 0.1 provided good shelter characteristics in the far wake region.(11)

Gupta studied in a wind tunnel the disturbed flow field over solid models varying from 5mm to 25mm. The drag coefficient C_{DO} is in good agreement with Garde et. al. (1969). The drag coefficient C_{DO} expressed as a function of H/Y^1, where Y^1 is roughness parameter given by 0.128 v/u_{*0} is good agreement with Raju et. al. (1976). The length of the standing eddy is found to be 14.5 H. the maximum velocity downstream of a fence occurred at about 3H from the fence.(8) The location of the maximum velocity remains approximately same for the solid bodies but the value of the maximum velocity changes with the change in body shape as evidenced by plate and Lin (12). The boundary layer growth redeveloping zone shows a similar variation in case of Plate et. al. and sinusoidal model as well as the wedge model. The redeveloping regions increases from zero to a maximum at about 120 H or so and thereafter decrease. This is in good agreement with that of Plate observation. (12)

Sang-Joon Lee investigated experimentally the effect of porous wind fences on the wind erosion of small sand particles from a two-dimensional triangular prism pile of sand. The mean velocity and turbulence intensity profiles measured at the sand pile location were simulated to fit to the atmospheric boundary layer over open terrain. Flow visualization was carried out to qualitatively determine the movement of the wind-blown sand particles.(19)

The fence of porosity $\eta = 30\%$ was found to have the highest threshold velocity, indicating a good shelter effect for abating wind-blown sand particles. The threshold velocity was found to increase with increasing sand particle diameter. The threshold velocity was also enhanced when the height of the sand pile was lower than the fence height.(19)

After review of literature, it is concluded that there has been no study of redeveloping zone of disturbed turbulent flow past an obstacles shape of Quadrant of circle & shape of Quadrant of ellipse with porosity 18%, 35% and 45% element mounted on the surface. This aspect of research is being investigated in this study.

3. ANALYTICAL CONSIDERATIONS

The shear flow downstream of bluff bodies gets separated at the crest and again reattaches to the boundary some downstream. The flow starts redeveloping along the wall downstream of the point of reattachment. In the near field region (region between fence and up to point of reattachment) the flow is like a free shear flow, whereas it is like a wall shear flow downstream of the reattachment point in the far field region. Thus, for convenience the shear flow past an obstacle can be split in two regions, namely: (fig 3.1)

(1) The near field region extending from the obstacle to the point of reattachment characterized by a free stream flow and

(2) The far field region downstream of the point of reattachment characterized by wall shear flow.

Only second aspect of shear layer is investigated in this study.

The turbulent boundary layer is considered to consist of an inner region and an outer region. The thickness of inner region of turbulent boundary layers generally various from 10 percent to 20 percent of the boundary layer thickness, δ. The "Law of Wall" gives the mean velocity distribution in inner region, viz.

$$\frac{u}{U_{*0}} = f\left(\frac{y \quad U_{*0}}{v}\right) \qquad (3.0)$$

At values of u_{*0} y/v < 30, the velocity distribution in the inner region is given by the velocity distribution law for turbulent flow, viz

$$\frac{u}{U_{*0}} = \frac{1}{k}\log\left(\frac{yU_{*0}}{v}\right) + c \qquad (3.1)$$

Where, values of k and are c are 0.40 and 5.10 respectively.

Some investigators describe the mean velocity distribution in the outer region as "Velocity defect law"

$$\frac{U_0 - u}{U_{*0}} = f_1\left(\frac{y}{\delta}\right) \qquad (3.2)$$

Or $$\frac{U_0 - u}{U_{*0}} = f_2\left(\frac{y}{\Delta}\right) \qquad (3.3)$$

Here, $$\Delta = \frac{\delta_{*0}\,U_0}{U_{*0}}$$

The function f_1 ,f_2 have been found to be independent of Reynolds number of the flow and roughness of the wall , but affected by the stream wise pressure gradient .

In 1956, Cole's postulated a "Law of Wake" to describe the mean velocity distribution in the outer region of the turbulent boundary layer,

$$\frac{u}{U_{*0}} = \frac{1}{k}Log_e\left(\frac{yU_{*0}}{v}\right) + \frac{\Pi}{k}w\left(\frac{y}{\delta_0}\right) + c \qquad (3.4)$$

Here, Л is a profile parameter and varies from one flow to another and w is known as universal wake function dependent only on the dimensionless distance from the wall y/δ for an equilibrium boundary layer with zero pressure gradients. Cole's shown that the flow is locally a pure wake flow at the point of reattachment of turbulent boundary layer. The associated velocity defect of this wake is given by [ЛU_{*0} (2-*w*)/k] which reduces to [2Л U_{*0}/K] at wall. Accordingly, the law of wake is view as manifestation of large scales mixing similar to the flow in a wake, in that it is constrained primarily by insertion rather than by viscosity. But when the flow is bounded by a wall, it has to satisfy the zero velocity condition at the wall, which in turn modifies the mean velocity distribution.

Cole's model thus envisages the flow in a turbulent boundary layer as a combination of the logarithmic law of the wall and law of wake resulting from separation of flow past a bluff body. Even in a redeveloping region downstream of a fence or a similar body.

Cole's model in well suited to describe the velocity field within the redeveloping region, with a wake function which is such more complex than that for an equilibrium boundary layer. Considering the large pressure gradient in the flow direction close to the point of reattachment, the complex nature of the flow in this region and the departure from the universal law of wall shown by the experimental data of Bradshaw and Wong (1972) in the redeveloping region, one may hypothesis that the law of wall applicable to this section may be written as

$$\frac{u}{U_*} = \frac{1}{k}\log\left(\frac{U_* y}{v}\right) + c \qquad (3.5)$$

Where, k and c could be different from Cole's value. For the sake of simplicity and in view of the relative constancy of k under highly varying conditions, k may be treated as constant, and equal to 0.4, so that the foregoing equation may be written as

$$\frac{u}{U_*} = 2.5\,\mathrm{In}\left(\frac{U_* y}{v}\right) + c \qquad (3.6)$$

In which

$$C = f_3\left(\frac{x}{H,}, \frac{H}{\delta_0}, shape\ of\ body\ , \eta\right) \qquad (3.7)$$

The velocity profile in the redeveloping region could be expressed as

$$\frac{u}{u_*} = 2.5\ In\left(\frac{u_{*,}y}{v}\right) + c + w \qquad (3.8)$$

$$W = f_4\left(\frac{y}{\delta}, \frac{x}{H}, \frac{H}{\delta_0}, shape\ of\ body, \eta\right) \qquad (3.9)$$

There can be some doubts as to the correctness or otherwise of omitting parameters like, u_o H/ υ and u_{o*} H/ υ including a parameter, like H/δ_o in their place in equation (3.7) and (3.9). Experimental data alone will enable determination of the correctness of the choice of parameters. One may, however postulate that the influence of u_o H/v is likely to be secondary in case of sharp edged bodes and H/δ_0 may be superior to u_{0*} H/v for purposes of analysis, in that the former shows a larger variation of varying approach characteristics.

4. EXPERIMENTAL SETUP

The work was planned and carried out to provide detailed information of the mean velocity field past two – dimensional porous obstacles of shape, Quadrant of circle & Quadrant of Ellipse with porosity of 18%, 35% & 45%. The experimental work comprised of the wind tunnel

i) Study of undisturbed boundary layer obtained in the wind tunnel

ii) Study of the standing eddy zone extending toward downstream side of obstacle

The experiments was conducted in an open circuit subsonic wind tunnel of cross section 450 mm x 450 mm and a test section of length 3000 mm .The tunnel was provided With grids and screens upstream of the entrance to the test section to give a good velocity distribution and reduce the level of the turbulence intensity of the free stream. Numbers of pressure taping were provided along the floor of the tunnel to measure the floor pressure. A variable voltage controller with range of 0-100 % of full voltage is available for providing high speeds.

The model or porous obstacles was of cross sectional shape of Quadrant of circle and cross sectional shape of Quadrant of ellipse and each having three porosity of 18%, 35% & 45% (open area percentage). The model was of the length of 450 mm and base width 30 & 45 mm but its height was 30 mm. The porous obstacles were made of wood and circular holes were uniformly punctured by drilling, giving geometric porosity (η) i.e. open area percentage of 18%, 35% and 45% respectively as shown in table given below. The model was installed at a position 300 mm downstream of the inlet of the test section.

Porosity (%)	Hole Dia. (mm)	No. of Hole
18	3	348
35	4	376
45	5	310

The mean velocity and pressure traverses were obtained by means of probes mounted on a carriage whose position could be varied from outside. An inclined manometer with inclination angle of 15^0 was used to measure the pressure. The fluid used in the manometer was benzene 0.79. The right limb "l_r" was connected to the total head tube whereas the left limb "l_l" was connected to the nozzles provided at the base of the wind tunnel. The difference of readings of both the limbs were measured in centimeter, it was converted into meter by dividing by 100 and multiplied by sin 15^0 gave the vertical difference in the two limbs reading i.e. “h” and when this h was multiplied by specific weight (sp. Gravity) gives pressure “p”

$$h = \left(\frac{l_{l-}l_r}{100}\right) \times sin15^0$$

$$p = \left(\frac{l_{l-}l_r}{100}\right) \times sin15^0 \times 9810 \times 0.79$$

The experiment was performed at temperature of 26^0C-32^0C. the mass density of air “ρ_a” at this temperature was taken as 1.17 kg/M^3 the mass density of air ρ_a was calculated by using the formula

$$\rho_a = \frac{P}{RT}$$

Where P is standard atmospheric pressure at sea Level (101. 325knm^2)

R is specific gas constant (287 m^2/s^2 k)

T is working temperature in Kelvin. The velocity of air was measured by using the formula

$$u = \sqrt{\frac{2p}{\rho_a}}$$

The mean velocity profiles were measured by means of a flat tipped total head tube and static tube of 0.2 mm diameter. The flattened measuring tips minimize potential error in total pressure measurement due to flow turbulence and acceleration.

The Quadrant of circle shape & Quadrant of elapse shape solid model of 30 mm height was placed at 30mm. The total head and static head probe was used to measure the mean velocity measurements in the region between the model and the reattachment point and after the reattachment point. The measurements were made at the velocities of 10m/sec and 15m/sec.

The twin static tube set was used to measure the differential pressure so that the reattachment point is located. This is done by placing the twin static tube at various test sections downstream of the model. At the point of reattachment the differential pressure should be zero. Therefore, by careful measurement of this differential pressure and their subsequent plotting against the distance from the model, the point of reattachment is located

After finding the reattachment point, the observations were taken in redeveloping zone and various graphs were plotted for study of the redeveloping zone of disturbed boundary layer.

5. ANALYSIS AND RESULT

The experiment is performed and the data is collected .The collected data is analyzed and the result is represented. The mean flow characteristics have been studied. The undisturbed turbulent boundary layer flow characteristic is studied first. It is than followed by the study of the flow in redeveloping zone downstream of a porous model .This study is related to the disturbed turbulent boundary layer flow in the region downstream of the reattachment point.

Before studying the flow field downstream of a porous model placed submerged in a turbulent boundary layer it is necessary to study the characteristics of undisturbed turbulent boundary layer. This is because the disturbed flow is as much a function of the obstacle geometry as of the characteristics of the approach flow.

The nominal thickness of boundary layer is defined as the distance from the floor to the level where the velocity is 1% less than the free stream velocity U_o

$$\text{i.e.}\delta_o = 0.99\, U_o \tag{5.1}$$

The displacement thickness δ_{*0} is defined as

$$\delta_{*o} = \int_0^{\delta} \left(1 - \frac{u}{U_o}\right) dy \tag{5.2}$$

$$\theta_o = \int_0^{\delta} \frac{u}{U_o}\left(1 - \frac{u}{U_o}\right) dy \tag{5.3}$$

The mean velocity profiles for two velocities i.e. 10m/sec (Fig5.1) and 15m/sec (Fig 5.2) are drawn at different stations along the wind tunnel .The δ, δ_{*0} and θ_o measurement and its plotting for 10m.sec and 15m/sec are shown in Fig5.3,Fig.5.4,Fig5.5 respectively.

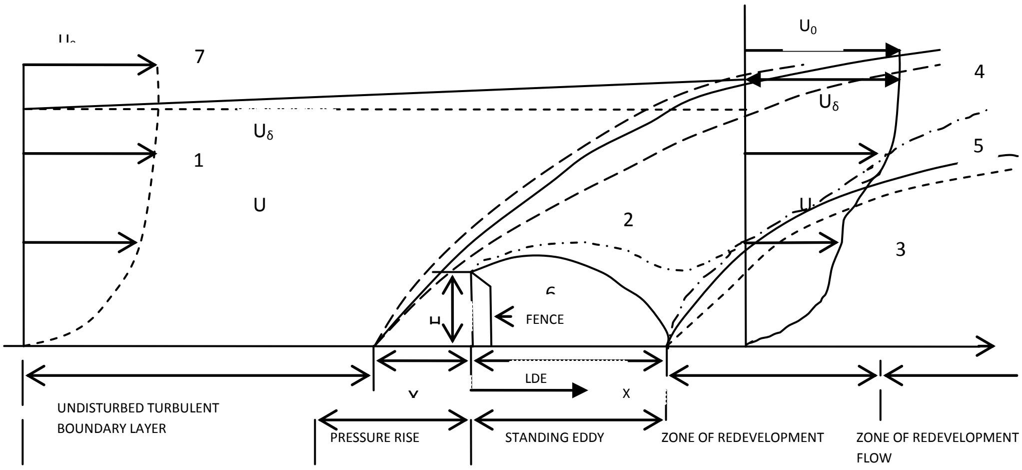

Fig 1 Different Zones of Flow Of Boundary Layer Disturbed By A Fence

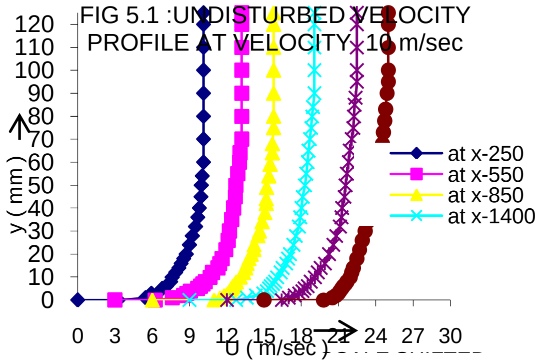
FIG 5.1 :UNDISTURBED VELOCITY PROFILE AT VELOCITY 10 m/sec

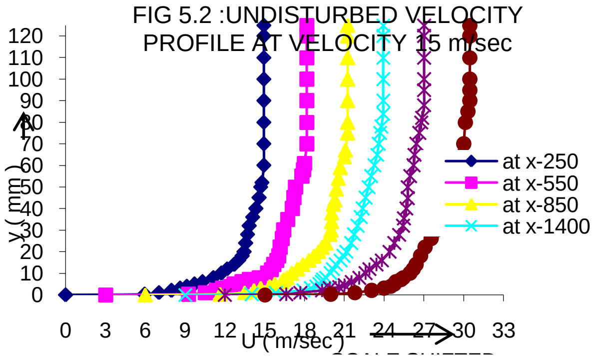
FIG 5.2 :UNDISTURBED VELOCITY PROFILE AT VELOCITY 15 m/sec

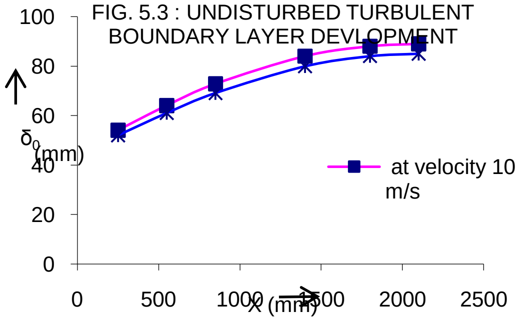
FIG. 5.3 : UNDISTURBED TURBULENT BOUNDARY LAYER DEVLOPMENT

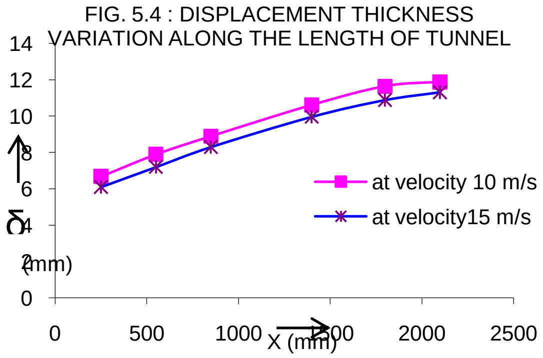
FIG. 5.4 : DISPLACEMENT THICKNESS VARIATION ALONG THE LENGTH OF TUNNEL

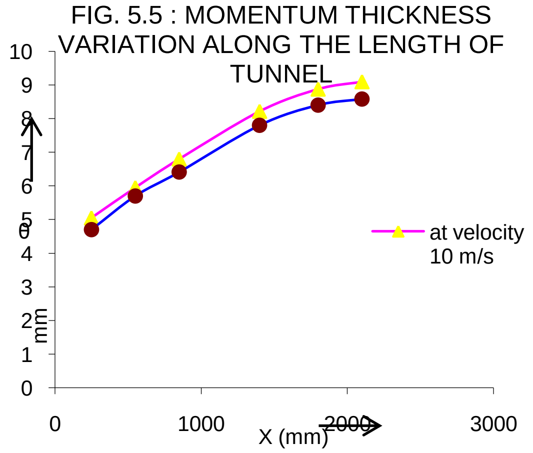
FIG. 5.5 : MOMENTUM THICKNESS VARIATION ALONG THE LENGTH OF TUNNEL

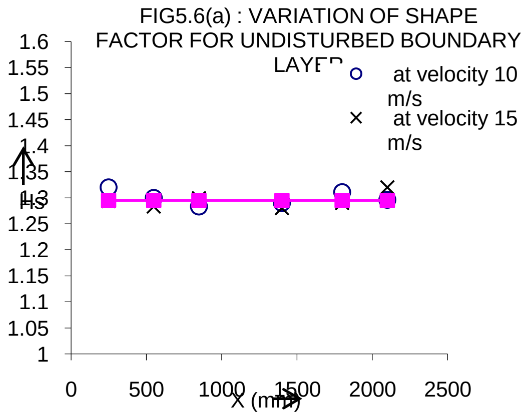
FIG5.6(a) : VARIATION OF SHAPE FACTOR FOR UNDISTURBED BOUNDARY LAYER

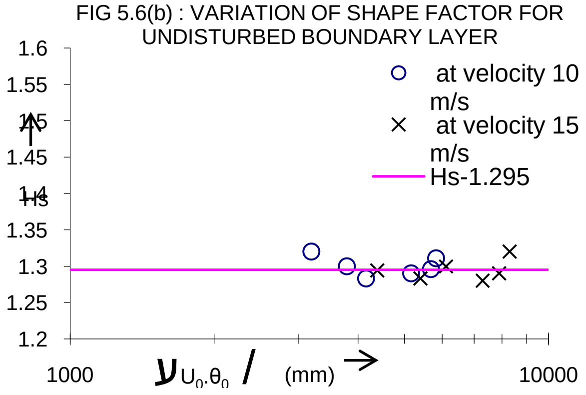
FIG 5.6(b) : VARIATION OF SHAPE FACTOR FOR UNDISTURBED BOUNDARY LAYER

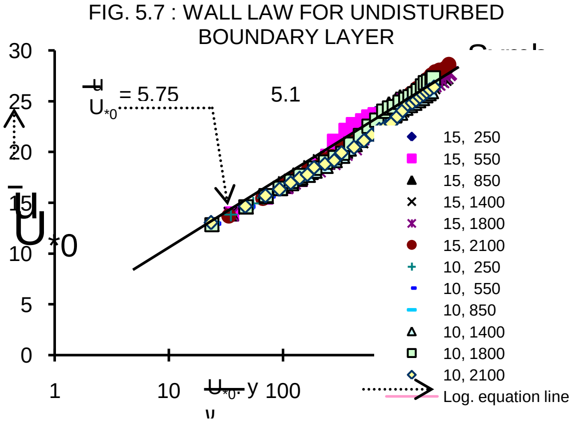
FIG. 5.7 : WALL LAW FOR UNDISTURBED BOUNDARY LAYER

The variation of shape factor H_s ($=\delta_{*0} / \theta_o$) with Reynolds number ($U_0\ \theta_o/\upsilon$) for 10m/sec and 15m/sec is shown in (fig 5.6). After studying the characteristics of undisturbed turbulent boundary layer the study of disturbed turbulent boundary layer flow characteristics is taken. The porous obstacle is placed submerged in the turbulent boundary layer and the flow past porous fences reattaches to the floor at a point downstream of a model i.e. at the end of the standing eddy. This point of reattachment was found by a twin static tube assembly, which was used to measure the differential static pressure. At reattachment point this measured differential static pressure is zero. The mean velocity profiles are plotted in redeveloping zone, downstream of the porous fences, at points having similar distance from the beginning of tunnel. The profiles study is restricted to only those lying between reattachment point and redeveloping zone. The value of standing eddy (L_{DE}) in the present experiment is found as in table given below:

Table 5.1

Shape of model	porosity	L_{DE}/H
Quadrant of ellipse	18%	8.5
Quadrant of ellipse	35%	6.5
Quadrant of ellipse	45%	2.1
Quadrant of circle	18%	9.0
Quadrant of circle	35%	7.6
Quadrant of circle	45%	2.1

6. CONCLUSION

Measurements of mean velocity profiles for undisturbed turbulent boundary layer and within the redeveloping zone downstream of porous fences having porosity 18%, 35%, and 45% with cross sectional shape of quadrant of circle and quadrant of ellipse for disturbed turbulent boundary layer were carried out. A significance difference is indicated between the characteristics of the undisturbed and disturbed turbulent boundary layer. The flow for disturbed turbulent boundary layer past a porous fence gets separated at the crest of the downstream edge of fence and then reattaches to the wall at some distance downstream of the fence. The point at which the separated flow reattaches to the wall is called the reattachment point. The region lying between the porous model and the reattachment point is called the standing eddy and the region lying after the reattachment point is called the redeveloping zone.

The mean velocity profiles show the existence of the no-slip condition. Though the viscosity was small and velocity measurements were made very close to the boundary, it was found that near the wall the velocity was not zero and as we move away from the wall the velocity increases and becomes constant at some distance away from the wall.

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