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CONTROL OF VORTEX INTERACTIONS IN A REATTACHING SEPARATED FLOW

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ABSTRACT

Several experimental studies have shown that large scale organized vortex rings are produced in reattaching separated flows. Understanding of the interactions between these vortex rings are much important in the development of such flows in the downstream. An experimental work from a backward facing step have been made in the control of mixing by the use of techniques that affect the behavior of the vortex formed in the recirculating zone. Active controlling in the form of periodic flow perturbations caused by changing the step angle has been found to be effective in forming the flow over backward facing step by encouraging / discouraging pairing of the large scale structures that are responsible for much of the entrainment. Also, such a technique allows higher pressure at the base and hence low base drag which may provide useful design guidance for perojectiles. A finite difference solution using boundary layer equations with marching technique was also performed for comparison with experimental results. A flow visualization gives some idea for the spreading of the flow over the step. Applying the present active mixing control technique leads to a shorter reattachment length and faster spreading which is particularly important in dump combustors, since a shorter recirculating zone allows a shorter overall design of the system.

يتناول البحث دراسة عملية ونظرية لعملية التحكم في شكل تطور سريان من الهواء ذي سرعات مختلفة أثناء مروره في اتساع مفاجئ. ولقد صمم هذا الجزء ليعطي نسبة اتساع مقدارها ١,٣ وكانت النسبة بين عرض هذا الجزء وبين مقدار الاتساع ١٣,٣ كي يحافظ على جعل السريان ثنائي البعد. وتمت الدراسة مع التحكم في تطور السريان عن طريق تغيير زاوية هجوم السريان فوق الجزء المتسع. كذلك طورت دراسة نظرية استخدمت فيها معادلات الحركة والاستمرارية وبينت الدراسة أن عملية التحكم المقترحة أدت إلى زيادة التداخل مما يساعد على تحسين عملية الخلط وكذلك تقصير طول إعادة الانفصال والذي له أهمية كبيرة في تصغير حجم الأجهزة المستخدم فيها هذا النوع من السريان. واتضح من الدراسة النظرية صحة النتائج العملية وقورنت النتائج العملية والنظرية مع ما سبق نشره وكان هناك توافق جيد وأيضا تم تصوير مجال السريان وأوضحت عينة النتائج عملية انتشار السريان خلال الاتساع المفاجئ.

Keywords: backward facing step, recirculating zone, reattachment length, finite difference, flow visualization.

NOMENCLATURE

AR : Aspect ratio
ER : Expansion ratio
H : Upstream channel height
h : Step height
P : pressure
Re : Reynolds number
S : Channel width
u : velocity in x-direction
v : velocity in y-direction
X_r : Reattachment length
X,Y,Z: coordinate directions
α : step angle
μ : dynamic viscosity
ρ : density

SUBSCRIPTS

a : ambient condition
b : condition at the base
o : up-stream condition
∞: free-stream condition

1. INTRODUCTION

A separated flow is very important and has applications in many engineering problems. Such a flow exists in the natural environment and in man made devices such as flows around building, water flows in rivers and channels, heat exchangers, ducts, fuel burners, in microelectronic circuit boards, separated flow in diffusers and separation bubbles on airfoils. This flow field is very complex including separation and reattachment. Among these complexities such a flow has been studied most extensively. The backward facing step is one of the simplest geometry to produce a sudden expansion including separation and reattachment of turbulent shear layers.

Numerous investigations have been aimed at developing a better understanding of such a flow. The flow field consists of a main stream upstream of the step, the recirculating zone, the reattachment zone including the reattachment point and the recovery (redeveloping) region. The pressure in the recirculating region, which is generally uniform, is below the free stream pressure, and is termed the base pressure. This pressure is one of the main parameters in the study of sudden expansion, especially at higher values of the upstream velocity. The main aim of most studies in this area is to increase the base pressure and thus decrease the base drag, which has many applications especially for high speed flows.

Also, reattachment problems of a separated flow on a solid surface such as an airfoil, diffuser, cavity wall, etc, are of interest because a rapid rise of pressure and heat transfer takes place at the reattachment zone. A number of investigations for such flows showed that the reattachment length, which is known as the length of the distance from the step to the reattachment point in the flow direction, is one of the important properties because it indicates the rate of mixing of the separated shear layer. This length has been found to be sensitive to many parameters, Reynolds number, background turbulence level, and stream wise pressure gradient. Near the reattachment region, the local turbulence intensity and Reynolds stresses reach their peak values, which can be attributed to the impingement of the unsteady shear layer onto the step's floor. A detailed review of such a situation has been offered by Bradshaw and Wong (1972) and later by Eaton and Johnston (1981).

An experimental finding of de-Brederode and Bradshaw (1972) showed that the two dimensional flow upstream of separation, if $AR > 10$, remains two dimensional downstream of separation, whereas if $AR < 10$, separated flow becomes three dimensional. For $AR = 3$, Shih and Chih-Ming (1994) indicated that while the velocity field just upstream of the step is laminar and two dimensional, the velocity field reveals that the reattachment and the flow in the recirculating zone are highly three dimensional due to the small aspect ratio. The plane sudden expansion was numerically investigated by Acrivos and Schrader (1982), in which the dependence of the separation length on the Reynolds number and on the ratio of the upstream channel half-width to the step height was investigated in the limit of large Reynolds numbers. It was found that the separation length was proportional to Reynolds number when the inlet profile was fully developed. When a uniform inlet velocity was considered, there was a critical ratio at which this linear growth disappeared. The physical processes associated with the interaction of a shear layer and a wall have been studied in detail by Chandrsuda and Bradshaw (1981), who emphasized the role of the wall in damping the normal fluctuations and reducing the dissipation length scale. Thus, the exact geometry and turbulence structure of the reattachment zone is governed by the separated shear layer structure and the reattachment geometry. The nature, scale, and intensity of the turbulence structure in the shear layer, after separation , is dependent upon the shear layer initial conditions. The effect of the separating shear layer thickness and shape on the structure of the flow in the reattachment region of a backward facing step was examined by Adams and Johnston (1988).

Recent experimental observations have shown that large scale organized vortices are produced in reattaching separated flows. Controlling the interaction between these vortices are important in the development of such flows in the downstream. In fact, the term boundary layer control includes any mechanism or process through which the boundary layer is caused to behave differently than it normally would, where the flow developing naturally along a smooth straight surface. Separation control is of immense importance to the performance of air, land or sea vehicles, turbomachines, diffusers, and a variety of other technologically important systems involving fluid flow. Generally, it is desired to postpone separation so that form drag is reduced, stall is delayed, lift is enhanced, and pressure recovery is improved, Gad-el-Hak and Bushnell (1991). In the present work, experimental studies from a downstream facing step flow are carried out to demonstrate the substantial changes in a reattaching flow which may be produced by controlling the flow angle of attack (the angle of step). Such a technique have a significant effect on the development of reattaching separated flows. The effect increases in the mean velocity profile that provided the presence of vortices in the outer shear layer created by the separation region. The increased spread in the separated shear layer results in a shorter reattachment region. This reduction in the reattachment region may have important applications for some technological situations. Also, a numerical investigation has been given for comparison with experimental data. Visualization of the flow field using water tunnel shows some details about the flow structure.

2. EXPERIMENTAL SET UP AND PROCEDURE

An open circuit compressed air tunnel was used in this investigation, Fig.1. Two air compressors were used to give the required discharge of air which passed through an air drier and an oil separator units before restored in a cylindrical air tank of 8.3 m^3. The pressure in the air tank was automatically controlled, the maximum pressure was 8 bar. The air flows from the air tank through a 3 inches pipe to stagnate in a reservoir (1.75 m long and 0.8 m diameter) before passing into the test model. Two wire mesh screens were fixed into the reservoir to reduce the air disturbances at the inlet of the test model. The channel of a backward facing step was made of Plexiglass. The upstream channel height was 50 mm and the step was 15 mm which gives an expansion ratio (ER) of 1.3. The channel span was 200mm that gives an aspect ratio (AR) of 13.33. The channel length in the x direction was 450 mm. The leading edge of the facing step was contoured to prevent vortex shedding in the inlet section of the channel, so that the flow attack angle (the angle of step, α) was varied from 0° to 15°.

Measurements of total and wall pressures were made in x , y and z directions. Pressure taps of 0.5 mm inner diameter were made on the lower surface in both x and z directions. The first tap was at 5 mm from the step and then with an interval of 10 mm. In the upstream of the step, the pressure was measured via one tap at about 10 mm. The pressure at the base was measured through one tap made at the center of the base. The total pressure was measured using a pitot tube that moves in the x, y and z directions, with the help of a three dimensional traverse system. The inner diameter of the pitot tube was 0.5 mm. All pressure readings were taken using a U-tube water manometer with an accuracy of ± 0.65 %. All experiments were made at different initial flow velocities. Hence, the initial Reynolds number based on the step height was varied from 6.8 x 10^4 to 1.2 x 10^5. A flow visualization using water tunnel with exposure was carried out at a flow velocity of 2.5 cm/s, which corresponds to a Reynolds number of 2600.

The uncertainty in the tap location in all directions was ± 0.5 %. The spatial resolution of the traverse system is 0.5 mm in all directions which is approximately ± 3 %.The stagnation pressure in the settling chamber was measured using a digital manometer, with uncertainty of ± 0.35%. The ambient atmospheric pressure was measured using a barometer with an accuracy of about ± 0.25%. The stagnation temperature in the settling chamber was measured using a digital thermometer whereas; a mercury thermometer was used to measure the ambient temperature. The temperature was uniform with an accuracy of ± 0.5 °C.

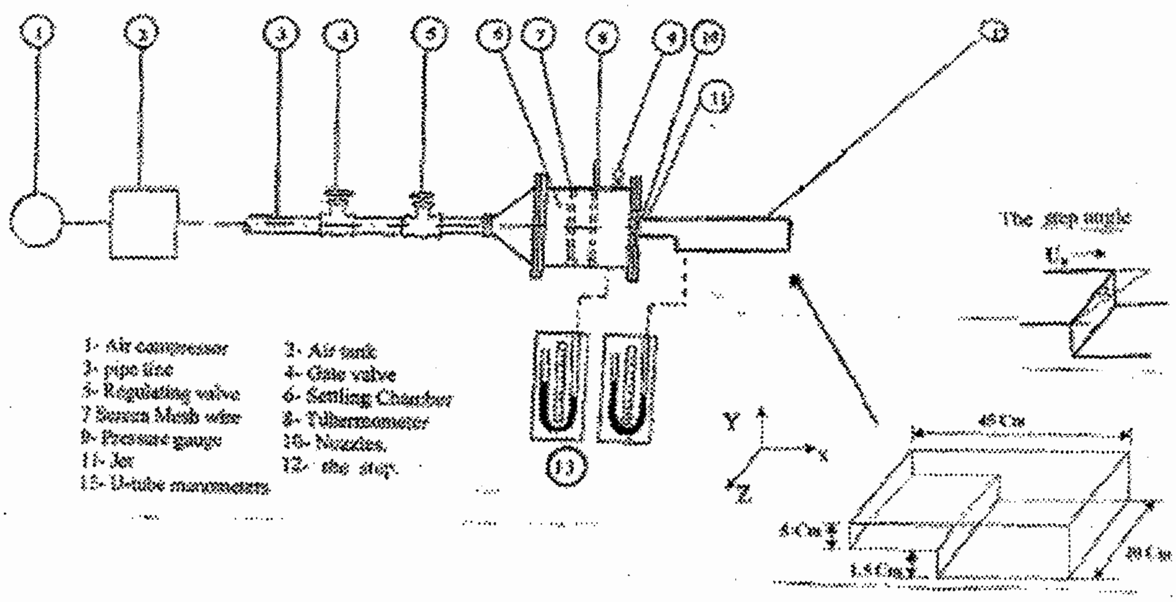

Fig. 1 Experimental Set up

3. NUMERICAL ANALYSIS

For incompressible steady, two dimensional flows with constant properties, the boundary layer governing equations are written as follows:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

Momentum equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{dp}{dx}+\mu\frac{\partial^2 u}{\partial y^2} \qquad (2)$$

The boundary conditions are;

The governing set of partial differential equations has to be solved with the following boundary conditions. The no slip boundary condition is enforced by setting the contra-variant velocities (u, v) to zero on the wall surface. At the inlet, all of the quantities are specified according to the uniform inlet velocity condition. Hence,

$$\begin{aligned} &u(x,0)=0 \qquad && u(x,\infty)=u_\infty(x)\\ &v(x,0)=0 && u(0,y)=u_\infty(0)\end{aligned} \qquad (3)$$

Note that at the entrance, $u_{\infty(0)}=u_o$

The basic equations are made dimensionless as follows:

$$U=\frac{u}{u_o} \qquad V=\frac{\rho v h}{\mu} \qquad P=\frac{p-p_o}{\rho u_o^2}$$
$$X=\frac{x\mu}{h^2\rho u_o} \qquad Y=\frac{y}{h} \qquad (4)$$

The differential equations in dimensionless form become:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (5)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{dP}{dX}+\frac{\partial^2 U}{\partial Y^2} \qquad (6)$$

The boundary conditions in the dimensionless form become:

$$\begin{aligned} &U(X,0)=0 \qquad && U(X,\infty)=U_\infty(x)\\ &V(X,0)=0 && U(0,Y)=U_\infty(0)\end{aligned} \qquad (7)$$

The above equations may be written in the finite difference form. A simple explicit form is used for Equation (5):

$$\frac{U_{j+1,k+1}-U_{j,k+1}}{\Delta X}+\frac{V_{j+1,k+1}-V_{j+1,k}}{\Delta Y}=0 \qquad (8)$$

The most useful representation for equation (6) is the following implicit form:

$$U_{j,k}\frac{U_{j+1,k}-U_{j,k}}{\Delta X}+V_{j,k}\frac{U_{j+1,k+1}-U_{j+1,k-1}}{2\Delta Y}=-\frac{P_{j+1}-P_j}{\Delta X}+\frac{U_{j+1,k+1}-2U_{j+1,k}+U_{j+1,k-1}}{(\Delta Y)^2} \qquad (9)$$

Equation (9) may now be re-written as follows:

$$\left[-\frac{V_{j,k}}{2\Delta Y}-\frac{1}{(\Delta Y)^2}\right]U_{j+1,k-1}+\left[\frac{U_{j,k}}{\Delta X}+\frac{2}{(\Delta Y)^2}\right]U_{j+1,k}+\left[\frac{V_{j,k}}{2\Delta Y}-\frac{1}{(\Delta Y)^2}\right]U_{j+1,k+1}=\frac{P_j-P_{j+1}+U_{j,k}^2}{\Delta X} \qquad (10)$$

Equation (10) is now written for all values of k from k=1 to a sufficiently large value of Y to ensure that the free stream has been reached. Hence, the set of linear algebraic equations corresponding to Eq.(10) for k=1 (1) n (k vary from 1 to n step of 1) may now be written in matrix form as :

$$\begin{vmatrix} \beta_1 \cdot\cdot \gamma_1 \\ \alpha_2 \cdot\cdot \beta_2 \cdot\cdot \gamma_2 \\ \ldots\ldots \alpha_3 \cdot\cdot \beta_3 \cdot\cdot \gamma_3 \\ \ldots \quad \ldots \quad \ldots \\ \ldots \quad \ldots \\ \ldots\ldots \\ \ldots \alpha_{n-1} \cdot\cdot \beta_{n-1} \cdot\cdot \gamma_{n-1} \\ \ldots\ldots \alpha_n \quad \beta_n \end{vmatrix} x \begin{vmatrix} U_{j+1,1} \\ U_{j+1,2} \\ U_{j+1,3} \\ \ldots \\ \ldots \\ \ldots \\ U_{j+1,n-1} \\ U_{j+1,n} \end{vmatrix} = \begin{vmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \ldots \\ \ldots \\ \ldots \\ \phi_{n-1} \\ \phi_n-\gamma_n U_\infty \end{vmatrix} \qquad (11)$$

where

$$\alpha_k=-\frac{V_{j,k}}{2\Delta Y}-\frac{1}{(\Delta Y)^2} \qquad \beta_k=\frac{U_{j,k}}{\Delta X}+\frac{2}{(\Delta Y)^2}$$
$$\gamma_k=\frac{V_{j,k}}{2\Delta Y}-\frac{1}{(\Delta Y)^2} \qquad \phi_k=\frac{P_j-P_{j+1}+U_{j,k}^2}{\Delta X} \qquad (12)$$

Note that in Equation (11), all elements are zero except those shown. The matrix of coefficients is tridiagonal: that is, the matrix consist of a band three elements wide centered on the main diagonal.

Once the values of $U_{j+1,k}$ have been found, Equation (8) may be solved for $V_{j+1,k+1}$ to give :

$$V_{j+1,k+1}=V_{j+1,k}-\frac{\Delta Y}{\Delta X}\left[U_{j+1,k+1}-U_{j,k+1}\right] \qquad (13)$$

Since $V_{j+1,0}=0$, this solution may be marched upward to the free stream, starting at the lower wall. The entire procedure may now be repeated at the next step downstream and continued as far as desired.

To specify the transverse velocity components at the entrance, Eq. (6) may be written as:

$$U_{j+1,k}\frac{U_{j+1,k}-U_{j,k}}{\Delta X}+V_{j+1,k}\frac{U_{j+1,k+1}-U_{j+1,k-1}}{2\Delta Y}=-\frac{P_{j+1}-P_j}{\Delta X}+\frac{U_{j+1,k+1}-2U_{j+1,k}+U_{j+1,k-1}}{(\Delta Y)^2} \qquad (14)$$

This equation and Equation (8) has been written for k=1(1) n provide 2 n simultaneous algebraic equations in the 2 n unknowns $U_{j+1,k}$ and $V_{j+1,k}$. Since Equation (14) is nonlinear in the unknown, these equations must be solved by an iterative process.

The truncation error of the finite difference representation at each step is of $o(\Delta Y^2)$ and $o(\Delta X)$ for the momentum and of $o(\Delta Y)$ and $o(\Delta X)$ for continuity.

The solution is universally stable for $U \geq 0$. If $U < 0$ as will occur at and past the separation, the stability criteria are given by Anderson, et al. (1984) as:

$$\frac{\Delta X}{|U|(\Delta Y)^2} \geq \frac{1}{2}, \qquad V \geq \sqrt{\frac{2|U|}{\Delta X}} \tag{15}$$

4. RESULTS AND DISCUSSION

The time average lower wall surface pressure distributions are shown in Fig. 2 for different values of the initial Reynolds number ($6.8 \times 10^4 \leq Re \leq 1.2 \times 10^5$) and step angle ($\alpha = 0°, 5°, 10°$ and $15°$). The wall pressure develops from different negative values just close to the base and converges to the atmospheric pressure at the end of the channel. The negative pressure, in the recirculation zone increases with the increase of the initial Reynolds number. The existence of the negative pressure near the step is related to the flow separation at the step and the backward flow in the recirculation zone. The development of the wall pressure is clearly affected by the change of step angle, in which is the length at which the wall pressure achieves the ambient pressure changes with the step angle. This in fact affects the recirculation zone length which of primary importance to many flow applications using a sudden expansion, such as dump combustors. The general behavior of the pressure profiles shows independence of the initial Reynolds number. This result is in agreement with the data of Back and Roshke (1972) .

The wall pressure distributions in the z-direction are given in Fig.3 at a location in the streamwise direction x/h = 3 for different values of the Reynolds number and step angle. The reattachment point was expected at about $4 < x/h < 8$. Thus, x/h = 3 corresponds to the position in the recirculation region. The wall pressure in this zone is negative and the averaged pressure profile is noticeably altered by the change of step angle. This is due to the change in the mean structure of the backward flow in the recirculation zone which changes the interaction of the vortex rings. Hence, the present data have shown a dependence on the step angle as well as on the Reynolds number. This indicates that the physical structure of the vortex rings in the recirculation zone changes with the step angle, implying that the growth of the separated shear layer may be strongly dependent on the vortex generation process. This affects the reattachment length and in turn enhances the mixing process.

The base pressure as a function of the initial Reynolds number is given in Fig.4 for different step angles. As expected, the base pressure decreases (the base drag increases) as the Reynolds number is increased. This is in agreement with the results obtained by Sahu, et.al., (1985). The base pressure increases with the increase of the step angle. The increasing value is altered with the change of step angle. The increasing in the base pressure is very effective in reducing the total drag of the system. One can say that the present boundary control technique leads to an increase in the base pressure and in turn much reduction in the base drag.

Fig 5. presents profiles of the averaged mean velocity (u/u_o) for different values of Reynolds number and step angle. One can see that the overall features of the flow through the backward facing step are reproduced. Measurements were taken inside and after the recirculation region in order to understand this highly features flow field. Thus, several different locations along the flow stream measuring planes were chosen to display the inner structures of this complex flow field. As expected, the reattachment point was about $x/h \geq 4$, Thus, x/h = 0.7 corresponds to the position in the recirculating region, x/h = 4.7 to the position near the reattachment point, and $x/h \geq 8$. The position in the flow redeveloping region. The results are in agreement with those of Amano and Goel (1985) and Suzuki, et al. (1991). It is demonstrated that the use of present active control is effective for altering the average velocity field. This change in the flow field characteristics affects the behavior of the vortex rings formed in the recirculation zone and hence enhancing the mixing process.

4.1 Reattachment Length

The reattachment distance (X_r) is defined as the location of the point in the streamwise flow direction (x-direction) where the axial component of velocity along the downstream wall changed from negative to positive, Roshko and Thomke (1966). Kiya et al. (1982) defined the position of the reattachment as the point where the surface velocity equals to zero. In the present study, the reattachment length was calculated according to the definition given by Roshko and Thomke (1966), Fig.6. It is seen that there is a strong effect of the step angle on the reattachment length. For constant initial conditions, the reattachment increases steadily as a function of the Reynolds number. However, as the step angle changes, the reattachment shortens with increasing the step angle. In this case, the recriculation region in the free shear layer after separation is closer to the step, and, therefore, the reattachment point also moves back to the step. This leads to faster spreading which is particularly important in dump combustors, since a shorter recriculation zone allows a shorter overall design of the system.

4.2 Numerical Results

Fig.7 gives the mean velocity contours for the flow through the backward facing step when $\alpha = 0°$. This is given to check the experimental results. It clearly indicates the recirculation zone and the position of the line that separates the recirculatory base flow from the main flow. Also, the qualitative features of the flow field in the base region is well evident. The reattachment point is about four step height downstream from the base which is in good agreement with the experimental data. This figure shows also that the reattachment point changes with changing of Reynolds number. These results agree well with the published results of Acrivos and Schrader (1982). It has to be known that the present numerical model gives a qualitative values of the velocity distributions. This is because it assumes that the flow is laminar, but in general fact the flow after the step is turbulent and needs the shear stress to be taken into account.

In Fig.8 another comparison is given in which the mean average velocity is plotted at different downstream locations, and $\alpha = 0°$. In Fig.8a the velocity profiles are plotted at $x/d = 2$ whereas in Fig.8b the velocity profiles are plotted at $x/d = 8.6$ which is located after the recirculation zone. Also, both experimental and computational results are compared with the data presented by Amano and Goel (1985). It is observed that the computational model reproduces the velocity profiles and there is an acceptable agreement between the measured and computed mean flow behavior.

4.3 Flow Visualization

Flow visualization has been conducted at different initial conditions and sample of these photographs is given in Fig.9. The flow field is clearly seen at which the shear layers were developed over the step. The spreading of the flow after the step is also seen.

5. CONCLUSIONS

The present article discussed the control of the flow field development behind a backward facing step at different initial flow conditions. The initial Reynolds number was varied from 6.8×10^4 to 1.2×10^5. The control technique is given as the change of the step attack angle. Thus, the step angle was chosen as $\alpha = 0°$, $5°$, $10°$, and $15°$. It is demonstrated that the change of the step angle is effective for altering the averaged mean velocity field. This change in the flow field characteristics lead to the enhancement of the mixing process. Applying the present active mixing control technique leads also to shorter reattachment length and faster spreading which is particularly important in dump combustors, since a shorter recirculating zone allows a shorter overall design of the system. The increase in the base pressure (reduction in the base drag) with using the present control technique is also clearly performed. A finite difference for boundary layer equations with marching technique was applied for comparison with experimental data. Agreement between them and with other previous work is good. Flow visualization gives some idea about the flow pattern.

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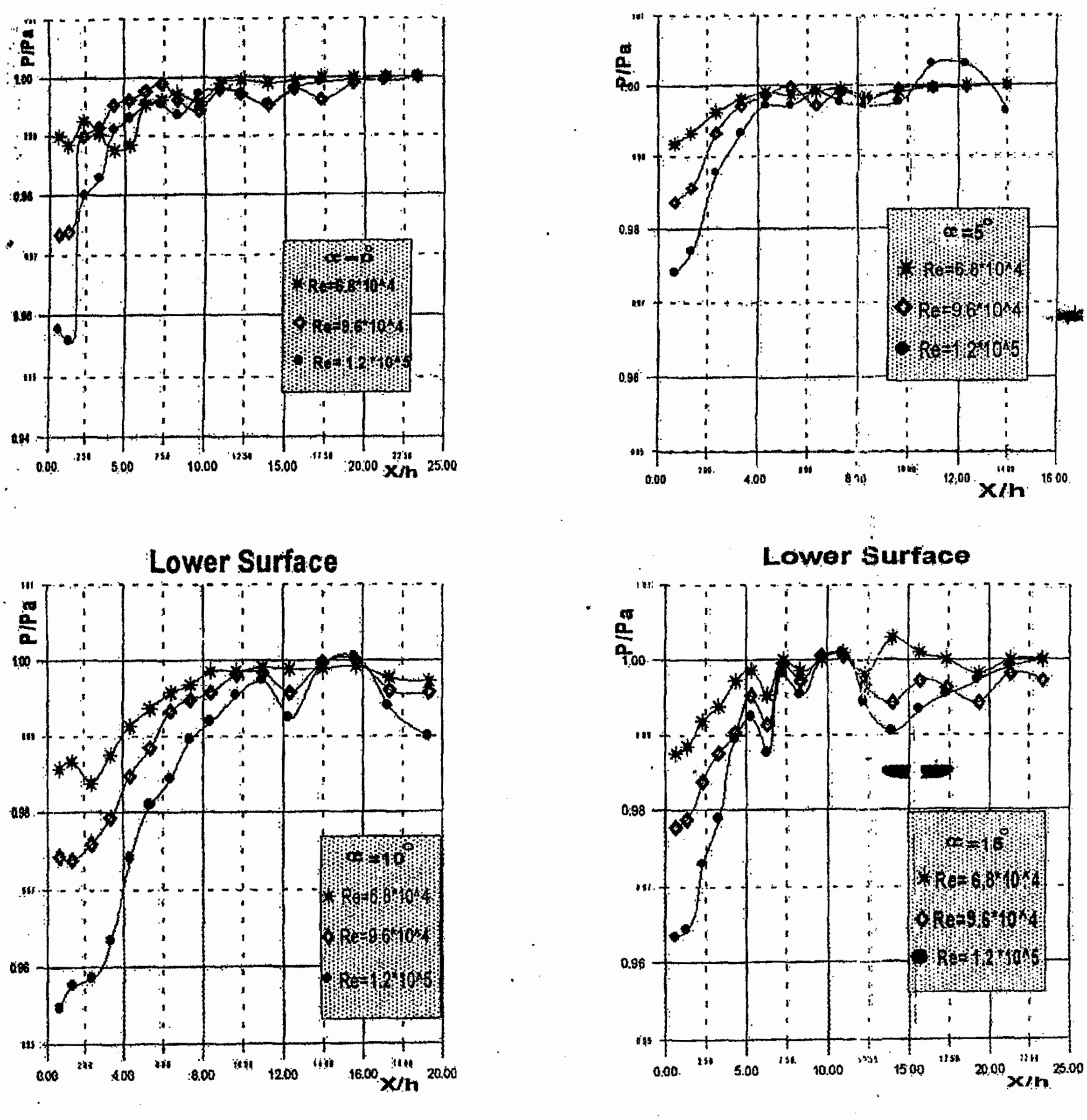


Fig. 2 Time average wall pressure distribution

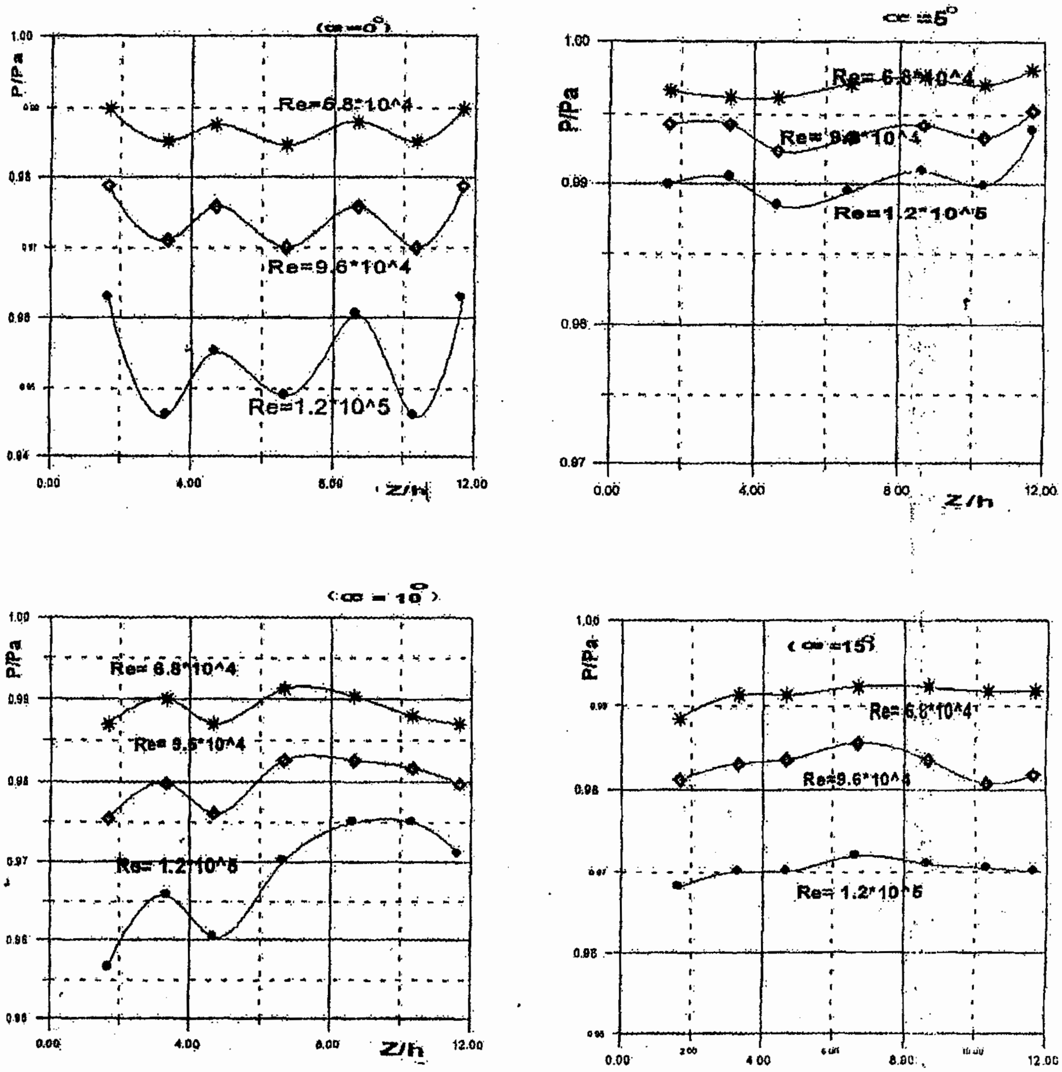


Fig. 3 Wall pressure profiles in the z-direction, x/h=3

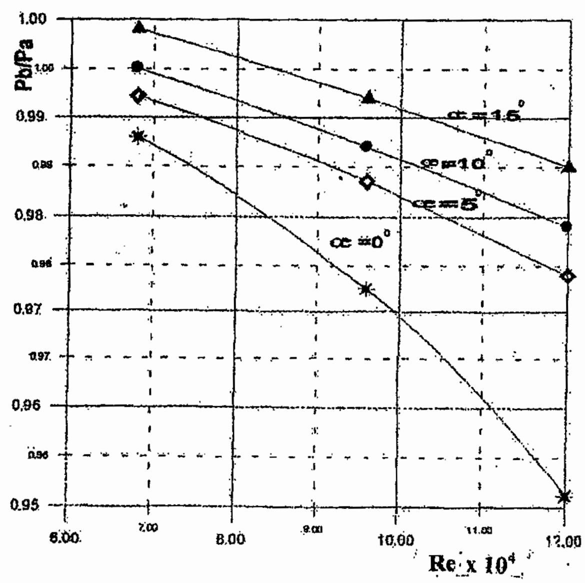


Fig. 4 Variation of the base pressure with Reynolds number

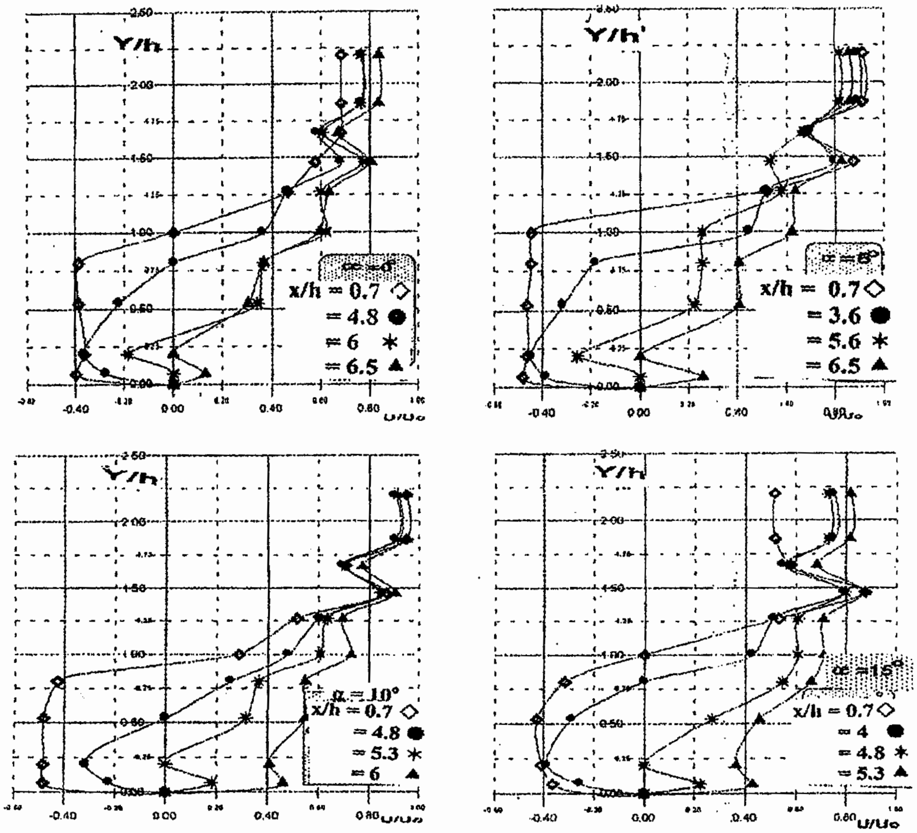
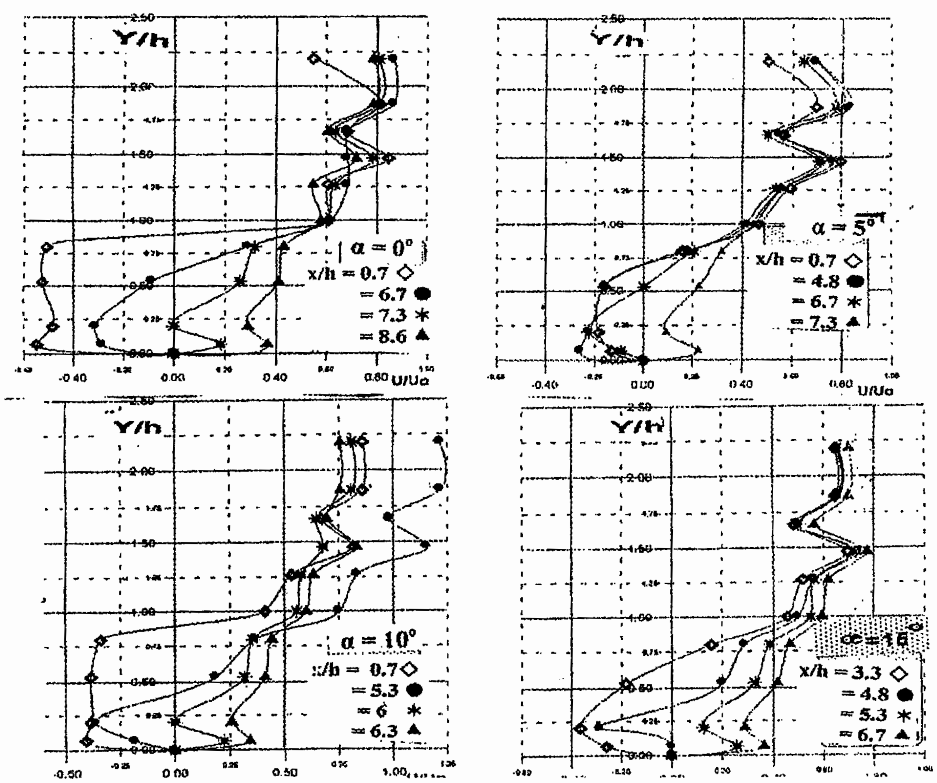


Fig.5a Mean velocity profiles various step angle, Re=6.8x10⁴



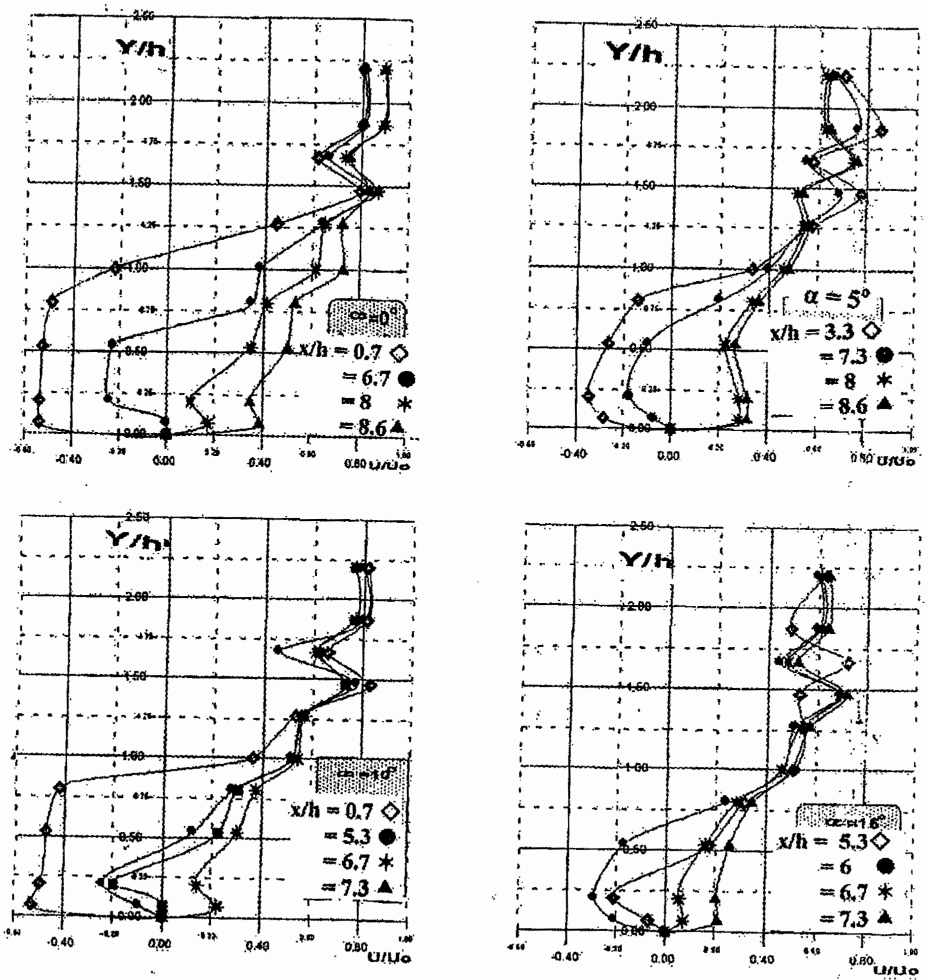


Fig. 5-c Mean velocity profiles various step angle, Re=1.2x10^5

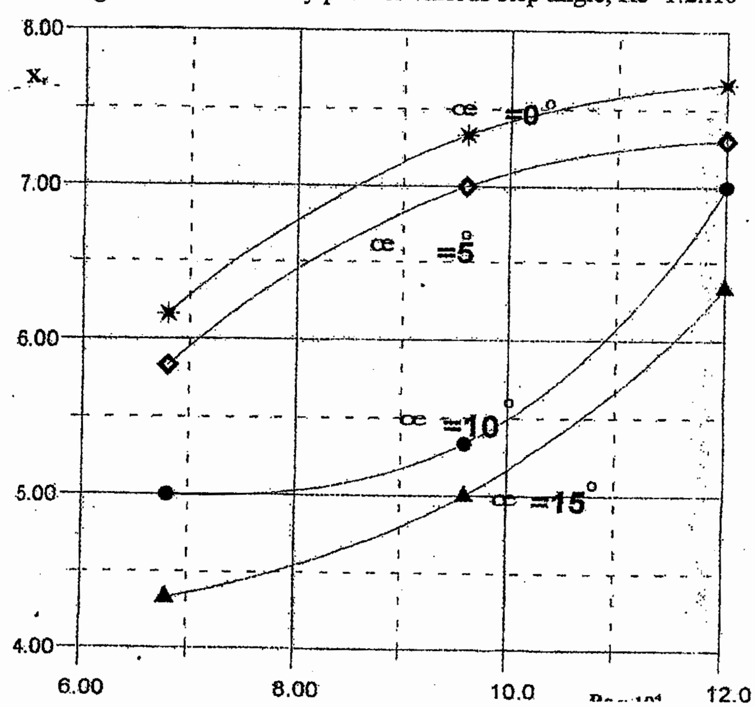


Fig. 6

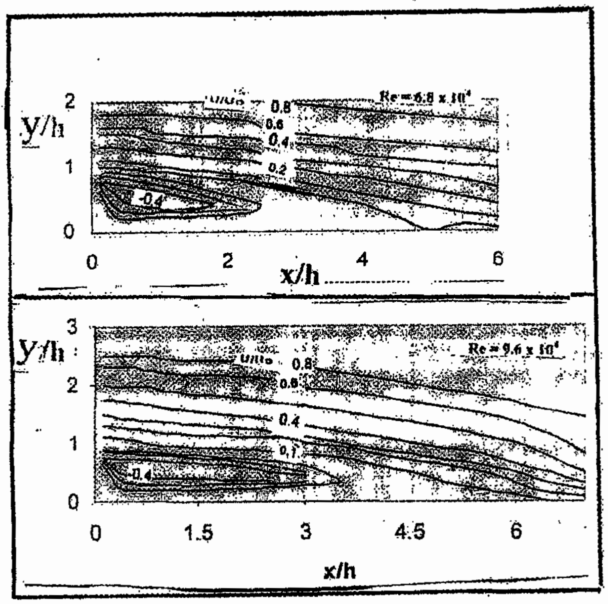


Fig. 7 Contours of the mean velocity

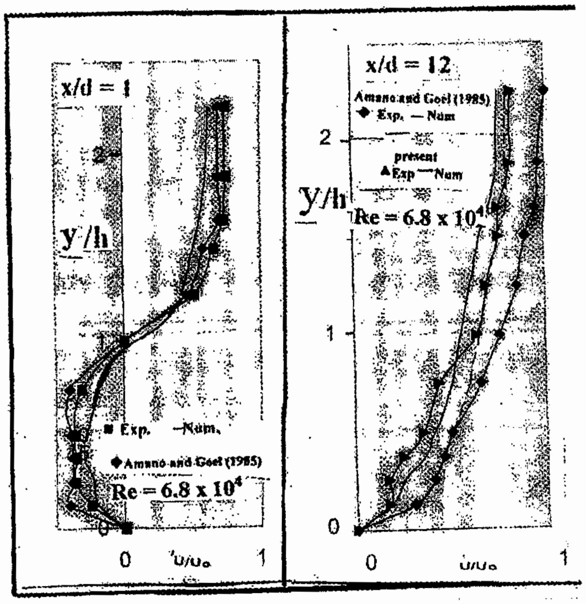


Fig. 8 Comparison between measured and computed mean velocity

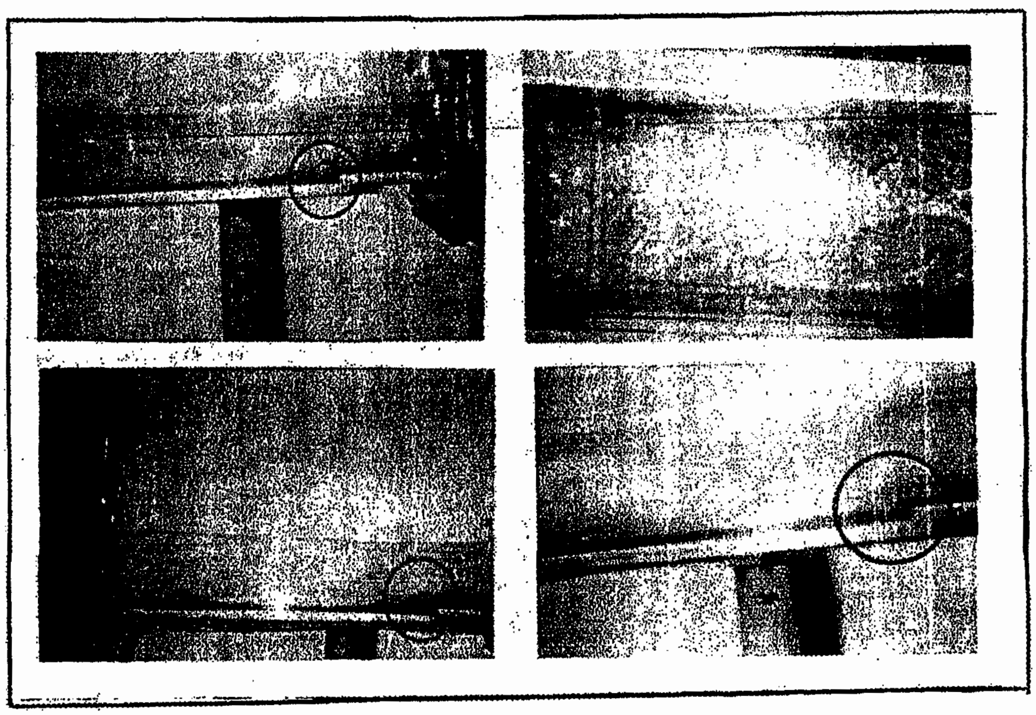


Fig. 9 Flow visualization of the back step flow field