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Two-dimensional flow field behind perforated plates on a flat surface

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Abstract

The wind tunnel experiments were conducted under highly turbulent and disturbed flow conditions over a solid/perforated plate with a long splitter plate in its plane of symmetry. The effect of plate perforation on the formation of separation bubble and its gradual disappearance was studied. The mean velocity measurements and surface mean pressure distributions were measured after preliminary flow visualization studies. The normal plate perforation level was varied from 0%–50% to give different levels of fluid interaction into the otherwise stable bubble that exists for a solid normal plate (0% perforation level). The Reynolds number based on step height was varied from 4×10^3 to 1.2×10^4. The reattachment length was obtained by a flow visualization technique, total pressure probe and shear velocity plots. Of all the three methods adopted the flow visualization method is simpler and gives better results. Mean pressures were found to be strongly dependent on perforation level of the normal plate. The shape and size of the bubble gets reduced both in height and length up to 30% perforation level. For higher perforation of the normal plate the bubble is completely swept out.

1. Introduction

Separating and reattaching flows are encountered in diverse fields. The wake behind an immersed body is of basic importance in applications to problems of turbulent wind interaction between structures, the dispersal of pollutants or spilt toxic material near buildings, aviation hazards, as well as the traditional agricultural areas of shelter, soil erosion and water conservation. Flow past a porous medium like a screen is of practical interest in many engineering problems; for example,

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Nomenclature

B	maximum height of the separated shear layer
C_p	mean pressure coefficient ($=(P-P_\infty)/0.5\rho U_\infty^2$)
$C_{p\mathrm{b}}$	base pressure coefficient ($=(P_\mathrm{b}-P_\infty)/0.5\rho U_\infty^2$)
C_{p*}	modified pressure coefficient ($=(C_p-C_{p\mathrm{b}})/(1-C_{p\mathrm{b}})$)
$C_{p\mathrm{t}}$	$\frac{1}{h}\int_0^{X_0} C_p\,\mathrm{d}X$
D	width of the two dimensional body
h	step height
P	mean static pressure
P_b	mean base static pressure
P_∞	free-stream pressure
Re_h	Reynolds number based on step height ($=U_\infty h/v$)
Re_d	Reynolds number based on body width ($=U_\infty D/v$)
U_∞	free-stream velocity
x	axial distance downstream of shoulder (point of separation)
X_R	reattachment length
X_0	distance downstream of separation to the point where $C_p=0$
y	distance normal to surface of the splitter plate
Y_δ	edge of the boundary layer, where $U/U_\infty=0.99$
Y_0	value of y where mean velocity is zero in the bubble region
η	perforation of the normal plate
v	kinematic viscosity of the fluid
ρ	density of the fluid

removal of dust from jet engine inlet flow, producing turbulence in wind tunnels, smoothing flows, application to parachute problems, etc.

Castro [1] investigated the flow in the wake behind two-dimensional perforated plates placed normal to the air-stream. He made measurements of the time-averaged velocity and turbulence intensity variation in the longitudinal direction, in the highly turbulent region behind a plate of 0.425 porosity, and along the line parallel to the flow and normal to the center-line of the plates. In the case of low porosity, he observed that the bubble that exists behind an ordinary flat plate detaches and moves downstream so that there are two stagnation points, one at either end of the bubble.

The flow over a bluff plate with a long splitter plate in its plane of symmetry is investigated by several investigators [2–5] and so on. The flow of a real fluid past a two-dimensional plate held perpendicular to flow in the midstream has been studied extensively in the past. Few studies are available on the flow past a two-dimensional plate with splitter plate placed in midstream. This case essentially corresponds to a flow past a flat plate held perpendicular to the boundary except for the fact that approach flow is of constant velocity, unlike in the case of boundary layer flow.

The purpose of this paper is to study the behavior of the separated bubble with variation in the value of plate porosity.

2. Experimental setup and methods

2.1. Facility

The facility used for the present experimental study is a suction-type low-speed wind tunnel driven by a four-bladed fan connected to a 15 HP slip-ring induction motor. Speed control of the 15 HP slip-ring induction motor over a wide range is achieved by using a combination of stator voltage control and rotor resistance control. The cross-sectional area of the test section is 610 mm $\times$ 610 mm and its length is 2100 mm. The tunnel contraction ratio is 9:1. Several screens and a honeycomb are provided in the upstream settling chamber with a fine mull cloth cover at the bell mouth entry. A velocity survey in the test section showed that it was uniform within 2% of the center-line velocity except for the boundary layer regions. The center-line turbulence level ($U'_{\mathrm{rms}}/U_\infty$) was measured to be about 0.3% within the present experimental velocity range of 5–15 m/s. At a distance of 500 mm from the entry location of the test section, the tunnel-wall boundary layer thickness was found to be about 1.5% of the tunnel height, where the test model is positioned.

The alignment of the plate was first set by physical measurements, i.e. the model was installed at the centerline of the test section and the splitter plate having nominal zero angle of incidence to the stream. Then it was checked by matching the pressures recorded on tappings located at the upper and lower surfaces of the splitter plate for any variations. In order to ascertain the existence of an adverse pressure gradient running along the test section, experiments were carried out with and without the model in position. It was found that an adverse static pressure gradient did not exist for the length of the splitter plate used. The pressure taps provided at equivalent position on top and bottom surfaces showed that the difference of C_p values is less than 0.02. This was measured by using a multitube alcohol manometer and also checked by a projection manometer, which can read to an accuracy of 0.1 mm of alcohol.

2.2. Details of the model and flow regime

The solid/perforated plate is of steel. The fence height 'h' above the splitter plate (of perspex, 10 mm thick and 650 mm long) is 12 mm for all the cases except 50% perforated normal plate, for which it is 14 mm. The configuration spanned the tunnel width. The perspex splitter plate has surface pressure tappings of hypodermic needles (0.7 mm ID) every 10 mm c/c, connected by rubber tubing, details of which are shown in Fig. 1.

The length of the splitter plate was kept much longer than the time-mean length of separation bubble, so that the interaction between the shear layers separated from both edges of the model was prevented. Six plates having 0%, 10%, 20%, 30%, 40% and 50% perforation levels were used in the present experiments. Table 1 gives the details of the model used in the present study.

For the configuration under study the flow separates at the sharp edge of the bluff plate and forms a free shear layer on top of the reverse flow region which is bounded

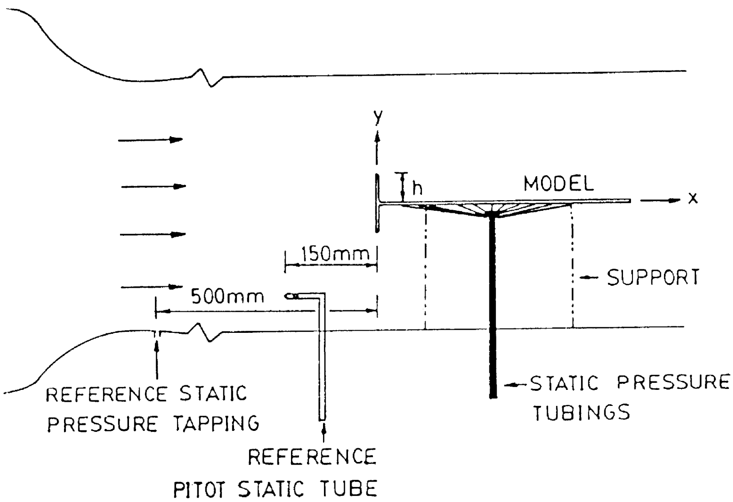

Fig. 1. Experimental configuration showing wind tunnel cross section.

on its other side by the splitter plate. The reattachment of the free shear layer takes place on the splitter plate over a narrow region, curved in span wise direction. Downstream of reattachment the shear flow adjusts slowly to the wall boundary conditions.

2.3. Flow visualization

Reattachment length was obtained by a flow-visualization technique. A mixture of titanium oxide, a little oil and soap solution was prepared and a thin coating of this paint was applied on the splitter plate behind the bluff body. Smooth brush and sponge were used for applying the paint evenly on the surface. When the tunnel was started, the mixture moved over the surface, leaving white trails of bigger accumulation indicating the reattachment region. Depending on the mixture proportion and the tunnel speed, different types of patterns were formed near reattachment region. The location of the reattachment point behind the obstructions was in this way found to be within an uncertainty of 5 mm. The reattachment point thus obtained is denoted as X_R. The reattachment point was also located by means of twin static tubes soldered together and having a small hole drilled on each of the opposite sides. This device was placed on the floor at right angles to the main flow direction. The reattachment point downstream of an obstacle was taken as the position at which the measured differential static pressure was zero.

2.4. Mean-pressure measurements

The mean-pressure measurements were made with the help of pressure tappings provided along the centreline of the splitter plate. The static pressure was measured

Table 1
Details of the models used in the study

Sl. No.	Model	Perforation level of the model (%)	Model notation	Aspect ratio	Solid bloc. (%)
1	Normal plate/splitter plate combination	0	NS-0	51	5.6
2	Normal plate/splitter plate combination	10	NS-10	51	5.6
3	Normal plate/splitter plate combination	20	NS-20	51	5.6
4	Normal plate/splitter plate combination	30	NS-30	51	5.6
5	Normal plate/splitter plate combination	40	NS-40	51	5.6
6	Normal plate/splitter plate combination	50	NS-50	44	6.2
7	Right angle corner blunt edge plate	100	RBP	61	1.6

using an alcohol projection manometer via scanivalve and the free-stream velocity was monitored simultaneously with the help of a standard Pitot tube and a second projection manometer. All the pressure measurements mentioned above were made with respect to the free-stream pressure measured at 500 mm upstream of the normal plate. The standard Pitot tube for obtaining free-stream velocity is located at a distance of 150 mm upstream of normal plate as shown in Fig. 1.

2.5. Mean velocity measurements

The mean velocities were measured using a single component hot wire anemometer type HWA 510 AD, manufactured and supplied by M/s Helio Industries, Bangalore, India. It is a constant temperature anemometer, that is the wollaston wire (manufactured and supplied by Sigmund Cohn Corp., Leico Industries, Inc., New York, USA) current is controlled by an electronic servo system that protects accidental wire burnout when the flow is suddenly reduced. The output of the hot wire anemometer is fed to the data acquisition system via the analogue to digital converter.

Table 2 gives the statement of experimental uncertainty.

Table 2
Statement of experimental uncertainty

Parameter	Estimated uncertainty	Main source of error
x	± 0.5 mm	—
y, h, D	± 0.1 mm	—
X_R	$\pm 5\%$	Locating the reattachment line from flow visualization studies
U_∞	$\pm 1.5\%$	Inaccuracies in reading the height of the meniscus in projection manometer
C_p	$\pm 6\%$	Inaccuracies in reading from projection manometer and day-to-day repeatability

3. Experimental results and discussions

3.1. Structure of the separation bubble

A large number of investigations have been reported regarding the structure of the recirculating bubble in the case of a solid normal plate (perforation being zero). Data concerning the influence of varying the perforation level of the normal plate on the size and shape of the bubble are scarce. Small jets of fluid (bleed air) coming through the perforated plate greatly influence the recirculation region behind the plate.

The time mean reattaching length of the separation bubble for different bluff body models, under different flow conditions were determined in the present experiments. In the case of bluff body separation, with a splitter plate in the downstream, physical dimension of the bubble region is important. It helps to understand and to identify the regions of unsteady velocity, unsteady pressure, reverse flow and also their dominant characteristic behavior. We may have to identify the separated shear layer region, the potential flow region (outside the shear layer where the velocity is U_∞) and the bubble region so that a careful study can be made using the precision measuring instrument at these locations.

The modification in the velocity field is brought about by change in perforation level of the obstacle apart from the characteristics of the approach flow itself. The detailed velocity measurements in the separated flow field give a fair idea of the flow structure, one can integrate the velocity profiles to get a streamline pattern. The mean velocity profiles are obtained from the measurements of a single component hot-wire anemometer. Hot wire survey has been done in the bubble region, under normal flow condition in the test section. The output of the hot-wire anemometer is taken directly to the data acquisition system via analogue to digital converter. The hot wire data are required for all the models for different perforation levels and for different free-stream velocities viz. 5.0, 7.5, 10.0, 12.5 and 15.0 m/s. The hot wire data are later processed to get mean velocity profiles.

The output of a hot-wire anemometer does not indicate the flow direction, in other words, the mean velocity output of the hot-wire anemometer is always positive. However, the reverse flow in the recirculation region could be identified with an increase and then a decrease in the positive voltage output of the anemometer for the mean velocity, as the probe approached the surface.

The mean velocity surveys were conducted for different levels of normal plate perforation viz. 0%, 10%, 20%, 30%, 40% and 50%. In all these cases the measurements were done along the centreline of the splitter plate at $x/h = 3, 6, 9, 12, 15, 18, 21, 24, 26$ and 28, covering the separation bubble region, reattachment region and some part of the redevelopment region. The velocity is varied from 5 to 15 m/s giving Reynolds number range of 4×10^3 to 1.2×10^4 based on step height.

Fig. 2 shows the streamline picture for various levels of perforation of the normal plate. It is clear from this figure that the $\psi = 0$ streamline defining the shape of the separated bubble undergoes drastic changes depending on the perforation level. It is seen that for perforation level greater than 30% the identity of the bubble could not be traced.

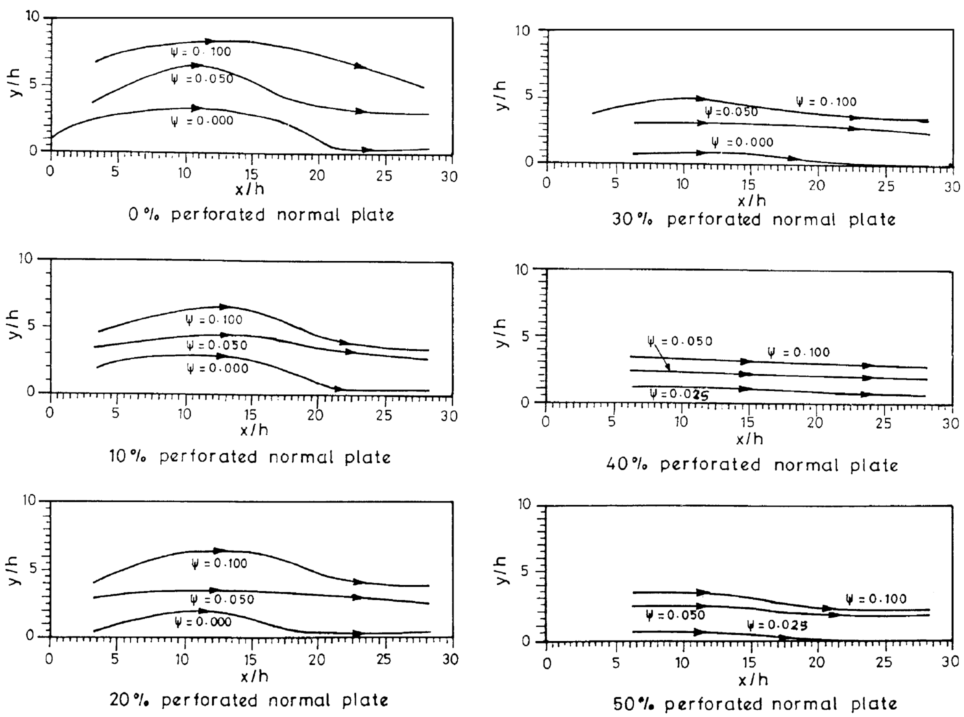

Fig. 2. Streamline plots for different levels of perforation of the normal plate.

Fig. 3 shows only the mean dividing streamlines (B) for different test models. The joining points of this with the x-axis (x/h values) are the reattachment points, and y-axis is normalized with step height. The mean dividing stream lines are not drawn for 40% and 50% perforated normal plates as the separation bubble does not exist. It can be seen from Fig. 3 that as the level of perforation increases, the height of the separated bubble decreases progressively and vanishes completely for perforation levels exceeding 30%.

Fig. 4 shows Y_δ, Y_0 and B values obtained for one typical case. Y_δ refers to the edge of the boundary layer, where $(U/U_\infty = 0.99)$, Y_0 is the y position, corresponding to zero mean velocity at a section and B is the maximum height of the separated shear layer.

Fig. 5 shows the edge of the boundary layer developing downstream of separation with the variation in the perforation level of the normal plate. The boundary layer thickness reduces in order as the bleed air quantity is increased. That is bleed air suppresses the recirculation zone due to its interaction thus bringing down the boundary layer thickness in order.

3.2. Reattachment length

The reattachment length X_R obtained on the splitter plate for different models by various techniques, namely the total pressure tube method, the flow visualization

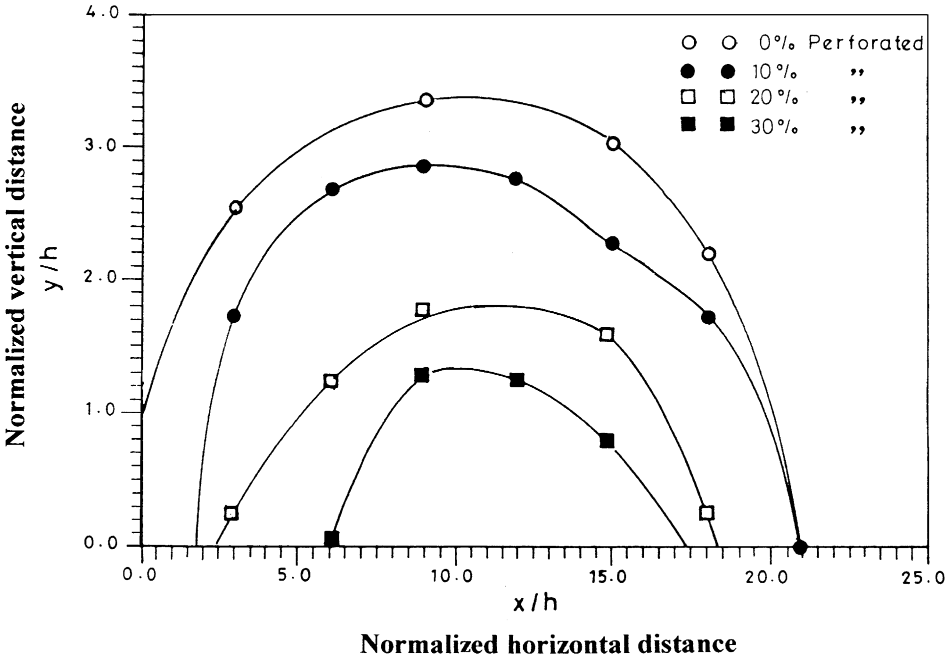

Fig. 3. Variation of the structure of the bubble with perforation.

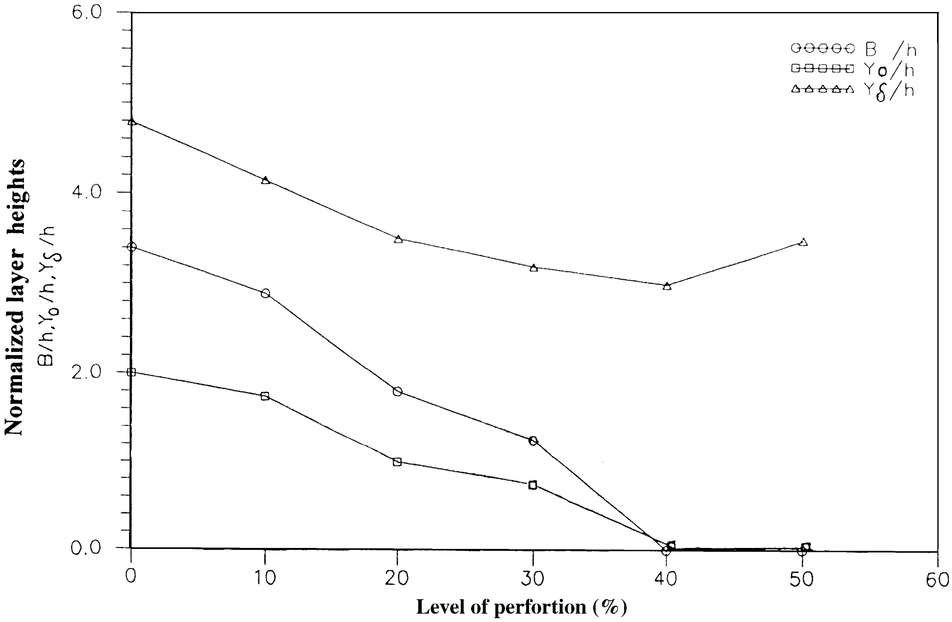

Fig. 4. Values of Y_δ, Y_0 and B for different levels of perforation of the normal plate.

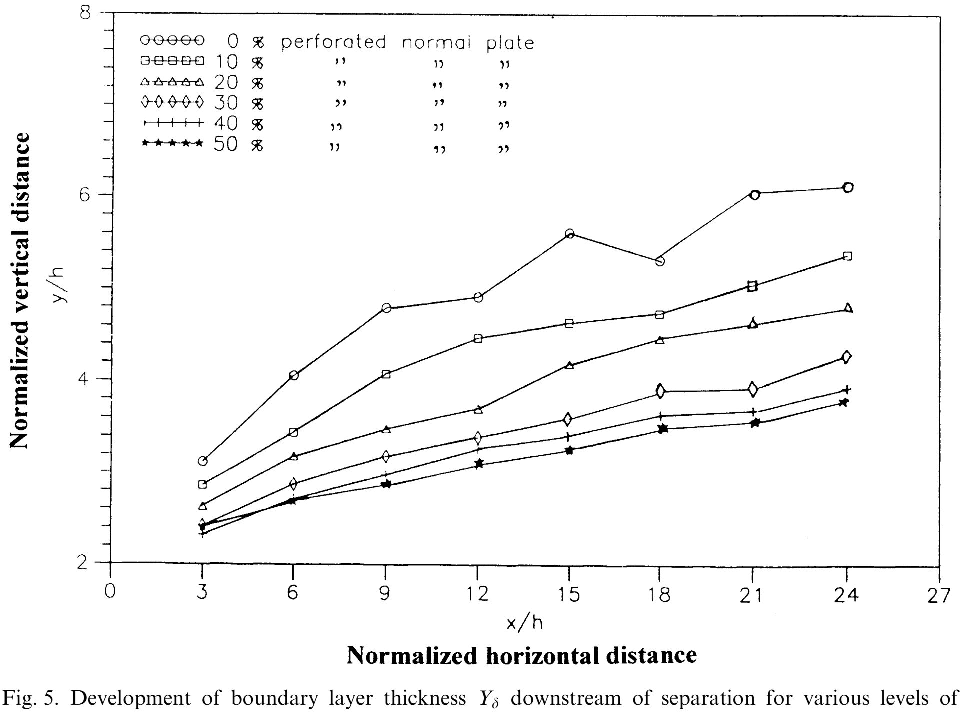

Fig. 5. Development of boundary layer thickness Y_δ downstream of separation for various levels of perforation.

Table 3
Reattachment lengths for different models by various techniques

Model notation	Non-dimensional reattachment distance (X_R/h)		
	Flow visualization method	Total pressure tube method	Shear velocity plot
NS-0	25.2	24.4	20.0
NS-10	24.0	23.7	19.0
NS-20	23.2	22.0	16.5
NS-30	23.2	22.3	16.5
NS-40	—	—	—
NS-50	—	—	—
RBP	4.8	5.0	4.7

method, and the shear velocity measurement method are compared in Table 3. It is to be noted here that results indicated in the above table refer to the average values that were obtained in the experiments. For averaging, a greater number of results was available in the case of flow visualization measurements, because of the extensive experiments conducted using this method. Locating reattachment length by using the shear velocity plot and the total pressure tube methods involved elaborate experimental procedure, and was time consuming, whereas the flow visualization method was very quick and simple.

The results in Table 3 clearly show that the shear velocity method gives relatively much lower value of X_R/h than that obtained by the flow visualization technique. The total pressure tube method also shows variation tendencies compared to flow visualization results. The reason may be that the presence of the pressure probe tube may disturb the flow in the reattachment region and X_R/h may change depending on the magnitude of the disturbance.

In Fig. 6, X_R/h is plotted against Reynolds number for different levels of perforation. It is seen that for all the perforation levels reattachment length is independent of Reynolds number in the present range of experiments.

3.3. Mean pressure survey

Mean pressure values along the splitter plate centerline for different test models were obtained over velocity range of 5–15 m/s. The pressure coefficient C_p, is defined as follows:

$$C_p = \frac{(P - P_\infty)}{0.5\rho U_\infty^2},$$

where P_∞ and U_∞ are the reference pressure and reference velocity respectively, P is the mean pressure at the point of measurement, $0.5\rho U_\infty^2$ corresponds to the reference dynamic pressure. The reference pressure and the velocity are obtained by the

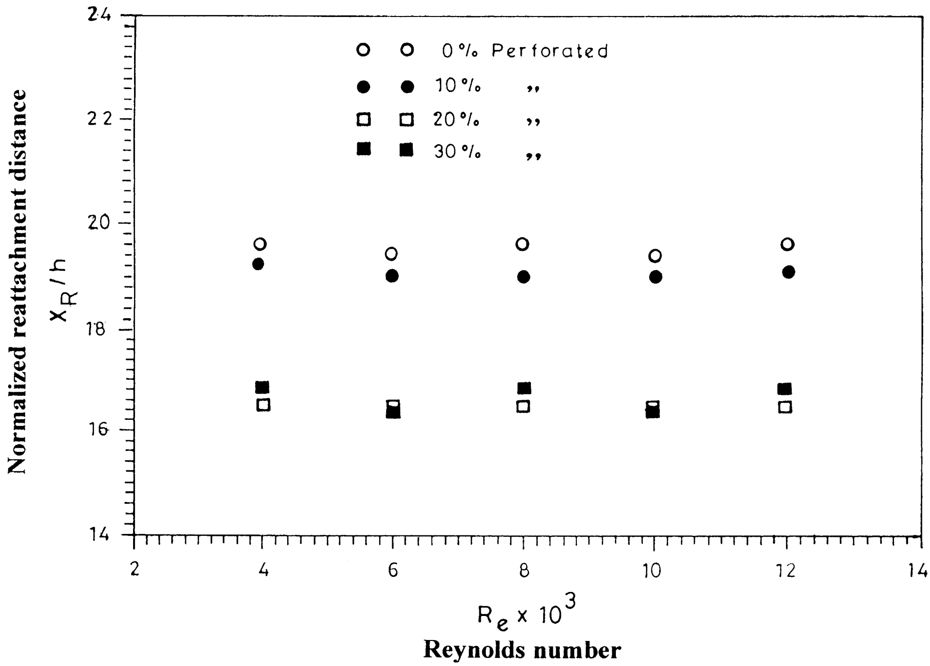

Fig. 6. Variation of non-dimensional reattachment length (X_R/h) with Reynolds number for varied level of perforation of the normal plate.

standard Pitot tube placed upstream of the model, well away from the possible disturbances from the model.

Figs. 7 and 8 show the trend of pressure recovery for 20% and 40% perforated normal plates, at various free-stream velocities. Except at 5 m/s, the pressure recovery curve for all other cases is independent of free-stream velocities. The recovery for the 20% perforated normal plate follows the conventional trend like the one for the solid normal plate. However, the recovery for the 40% perforated normal plate is faster and is monotonically increasing.

Fig. 9 shows mean pressure distribution on the splitter plate for varied degree of perforation of the normal plate used in the experiment for free-stream velocity of 15 m/s. The distance x along the plate is non-dimensionalised with respect to step height and corresponding C_p values are plotted. It is seen here that the behavior of pressure recovery is the same for normal plate perforation level of 0%, 10%, 20% and 30%, wherein the pressure first decreases and then increases. In the case of normal plates of perforation level 40% and 50% the pressure recovery is through monotonic rise. This could be attributed to the non-existence of the recirculating bubble region.

Roshko and Lau [6] postulated that the reattachment pressure rise would depend on the nature of the accelerated flow near the separation point of the bluff plate and the length of separation bubble. The modified pressure coefficient is given as

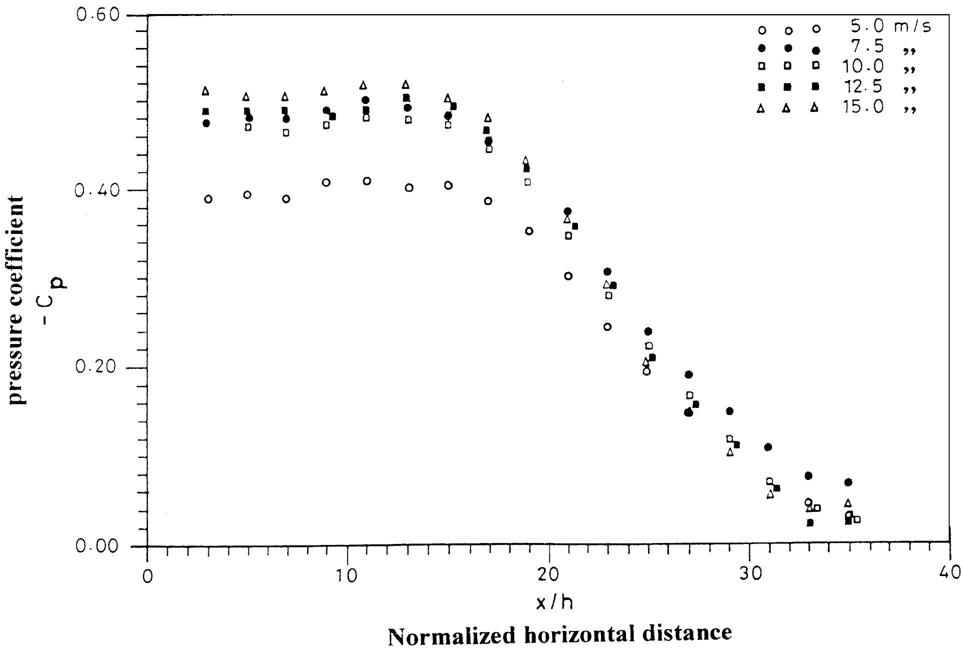

Fig. 7. Distribution of mean surface pressure coefficient on the centerline of the splitter plate for model NS-20.

follows:

$$C_p^* = \frac{(C_p - C_{pb})}{(1 - C_{pb})},$$

where C_{pb} is the base pressure coefficient calculated from the pressure at separation point P_b.

Fig. 10 shows the variation of modified pressure coefficient with axial distance measured from point of separation. It is seen as before that there is better collapse of data pertaining to normal plate perforation of 0%, 10%, 20% and 30% indicating the importance of the separation dynamic pressure in controlling the pressure recovery to reattachment. The data from the normal plate of perforation level 40% and 50% do not collapse on the universal curve of Roshko and Lau, the reason being the non-existence of the recirculating bubble as stated earlier.

In order to correlate the separation bubble formed by various bluff body configurations, the surface mean pressure coefficient (C_p) and non-dimensional reattachment length X_R/h values were tried. Taking into consideration that the wall pressure distribution represents the pressure difference across the separated shear layer, Fricke [7] studied flow behind a fence mounted on the wall, and found an expression of the following type which can be used to estimate reattachment location

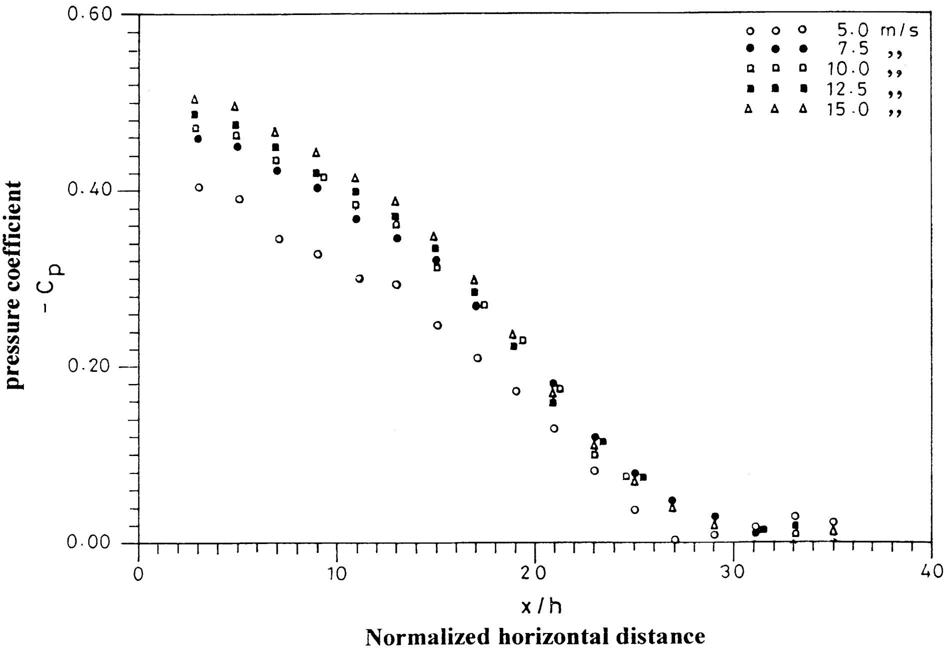

Fig. 8. Distribution of mean surface pressure coefficient on the centerline of the splitter plate for model NS-40.

in the case of widely varying separated flows,

$$\frac{X_R}{h} = \left(\frac{2.8}{h}\right) \int_0^{X_0} C_p \, dx + 3.9.$$

Fricke [7] found negligible difference in taking X_R in place of X_0.

In the present experimental results the static pressure readings along the splitter plate obtained for different bluff body configurations are used to calculate the quantity $\int_0^{X_0} C_p \, dx$, and then X_R/h versus $1/h \int_0^{X_0} C_p \, dx$, these are shown in Fig. 11. It is observed from the figure, that for the present experimental findings, considering the wall pressure distribution to represent the pressure difference across the separated shear layer results in good correlation with the non-dimensional reattachment length X_R/h.

4. Conclusions

The existence of the reattachment location or otherwise its locations for different levels of perforation of the normal plate and splitter plate configuration vary widely from each other. The reattachment length X_R was obtained by various techniques, namely the total pressure tube, flow visualization and shear velocity measurement

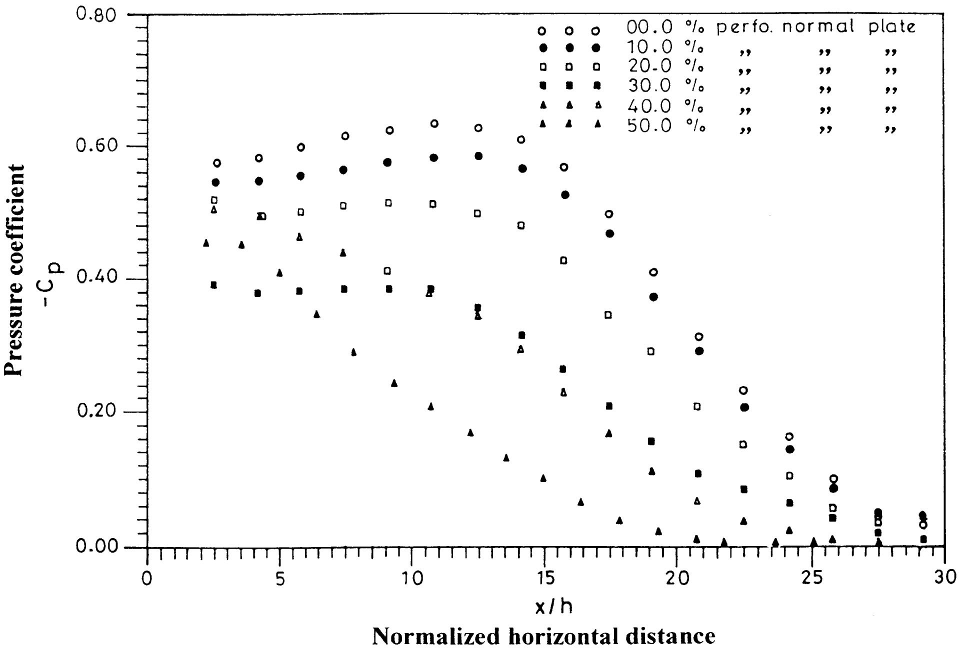

Fig. 9. Mean surface pressure coefficient distribution for different levels of perforation, $U_\infty = 15.0$ m/s.

methods. The shear velocity method gives relatively much lower values of X_R than that obtained by the flow visualization technique. The total pressure tube method also shows variation tendencies compared to flow visualization results. The reason may be that the presence of the pressure probe tube may disturb the flow in the reattachment region and X_R may change depending on the magnitude of disturbance.

The shape and size of the bubble vary with different levels of perforation of the normal plate, that is to say the bubble gets reduced both in height and length up to 30% perforation level. For higher perforation of the normal plate the bubble is completely swept out. As the perforation of the normal plate is increased; the bubble gets detached and undergoes change in shape and size and is pushed gradually downstream. As a consequence of this, vital changes are brought in the flow field that necessitate measurement of other flow characteristics and their behavior.

The method proposed by Fricke [7] is shown to hold good in the present experiments in relating C_{pt} values and X_R/h values.

The trend of mean pressure recovery is the same for normal plate perforation levels of 0%, 10%, 20% and 30%, where the pressure first decreases and then increases. However, for the 40% and 50% perforation levels of the normal plate, the pressure recovery is through monotonic rise. This could be attributed to the non-existence of the recirculating bubble region. By making use of the modified pressure

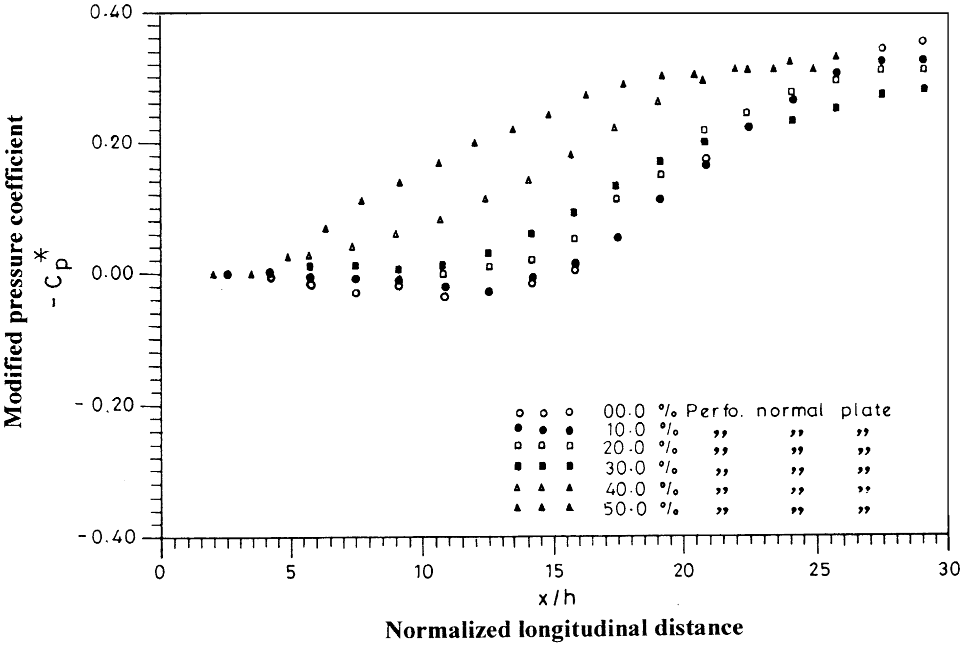

Fig. 10. Mean modified pressure coefficient distribution for different levels of perforation, $U_\infty = 15.0$ m/s.

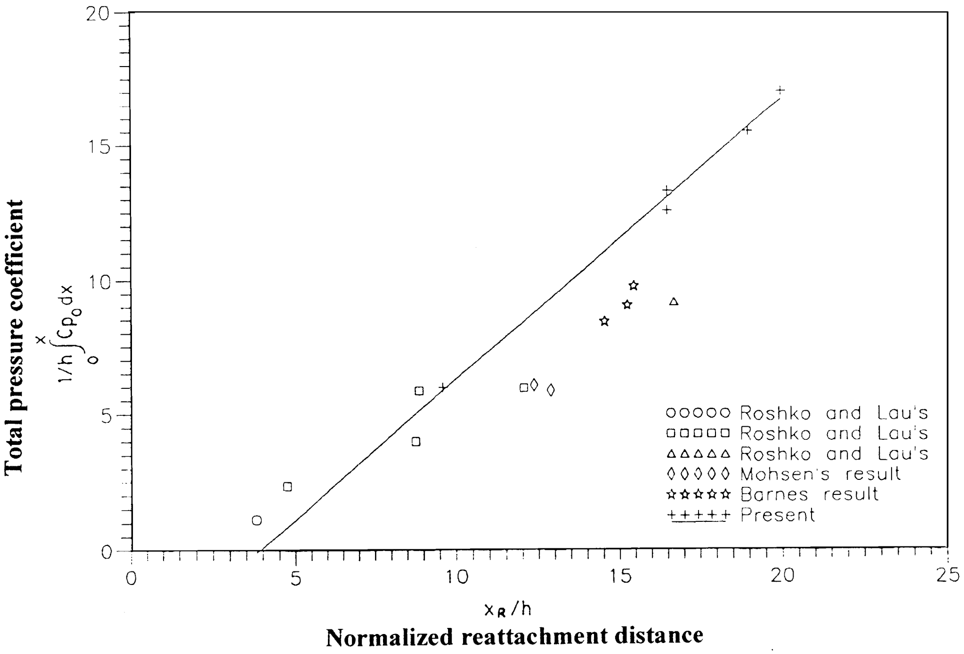

Fig. 11. Relation between the static pressure coefficient C_{pt} and non-dimensionalised reattachment length.

coefficient proposed by Roshko and Lau, it is observed that the data pertaining to normal plate perforations of 0%, 10%, 20% and 30% collapse to one curve indicating the importance of the separation dynamic pressure in controlling the pressure recovery to reattachment. The normal plate data for perforation levels 40% and 50% do not collapse on the universal curve of Roshko and Lau, the likely reason being the non-existence of the recirculating bubble.

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