The Use of a Tolerant Wind Tunnel for Bluff Body Testing

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By Miss K. M. De Coteau

Abstract

The Tolerant wind tunnel is a passive form of low-boundary correction test section, designed to produce low correction data for a wide variety of shapes of different sizes, at an optimum open area ratio (OAR). In its configuration here, for use in bluff body testing, the upper and lower plenum floor boundaries consist of evenly spaced aerofoils at zero incidence. The spacing is chosen so that the outer streamlines of the test section can pass into the plenum chambers and return to the test section in such a way that the overall streamline closely resembles the corresponding free air pattern. Experiments with flat plates normal to the flow, and of different sizes indicate the existence of an optimum test section configuration around OAR = 0.62. Experiments further suggest a maximum allowable blockage in the Tolerant wind tunnel would be equivalent to a flat plate of between 26 and 27%.

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1. Introduction

The use of wind tunnels in the engineering industry is of paramount importance. They are employed in almost every sphere of engineering for both aeronautical and non-aeronautical testing, and hence, the wind tunnel is an invaluable tool for collecting aerodynamic data. It is for this reason that wind tunnels need to be as cost effective and efficient as possible to build and operate. It is also essential that the tunnel interferes as little as possible with the flow of air around the model under investigation.

Unfortunately, due to the very nature of its construction, the wind tunnel imposes on the air flow boundary conditions which would not exist if the model were tested in "free air", i.e. unconstrained flow.

In closed jet tunnels (that is tunnels with completely solid boundaries surrounding the test model), the streamlines are squeezed together with the result that the effective velocity is increased, and so the measured loadings are too high; conversely, in open jet tunnels (i.e., those with **no** boundaries surrounding the test model), the streamlines display a tendency to over-expand, hence the effective velocity is decreased, and the measured loadings are too low. It becomes necessary therefore to "subtract out" these extraneous forces by applying various corrections to the test data obtained.

The effect of the flow constraints is more pronounced with increased model size, and this leads to difficulties, since it is desirable to test as large a model as possible for greater geometrical accuracy and to allow for the use of large enough Reynolds numbers. Furthermore, non-aeronautical testing applications usually involve separated flows with broad wakes which present other problems in that the corrections for these boundary effects cannot be calculated with the same accuracy possible in streamlined flows, since wake conditions are unpredictable. These problems are the main reasons for the particular interest in bluff body testing, and there is a great need to keep the necessary corrections as low as possible.

The solution of building very large tunnels is unsatisfactory, as they are expensive both to build and operate, and would therefore be unsuitable for use, for example in university laboratories.

Added to this is the fact that the use of correction procedures still limits the test model size to prevent having to make corrections which are of the order of magnitude of the data.

One alternative being investigated involves making use of the fact that the corrections for closed and open jet tunnels are of opposite signs, so that low corrections could result from partly-solid, partly-open boundaries.

This condition may be achieved actively by adjusting the flow through a feedback system using distributed boundary suction or a configuration of flexible walls. Alternatively, the flow streamline can be made to approach the free air pattern using a single configuration of the test section to test a wide range of model shapes and sizes as has happened in transonic wind tunnel testing.

Here, use has been made of patterns of holes or longitudinal slots in the walls. This same practice has been successfully used in recent designs for automotive wind tunnels [1]. The disadvantage of these configurations is the occurrence of multiple jet flows through the slots, the pressures of which cannot be predicted, and as such, suitable slot open-area ratios must be determined empirically.

An alternative to this approach is the use of the Tolerant wind tunnel [2, 3, 4 and 5], which has been developed for the two-dimensional testing of bluff bodies and aerofoils.

The aim then, of this work was to study the performance of the so-called "Tolerant" wind tunnel (i.e. a wind tunnel fitted with low correction walls fitted) when used for the testing of two-dimensional bluff bodies. In this case, as distinct from the more conventional system with longitudinal slots, the open area consists of the lateral spaces between aerofoils of small chord relative to the section dimensions and set to span the width of the tunnel.

The effect of different open-area ratios arising from different wall configurations, i.e. open jet, closed jet and partly-solid, partly-open jet is also investigated through measurements of pressure distribution and the mechanism of flow through the Tolerant test section is studied through flow visualisation.

A secondary aim of this work was to compare the results with those obtained by Professor Parkinson and Michel Hameury of the University of British Columbia, who first used a Tolerant wind tunnel of similar construction to test flat plates and circular cylinders (both with and without splitter plates attached).

This paper will present the experimental approach and gives the findings that result from the tests on the Tolerant wind tunnel system as used for two-dimensional flat plate testing.

This work was undertaken as an undergraduate research project at the City University, London in October 1991 - May 1992.

1.1 Study of the Mechanism of Flow Around Bluff Bodies in the Tolerant Wind Tunnel

In order to explain the mechanism of flow around bluff bodies in the Tolerant wind tunnel, it is first necessary to give a clearer indication of what is meant by the term "bluff body".

Bluff bodies then, are characterised by the fact that the flow past them generally forms well-separated turbulent wakes which originate from the detaching of the flow from the body surface.

Also note that for a two-dimensional bluff body, the separation points are fixed and are independent of the Reynolds number if salient points or sharp edges are responsible for flow separation. This contrasts sharply with the case of a well-rounded body, where the position of separation points will move according to surface roughness, whether or not the boundary layer is laminar or turbulent, and Reynolds number.

The Reynolds number will also have an effect in determining the behaviour of the shear layers downstream of the body. At low Reynolds numbers, the shear layers come together to create a situation in which a pair of vortices remains stationary behind the body. Above a critical Reynolds number value, the shear layers will become unstable at some distance downstream. They will then break up and form discrete vortices which proceed to move downstream at a slightly lower value than that of the main flow. As the Reynolds number increases, the break up of the vortex layers occurs closer to the body. At the back of a solid body, the vortices will be shed alternatively with the result that a double row of vortices will occur downstream, in which each vortex is opposite the mid-point of the interval between two vortices in the opposite row.

The qualitative effects of wall confinement on bluff bodies is detailed by many authors, one of whom is Pope [6]. The effects most relevant to this piece of work may be summarised as follows:-

1. Horizontal Buoyancy: A variation in the static pressure along the test section which produces a drag force known as horizontal buoyancy. This effect is usually small and occurs in the drag direction in closed test sections. This effect is negligible in open jet sections.

2. Solid Blocking: This is a lateral constraint on the flow pattern about the body. It is a result of the restriction, by the walls of the tunnel, of the lateral expansion of the streamtube. Its effect can be predicted using the principle of Conservation of Mass (Continuity), which correctly predicts an increase in the velocity around the model. Note that solid blockage in an open jet tunnel is of a smaller value, and of opposite sign.

3. Wake Blockage: This is a lateral constraint on the flow pattern about the wake, and the effect increases with an increase in wake size. In a closed section it will also increase the drag of the model and the effective velocity around it.

Thus, as a consequence of wall confinement, local velocities and therefore pressure values are all greatly altered, usually resulting in a higher drag and lower pressure coefficient than would otherwise be obtained in unconstrained flow.

It is thought that by "ventilating" the tunnel in the manner already outlined, these effects will be considerably reduced, or even eliminated, hence making the need for data corrections redundant.

1.2 The Origin of the Theoretical Base Pressure Distribution

The theoretical base pressure distribution shown in Figs. 3 - 5, is based on that used by Michel Hameury in his doctoral thesis. This is felt to be appropriate since this work is a comparative, as well as an investigative study.

Note however, that these "theoretical" pressure values are based on flat plate models with rear chamfered edges, and different blockage ratios from those used here, and it is difficult to obtain a correct base pressure distribution.

2. Design and Construction

The Tolerant test section is a two-dimensional insert designed to act as an alternative working section for an existing low speed, closed working section, open-circuit wind tunnel at the City University. It is made of wood, being 550mm wide x 400mm deep in cross-section and 1.970m long. Modifications to the existing wind tunnel consist of an inserted nozzle and diffuser section in addition to the 400 x 550mm test section.

The test section has two solid panels as side walls, while the walls above and below the model are changeable. The different walls occur in pairs (one to act as a floor for the upper plenum chamber, and the other to act as a floor for the lower plenum chamber), and may be completely solid, completely open, or "ventilated", i.e. consisting of horizontal, symmetrical, aerofoil-shaped wooden slats at zero incidence. Thus three separate open-area ratios can be created for test purposes.

The aerofoil-shaped slats are of section NACA 0015 and chord 70mm. They are set at zero incidence for ease of experimentation, but the angle of incidence of the slats may be adjusted, should this become necessary to prevent any flow separations from them. The slats are uniformly spaced (Fig. 1), so that the outer streamlines of the test section flow can pass into the plenum chambers and return to the test section downstream in such a way that the overall pattern closely approximates the corresponding free air pattern.

The design is a passive one in that a fixed optimal ventilated wall configuration comprising six aerofoil-shaped slats which produce an open-area ratio (OAR) of 0.58, is used to test all models. It is of fixed overall geometry and only the open-area ratio is varied for flat plates of different blockage ratios.

The test section is equipped with a total of 14 pressure tappings: 2 positioned on the solid floor centre line upstream, 9 along one of the side walls at the half height line, and a further 3 positioned on the solid floor, at the centre line position downstream of the model.

Three two-dimensional flat plates were tested. The heights of the plates were: 40mm (1.57ins), 85mm (3.35ins) and 130mm (5.12ins), which correspond to blockage ratios of 10.0%, 21.25% and 32.50% respectively. The 40mm and 85mm high models were made of steel, whilst the largest was made of steel, covered with wood, and had steel tongues to enable it to fit the turntable slots.

Each model features 14 pressure tappings: 7 on the upstream face, 5 on the downstream face, 1 at the mid-section position on top of the model, and 1 at a corresponding position on the bottom of the model. Mid-section tappings were placed on the front and rear of the model and the remaining tappings on each face were distributed equally from this datum position. The pressure tappings on the top and bottom of each plate served to ensure that the model was straight, and not inclined at an angle to the flow. By checking that the manometer readings at these stations were equal, the straight positioning of the model was possible.

The models were mounted vertically on a turntable, across the centre plane of the wind tunnel, and 710mm downstream of the upstream flange of the test section, so that they were normal to the flow.

Each test was carried out at Reynolds numbers of about 10^5, based on the heights of the plates. Actual values varied slightly, but this is not thought to have affected the results, as flat plates of this kind are relatively insensitive to such changes in Reynolds number.

Tunnel speed was determined using pressure readings from a Pitot-static tube mounted at the half height position of the side wall bearing the other pressure tappings, and being positioned at the test section entrance, 350mm downstream of the upstream bell-mouth flange.

The Pitot-static tube and each of the tunnel and model pressure tappings were connected to a liquid-in-glass multitube manometer using adapters and plastic tubing.

2.1 Testing Procedure

The testing procedure consisted of basically three phases:

1. test section calibration - to ensure that the velocity along the length of the tunnel is constant with each of the different wall configurations in place.
2. model surface pressure measurements, and
3. flow visualisation.

For the first phase of testing, the solid walls were inserted in the tunnel, producing an OAR of zero. The tunnel wall pressure tappings were connected to the manometer, and the tunnel was run at a wind speed of approximately 10 m/s, the speed required for the largest flat plate model (h = 130mm) to produce a Reynolds number of 10^5. Pressure values at each of the tappings along the length of the tunnel, as shown on the manometer were noted. The procedure is repeated with the open (OAR = 1), and then the ventilated (OAR = 0.58) walls in place.

The tunnel was allowed three to five minutes, depending on unsteadiness, to equilibrate, so that reproducible pressure coefficient values were obtained as far as possible.

For model surface pressure measurements, the models were mounted in the tunnel, in order of size, from the smallest to the largest. Positioning of the model always took place with the solid walls inserted, so that set squares could be used to help ensure the model was straight, and not inclined at an angle. As a consequence, the first test for each model was conducted using the solid wall configuration.

The solid walls were replaced with the open walls to obtain a new OAR, and testing began again. Finally, the ventilated walls were inserted, and a final set of test data recorded.

The cycle continued by modifying the wall configuration, and mounting another plate of a different size corresponding to a different blockage ratio, and the same measurements were taken again for the complete set of wall configurations.

A sample of results from the tests described above is shown in Figs.3, 4 and 5. The results of pressure measurements are shown for the three blockage ratios, at each of the three separate OAR's.

Finally, smoke flow visualisation was undertaken using heated-oil smoke introduced to the tunnel, which was run at about 10m/s. The flow visualisation was carried out with the ventilated walls only, the smoke being introduced 135mm downstream of the upstream bell-mouth flange. Flow patterns were recorded simply through sketches (Fig. 6).

3. Discussion

An OAR of 0.58 (i.e. approximately 0.60) was chosen for the "ventilated" tunnel tests. This value was selected on the basis of Michel Hameury's work, and especially on the basis of Figs. 8 and 10, which clearly indicate that an optimum OAR for this type of work lies somewhere in the 0.60 region.

The normal flat plate of 32.5% blockage demonstrated an effective size limitation on test models of bluff bodies. This type of anomaly was also observed by Michel Hameury at the University of British Columbia, when the model was placed in the upstream position (Fig. 8).

The anomaly appears in that:

1. The mean C_P for OAR = 1.0 is not in order of model blockage as would be expected (see Figs. 8 and 10).
2. The mean C_P for the model of 32.5% blockage is very much dependent on model position (see Figs 8 and 10).

Figs. 3 - 5 demonstrate that the Tolerant tunnel configuration for two-dimensional bluff body testing using a fixed OAR = 0.58, gives a good collapse of C_P - distribution data from the three sizes of test model, unto, or very close to the reference curve representing unconfined flow conditions. On the other hand, the C_P - distributions obtained for the same models in the presence of conventional solid and completely open walls are seen to deviate considerably from the theoretical distribution indicating the need for larger corrections.

The tunnel does not appear to be long enough to effect a reasonable pressure recovery, and this is indicated by the fact that for any one blockage ratio, the final static pressure value is considerably lower than the initial value. The re-entry of the flow caused by the sudden end of the plenum chambers, which is obviously more important at higher blockage ratios, where more air is deflected into the chambers, is responsible for an artificial shortening of the ventilated walls. This is clearly of fundamental importance, since the available length of the test section can become a limiting factor when trying to determine the maximum allowable blockage ratio.

The use of a slotted wall configuration in the Tolerant wind tunnel creates a situation in which simulation of unconfined flows is possible around models of quite large blockage ratios. To achieve this, the plenum floor limiting streamlines are allowed to separate as free shear layers, and flow downstream, behind the array of slats, into the plenum chambers in which they take a shape which in turn influences the nature of the flow around the Tolerant wind tunnel would not seem complete without a look at the flow inside the plenum chambers.

Fig. 6 is a sketch of the observations made during the smoke flow visualisation phase of this work. The flow was seen to enter the plenum chamber at the leading edge of the second upstream slat, and to exit again at the leading edge of the penultimate slat.

The flow around the aerofoil sections of the slats was observed to behave exactly as would be expected for any flow around symmetrical aerofoil, i.e. the flow divides at a point just under the leading edge, and then divides to travel over the upper and lower surfaces of the aerofoil, re-combining at the trailing edge.

Flow in the plenum chambers was observed to assume a swirling vortex configuration. The fact that the vortex was somewhat elongated indicates that there is a steady efflux, and that the flow is not dominated by the base of the plenum chamber.

The flow around the plates behaved as expected, separating at the front of the model to form a turbulent wake downstream, at the base of the model. Unfortunately, the angle of the flow through the aerofoil slats could not be clearly established.

The results of the tests carried out at the City University compared favourably with those obtained by the University of British Columbia. A comparison of Figs. 7 and 8 shows how the curves obtained by the separate institutions converge, although not at a single optimum OAR value.

Fig. 9 compares mean C_P against blockage ratio curves for the two institutions, at OAR = 0.58. Once again, the results agree quite well.

Inevitably, there are differences. These are attributable to the fact that different blockage ratios and different flat plates (British Columbia's flat plate models had rear chamfered edges) were used.

4. Concluding Remarks

From this series of tests, and the comparison with the University of British Columbia's results, it is concluded that the Tolerant wind tunnel is a very powerful tool, and is deemed to be successful in that low correction data was obtained.

A few minor modifications are required, but further tests should firmly establish the parameters about which uncertainty still exists.

For instance, two of the three models used point to an optimum OAR in the region of 0.62. The fact that the largest model (h/H = 32.5%) indicates an optimum OAR of 0.76, shows that the maximum permissible blockage ratio for this Tolerant wind tunnel test section is obviously a lower value, and the actual value may be established through a further series of experiments using flat plates of blockage ratios perhaps 26 to 27%.

The Tolerant test section used for this series of tests is not long enough to effect a reasonable pressure recovery, after the pressure value falls to a minimum at the base of the models. However, the length of the test section is of fundamental importance when determining the maximum allowable blockage ratio. Hence, care should be taken when in establishing this dimension.

It was encouraging to note the formation of a swirling vortex in the plenum chambers, as it indicated that there was a steady efflux through the test section.

Owing to the limited range of this work, the possibilities for its furtherance are quite extensive. A first step must be to establish the correct length of the test section, so that the pressure recovery is as complete as possible. Alternatively, the use of some form of suction, just upstream of the collector is suggested to facilitate pressure recovery. The optimum OAR and maximum blockage ratio values must also be finally established.

Acknowledgement

The author would like to thank the staff of the Centre of Aeronautics at the City University for granting their permission to publish this paper. Special thanks are also due to Professor Parkinson of the University of British Columbia for making the results of his work available to us.

Notation

C_P	Pressure Coefficient
c_{p_b}	Base Pressure Coefficient
h/H	Model Height / Test Section Height = Blockage Ratio

OAR	Open-Area Ratio = $\frac{a}{a+c}$, where:-
	a = length of the space between the aerofoil slats
	c = the chord of the aerofoil
	Model Height

References

1. **Raimondo, S. and Clark, P.J.F.**

   Slotted Wall Test Section for Automotive Aerodynamic Test Facilities

   AIAA 12th Aerodynamic Testing Conference, March 1982, Williamsburgh, Virginia, U.S.A,

   Paper AIAA - 82 - 0585 - CP

2. **Parkinson, G.V.**

   A Tolerant Wind Tunnel for Industrial Aerodynamics

   Journal Wind Eng. and Ind. Aero., 16, 1984, pp 293-300

3. **Hameury, M.**

   Development of the Tolerant Wind Tunnel for Bluff Body Testing

   PhD Thesis, Dept. of Mechanical Engineering, The University of British Columbia, February 1987

4. **Parkinson, G.V. and Hameury, M.**

   Performance of the Tolerant Tunnel for Bluff Body Testing

   Journal Wind Eng. and Ind. Aero., 31, 1988, pp 11-18

5. **Williams, C.D. and Parkinson, G.V.**

   A Low-Correction Wall Configuration for Airfoil Testing

   Proc. AGARD Conf. 174 on Wind Tunnel Design and Testing Techniques. London, pp 21.1-21.7,

   March 1986

6. **Pope, A.**

   Wind Tunnel Testing

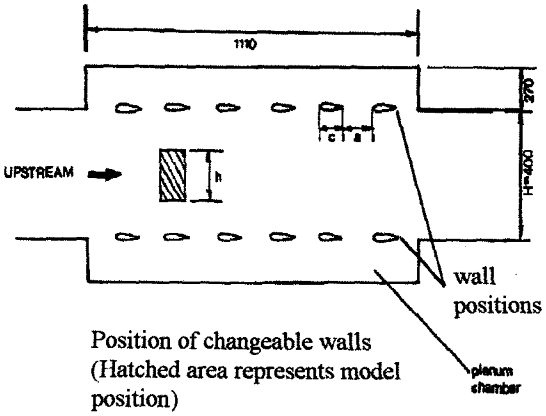
   John Wiley and Sons, Second Edition, 1954

7. **Garner, H.C., Rogers, E.W.E, Acum, W.E.A and Maskell, E.C.**

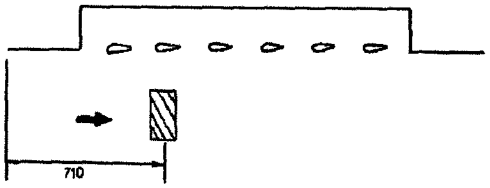
   Subsonic Wind Tunnel Wall Corrections

   AGARDograph 109, 1966

Figures



Position of changeable walls
(Hatched area represents model position)



Position of flat plate model in tunnel (in terms of distance from upstream bell-mouthed flange)

Fig 1. (All dimensions in mm; *not* to scale)

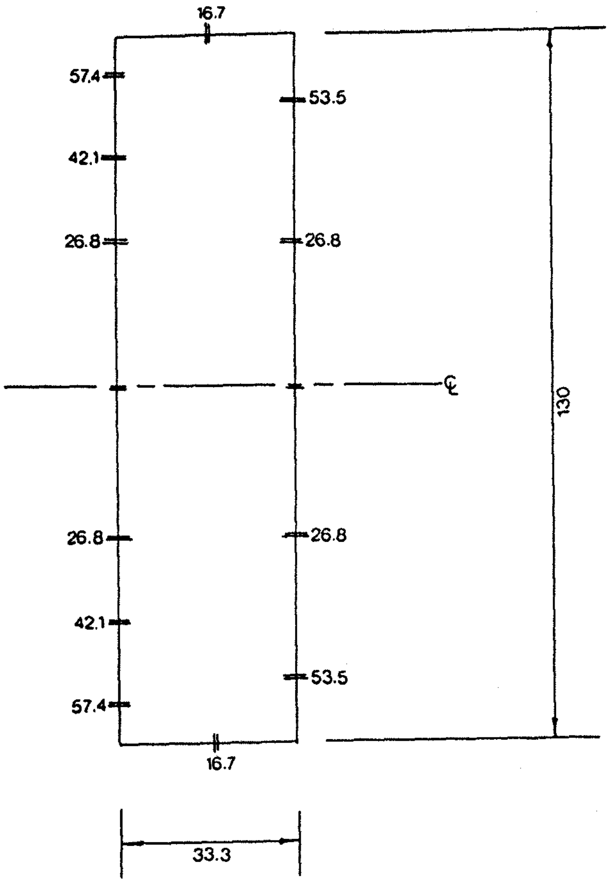


Fig 2. Largest flat plate model:
h/H = 32.5%

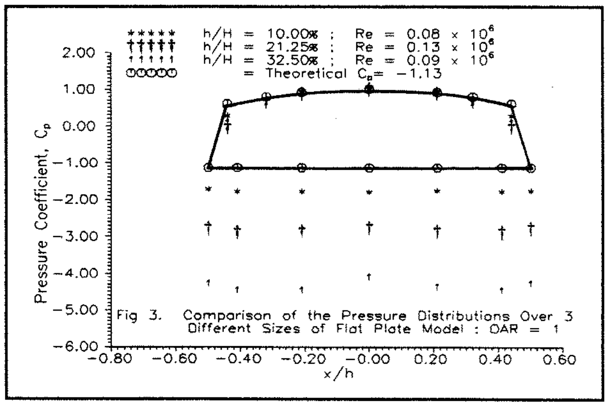


Fig 3. Comparison of the Pressure Distributions Over 3 Different Sizes of Flat Plate Model : OAR = 1

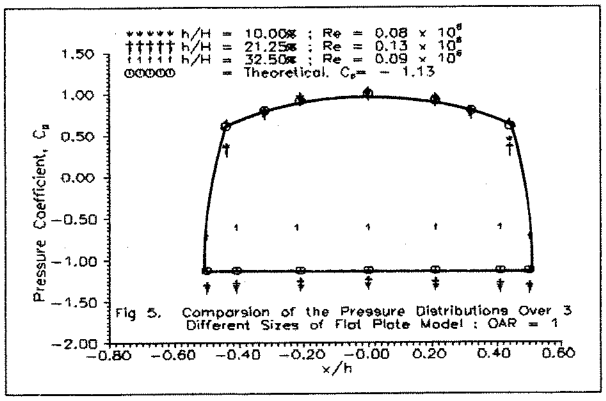


Fig 5. Comparsion of the Pressure Distributions Over 3 Different Sizes of Flat Plate Model : OAR = 1

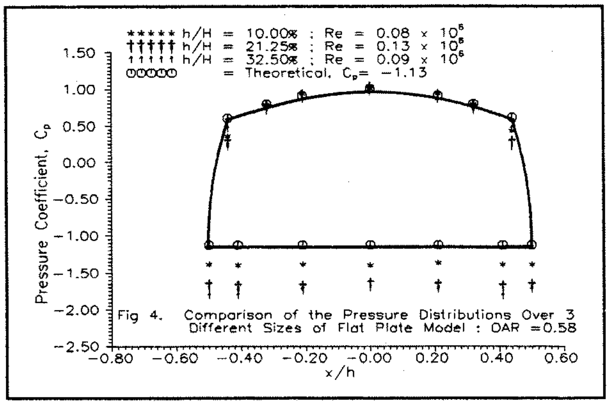


Fig 4. Comparison of the Pressure Distributions Over 3 Different Sizes of Flat Plate Model : OAR =0.58

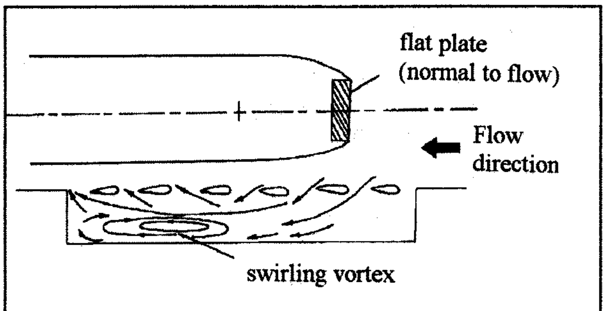


Fig 6. Flow Visualisation Sketch

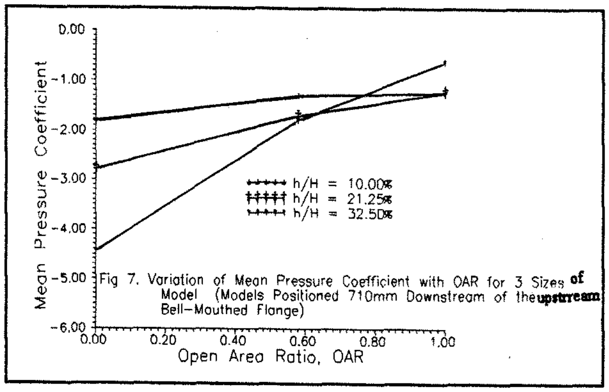


Fig 7. Variation of Mean Pressure Coefficient with OAR for 3 Sizes of Model (Models Positioned 710mm Downstream of the upstream Bell-Mouthed Flange)

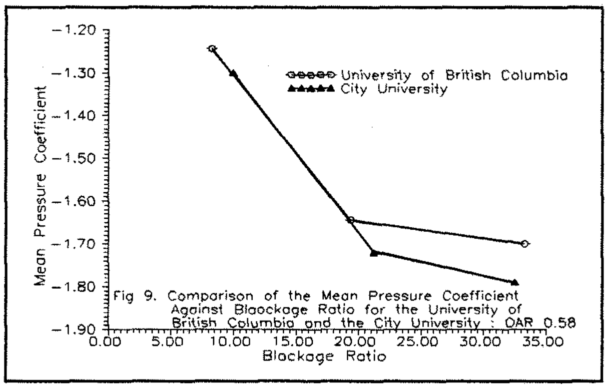


Fig 9. Comparison of the Mean Pressure Coefficient Against Blaockage Ratio for the University of British Columbia and the City University : OAR 0.58

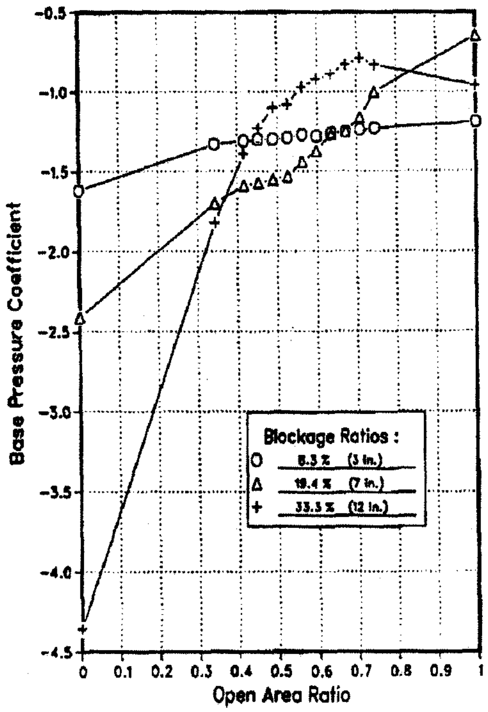


Fig 8. Variation of base pressure coefficient as a function of OAR for 3 sizes of flat plate model positioned 22 inches upstream of centre
(from Ref [3])

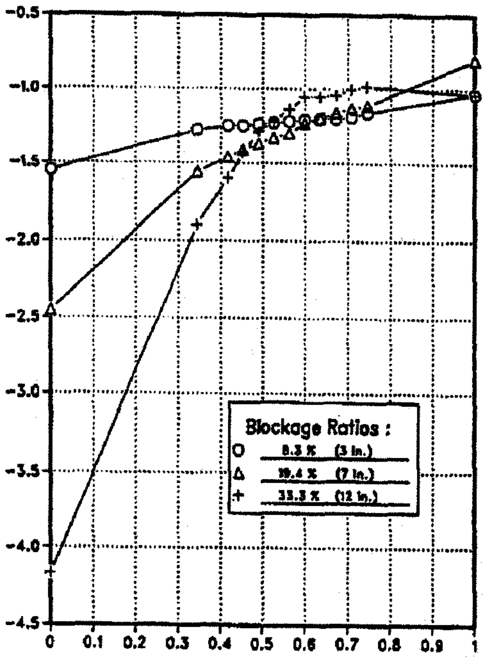


Fig 10. Variation of base pressure coefficient as a function of OAR for 3 sizes of flat plate model positioned at centre
(from Ref [3])