order of magnitude as that of model A. Since buildings in model A have set-backs from the street, the open space between the second and third rows is wider than the corresponding space in model B. It would be presumed that ventilation in lightwells connected to the street space would have higher values in model A than in model B. Velocity measurements prove otherwise, however, as demonstrated in Fig. 3. It is further noticed in Fig. 3 that the velocity in the third row lightwell of model A decays with increasing free stream velocity until it vanishes. This interesting behaviour is attributed to vortices taking place in street spaces (Ghazi 1975).

Model C was considered in order to study the effect of side passages. The only difference between models B and C is that the latter has no side passages. Measurements indicate that ventilation in the back space of the first side passage of model B is 12 times that of C. This is explained by the observation that the first side passage faces the wind directly, while the other passages are exposed to vortex flow, whereby they lose their effectiveness. Velocities at other locations in model B, however, are slightly lower than those in C. The indications are that, introduction of side passages significantly improves ventilation conditions in the first back space, whereas it adversely affects ventilation in the remaining rows.

5 Conclusions

Comparison between airflow measurements on models A and B, which represent detached and attached buildings, respectively, shows that ventilation in back spaces between rows of buildings in model B is superior to that in the narrow back spaces of model A. On the other hand, high airflow is attained in the side spaces of model A. The side passages of model B considerably improve ventilation conditions in the first back space, while marginally affecting the conditions of rear rows of a group of buildings. Furthermore, the airflow in lightwells of model B is not significantly influenced by the presence of side passages.

In conclusion, experimental results suggest that a combination of one frontal attached row with side passages, followed by rows of attached buildings with no side passages would be an arrangement superior to the layouts considered.

Acknowledgements

This work was partly sponsored by Grant AT-5-79 of King Abdulaziz City for Science and Technology (KACST).

References

Aynsley, R. M.; Melbourne, W.; Vickery, B. J. 1977: Architectural aerodynamics. London: Applied Science

Ghazi, M. A. 1975: Experimental investigation of the effect of surface discontinuity on step-backward flow. M.Sc. Thesis, Faculty of Engineering, Cairo University

Givoni, B. 1976: Man, climate and architecture. 2nd edn. London: Applied Science

Mohsen, M. A.; Olwi, I. A.; Ghazi, M. A. 1987: Aerodynamics and ventilation in buildings: Experimental investigation. Solar Wind Technol. 4, 501–507

Olgyay, V. 1963: Design with climate-bioclimatic approach to architectural regionalism. New Jersey: Prinston Univ. Press

Olwi, I. A.; Ghazi, M. A.; Mohsen, M. A. 1988: Wind tunnel simulation of airflow through rows of attached buildings. Solar Wind Technol. 5, 445–450

Penwarden, A. D.; Wise, A. F. E. 1975: Wind environment around buildings. Building Research Establishment Report. London: Dept. of the Environment, Building Research Establishment, Her Majesty's Stationery Office

Received November 6, 1989

On the use of end plates with circular cylinders

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1 Introduction

End plates are often employed in wind tunnel studies in an attempt to ensure that "two-dimensional" flow conditions occur around nominally two-dimensional bluff bodies. Indeed, this technique, which relies upon the reduction of interference effects generated at the fixed ends of the model, has been utilized in numerous investigations involving cylinders of circular crcss-section. A recent example is the work of Kourta et al. (1987).

Despite the widespread use of end plates with circular cylinders, there is only limited information available regarding the specific design criteria to be met when adopting this technique. In the case of effective size and shape parameters, an investigation by Stansby (1974) at Reynolds numbers in the range 1.6×10^4 to 8.0×10^4 established the basic requirements through mean base pressure measurements. The results showed that the plates should be rectangular with an upstream dimension (distance of leading edge from cylinder axis) sufficiently large to isolate the horseshoe vortex generated at the wall-model intersection, but small enough to avoid substantial boundary layer growth on the plate itself, and that the tail dimensions must be adequate to prevent any wake interference. These optimization experiments were, however, carried out at two fixed aspect ratios (length to diameter ratio of cylinder) between end plates of 8 and 16 and did not, therefore, take adequate account of plate spacing. Indeed, many subsequent studies involving circular cylinders have been performed using end plates of the proportions recommended by Stansby (1974) without consideration of the effect of the distance separating the plates.

The experiments reported in this note were designed to determine the effect of end plate spacing upon the mean base pressures and fluctuating lift and drag imposed on a smooth circular cylinder of low area blockage. The tests were performed in a uniform, low-turbulence airflow at Reynolds numbers in the range 3.3×10^4 to 13.2×10^4, which is in the upper subcritical flow regime for a circular cylinder, and therefore complement the previous work of Stansby (1974).

2 Experimental details

The experiments were carried out in the Dept. of Civil Engineering's low-speed closed circuit wind tunnel facility. This has working section dimensions of 1.215 m width × 0.815 m height × 3.5 m length and produces a steady uniform airflow with a freestream turbulence intensity of approximately 0.2%.

The models used in the tests consisted of two long, smooth, polished brass cylinders of 31.7 mm and 44 mm diameter. Each cylinder spanned, in turn, the working section horizontally at mid-height and passed through sealed holes in the vertical walls of the wind tunnel. This arrangement ensured that large aspect ratios could be achieved (38 and 27.5 without end plates fitted) with low area blockage (4% and 6% respectively). Aluminium end plates of the proportions recommended by Stansby (1974) (width of 7 *d*, upstream dimension of 2.5 *d* and distance from the cylinder's axis to trailing edge of 4.5 *d*, where *d* is the cylinder diameter) were used with each model and these were supported from the tunnel wall. The model passed through a tight fitting hole in each plate and the section between the plates was free from all obstructions. The plate spacing was varied through adjustment of the support assembly.

Mean base pressure was measured on the 31.7 mm model by the use of a 1.0 mm diameter surface tapping and the model could be displaced laterally to record spanwise distributions (the symmetry of the pressure field was used for alignment of the tapping at $\theta = 180°$). Pressures were measured by a Betz-type micromanometer, which could be read to within 0.1 mm of water, and a similar arrangement was used for the evaluation of freestream reference pressures. This system produced values of the coefficient of mean base pressure, C_{pb}, to within an accuracy of 1.0%.

Fluctuating lift and drag were measured by an arrangement of surface-mounted miniature pressure transducers at a cross-section of the 44 mm diameter model. The individual output signals were conditioned according to their orientation and summed analogically to give the lift or drag component on the chosen cross-section. Alignment with the flow and exact spanwise location were simply achieved. Values of the coefficient of fluctuating drag, C'_D, and coefficient of fluctuating lift, C'_L, were determined within an accuracy of 6% and 2% respectively through the use of this method.

3 Results and discussion

The spanwise distributions of the coefficient of mean base pressure, C_{pb}, measured at a Reynolds number of 4.4×10^4 for aspect ratios in the range $A = 7$ to 35 are presented for half of the span (symmetry assumed) in Fig. 1, together with the corresponding distribution recorded without end plates. The latter displays gross interference in close proximity to the wall, where the disturbed flow conditions lead to a significant increase in the value of C_{pb}, and a constant value over a short central portion of the span. In fact the distribution clearly shows that the wall interference effects persist to approximately 15 diameters from the fixed end of the cylinder, there being no significant disturbance evident in the region $|y/d| < 4$. This result suggests that if the aspect ratio of the cylinder between the tunnel walls is greater than 30, it is not necessary to use end plates to achieve "two-dimensional" conditions at the centre of the span.

The addition of end plates to the cylinder results in a similar central region of constant base pressure when the aspect ratio between the plates is above a critical minimum of 7. The base pressure distribution associated with the latter spacing displays variation along the whole span and is due to the merging of the interference effects generated by each plate. However, if the spacing is above this critical value, the distributions resemble those recorded for aspect ratios of 8 and 16 by Stansby (1974) at approximately the same Reynolds number with a central region of "two-dimensional" conditions and interference effects confined to the proximity of the plates.

Although Fig. 1 shows that the interference to base pressure is generally restricted to a spanwise length of 3.5 *d* for all aspect ratios when end plates are fitted, there are second order effects beyond this region in the results taken for aspect ratios of 28 and 35. These second order variations are, however, within 2% of the value of C_{pb} recorded at the centre of the span and can reasonably be ignored. Thus, the spanwise length of the central region of "two-dimensional" flow conditions is seen to be linearly related to the aspect ratio of the cylinder between the end plates. This result is consistent with the findings of Toy and Fox (1986) in the case of similar mean base pressure distributions recorded on a cylinder of square cross-section fitted with end plates at various aspect ratios.

A number of previous authors, including Stansby (1974) and Kourta et al. (1987), have noted a decrease in the value of C_{pb} at the centre of a circular cylinder upon the addition of end plates. However, such tests were carried out with cylinders of aspect ratio less than 30 between tunnel walls and, therefore, the base pressure at the centre-line would not have achieved a "two-dimensional" value without plates fit-

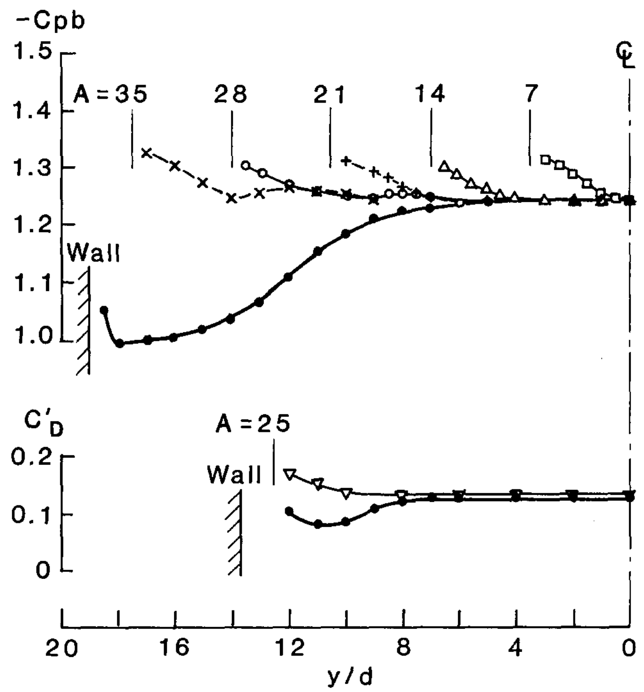

Fig. 1. Spanwise distributions of the coefficient of mean base pressure and coefficient of fluctuating drag measured at a Reynolds number of 4.4×10^4 with and without end plates fitted at aspect ratios in the range $A = 7$ to 35

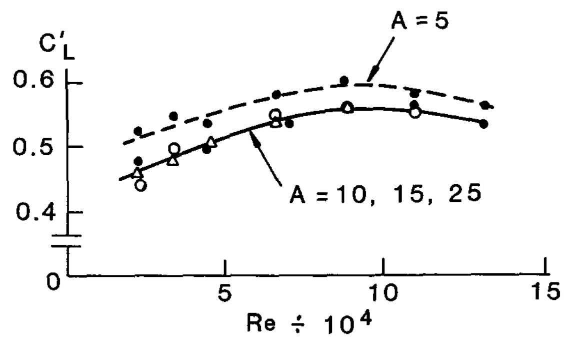

Fig. 2. Variation of the fluctuating lift coefficient at the centre of the cylinder fitted with end plates for Reynolds numbers in the range 3.3×10^4 to 13.2×10^4 and aspect ratios of $A = 5$ to 25

ted. The results presented in Fig. 1 show that the addition of end plates to a long enough cylinder has no effect upon the value of C_{pb} at the centre of the span.

Figure 1 also presents the spanwise distribution of fluctuating drag measured on the 44 mm diameter cylinder with and without end plates fitted at an aspect ratio of 25. The results are generally similar in shape to the mean base pressure distributions discussed above and the spanwise extent of the interference effects associated with the plate is confirmed as 3.5 *d*. However, given that fluctuating drag is particularly susceptible to secondary influences, it is of interest to note that the "two-dimensional" condition without end plates is larger than that based on mean base pressures.

To examine the effect of end plate spacing upon the fluctuating lift imposed on a cylinder, this component was determined at the centre-line of the 44 mm model for a comparable series of aspect ratios. The results are presented in Fig. 2 for Reynolds numbers in the range 3.3×10^4 to 13.2×10^4. From these it is clear that the lift coefficient exhibits a degree of Reynolds number dependency, this being consistent with the data obtained by Surry (1972) and Sonneville (1976). However, the results also show that at aspect ratios greater than the critical value of 7, all coefficients of lift for a given Reynolds number lie on a single curve, whereas the values for aspect ratios less than 7 are as much as 15% greater, thereby emphasizing the importance of testing at the correct plate spacing.

4 Conclusions

The experiments described in this note have identified criteria for the use of end plates to achieve "two-dimensional" flow conditions around a smooth circular cylinder at Reynolds numbers in the upper subcritical regime. It was found that if end plates of the proportions recommended by Stansby (1974) are used, then: (i) the aspect ratio of the cylinder between the plates must be greater than a critical minimum of 7 to ensure the presence of a region of "two-dimensional" flow conditions over a central portion of the span; (ii) the interference effects associated with each plate extend over a constant distance of 3.5 *d* from the plate so that the length of the "two-dimensional" region is linearly related to the aspect ratio of the cylinder between the end plates.

In addition, it was found that if the aspect ratio of the cylinder between the tunnel walls is greater than 30, it is not necessary to use end plates to achieve "two-dimensional" conditions at the centre of the span. In such cases, the fitting of end plates to the cylinder makes no difference to the value of C_{pb} recorded on the centre-line.

Acknowledgements

T. A. Fox is a Post-doctoral Research Fellow funded by the Dept. of Civil Engineering, The University of Queensland, and is grateful for this support.

References

Kourta, A.; Boisson, H. C.; Chassaing, P.; Ha Minh, H. 1987: Nonlinear interaction and the transition to turbulence in the wake of a circular cylinder. J. Fluid Mech. 181, 141–161

Sonneville, P. 1976: Etude de la Structure Tridimensionelle des Ecoulements Autour d'un Cylindre Circulaire. Bull. de la Direction des Etudes et Recherches E. de F(A) No. 3

Stansby, P. K. 1974: The effects of end plates on the base pressure coefficient of a circular cylinder. Aeronaut. J. 78, 36–37

Surry, D. 1972: Some effects of intense turbulence on the aerodynamics of a circular cylinder at subcritical Reynolds numbers. J. Fluid Mech. 52, 543–563

Toy, N.; Fox, T. A. 1986: The effect of aspect ratio of end plate separation upon base pressures recorded on a square bar. Exp. Fluids 4, 266–268

Received December 15, 1989