*Building and Environment*, Vol. 12, pp. 223–230. Pergamon Press 1977. Printed in Great Britain

# A Parametric Study of Airflow Within Rectangular Walled Enclosures

F. SMITH*
C. B. WILSON†

*This paper describes a set of velocity measurements which were made within a series of models of rectangular enclosures whose dimensions in plan were varied, the heights of the walls being held constant. The airflow's speed was measured at each of the points of a rectangular grid and the arithmetic mean of these measurements was adopted as a measure of the enclosure's performance in providing shelter from the wind, and was used to compare the effectiveness of one geometry against another. It was found that the degree of shelter could be optimised by a correct choice of geometry.*

## INTRODUCTION

THE WORK on the environmental aspects of the interaction between buildings and the wind may be divided into two categories. The first and most commonly reported kind of investigation is the 'one off' type in which the wind conditions due to a particular building or complex are determined in the context of a specific site. Tests of this type have generally been undertaken as part of the design process or in order to find a remedy in cases where unacceptable wind conditions have been found after the building's construction. Some examples of this kind of work may be found in Penwarden and Wise[1]. Although some broad conclusions may be drawn from such tests, their specific nature tends to limit their value as a source of design information.

The second and perhaps more fruitful type of investigation is one in which, over a series of tests, one or more of the parameters which describe the building are allowed to vary so that the relationship between the form and its performance, in terms of the local conditions it creates, can be deduced. Once determined, such a relationship can serve as a guide to the likely type and magnitude of the changes to the airflow which accompany a change in form.

Presumably because of the amount of testing that is required to deduce form/performance relationships for even the simplest geometrical configurations, few results of interest to the architectural community have been published. The flows due to various combinations of a low- and a high-rise block have been investigated by the Building Research Establishment and results have been published by Wise[2]. The conditions between a pair of parallel blocks at a series of spacings and orientations to the wind have been determined and discussed by Hassan[3]. In this paper, we present results pertaining to the flow within a space enclosed by a thin, rectangular wall whose dimensions in plan were systematically varied, the height being held constant. Results were obtained for cases when the enclosure was orientated at 0, 30, 60 and 90 degrees to the undisturbed flow direction.

Before proceeding to describe the experiments and results, we would like to make some comments about the utility of parametric tests and the spirit in which the data are presented.

A complete appraisal of the environmental effects of the airflow in the vicinity of a building would need to include the following elements:

(i) A fairly detailed prediction of the meteorological conditions likely to be found at the site,

(ii) An accurate wind tunnel simulation of the Earth's boundary layer in the light of (i),

(iii) Detailed wind tunnel measurements of the velocity field (both mean speeds and turbulence) in the spaces under consideration, using a sufficiently accurate model of the building and its surroundings,

(iv) A sufficiently complete knowledge of the physiological and psychological responses of humans to air movements so that the effects of the measured velocities could be interpreted in terms of comfort or other criteria.

If all of this information were available and if the assessment procedure were adhered to, one could reasonably expect to make an absolute judgement concerning the quality of the micro-climate generated by a building, at least in a statistical sense. All the necessary information is not available, however. For example, it is difficult to obtain any but the broadest prediction of the climate at a site unless it happens to be close to a meteorological monitoring station. Additionally, it is presently not possible to simulate the Earth's boundary layer in a wind tunnel unless the vertical variation of temperature follows the adiabatic lapse rate which it rarely does in the moderate winds of interest in micro-climatic design. See Jones *et al.*[4] for a discussion of this point. Finally, human response to the wind is still inadequately understood despite the valuable contributions of several workers, for example Penwarden[5] and Hunt *et al.*[6].

In view of such gaps in our understanding, the best course, at present, seems to be to provide the designer with

---

*Research Fellow, Department of Architecture, University of Edinburgh.

†Professor of Architectural Science, University of Edinburgh.

sufficient information to form relative judgements about possible schemes: that is to indicate which parameters of forms are critical and which ranges of parameters are likely to lead to good or bad performance. We present our results in this spirit and as a demonstration of the value of making form/performance investigations. We have neither attempted to model any particular site or wind condition nor have we tried to develop any sophisticated measure of the observed flow conditions or to relate them to human response. We have simply used the average speed within the enclosure to compare the performance of one geometry with that of another. More sophisticated measures were, however, proposed by Hassan[3]. We have also tried to interpret the data in terms of a phenomenological model of the motions within the enclosure since we believe that this will help the designer to understand them more clearly.

## EXPERIMENTAL PROCEDURE

The diagram given in Fig. 1 shows a typical model and grid of measurement points, together with the nomenclature. In all cases, the height, $H$, of the enclosure walls was 100 mm and measurements were taken 30 mm above the ground plane. The models were made from pieces of smooth planed 50 × 100 mm timber which were cut to a selection of lengths so that the combination of enclosures given in Table 1 could be constructed. The joints between the parts of the enclosure and between the enclosure and the tunnel floor were sealed with masking tape so as to prevent any leakage of air from affecting the results. In cases where the model was rotated at an angle to the flow, it was placed so as to be centrally disposed within the tunnel.

The tests were conducted in the wind tunnel at the Department of Civil Engineering and Building Science, University of Edinburgh. The tunnel is of the straight through, open jet type and has a working section consisting of a platform measuring 1.75 m in the streamwise direction by 1.53 m wide. As the flow enters the working section it is 1.07 m deep.

A velocity profile representative of the atmospheric boundary layer encountered in open country or small towns was produced by the combination of a castellated step, four quarter elliptic wedges and a set of small, randomly orientated blocks placed upstream of the model.

The velocities measured within the models were non-dimensionalised using a reference value, $V_{ref}$, which was taken 30 mm above the centre line of the tunnel at the start of the working table and in the absence of the model. The value was measured both before and after tests were made within each model so as to check against excessive drift in the tunnel speed. If a change of more than 5% was recorded either the whole test was repeated or the results were corrected by assuming the drift to be linear in time.

All velocities were measured by means of a hot wire anemometer which was connected, via a lineariser and an averaging network, to a strip chart recorder. After each movement of the probe, 10–15 s were allowed for transients in the flow and circuitry to damp out and then readings were taken for a further 10–15 s. The mean speed at any point was obtained by taking the average of the trace by eye. A fine thread mounted on a thin metal rod was used to determine the local flow direction so that the hot wire could be orientated normally to it.

The arithmetic mean, $V_{av}$, of the readings over the whole grid was calculated and expressed as a percentage of the reference speed, $V_{ref}$. The ratio was adopted as a measure of the conditions within the enclosure.

## RESULTS AND DISCUSSION

The results of the experiments are presented in Table 1 and are given graphically in Figs. 2, 8, 9 and 10.

*Variation of average speed with length (Fig. 2)*

The graph shows the effect of lengthening the stream-

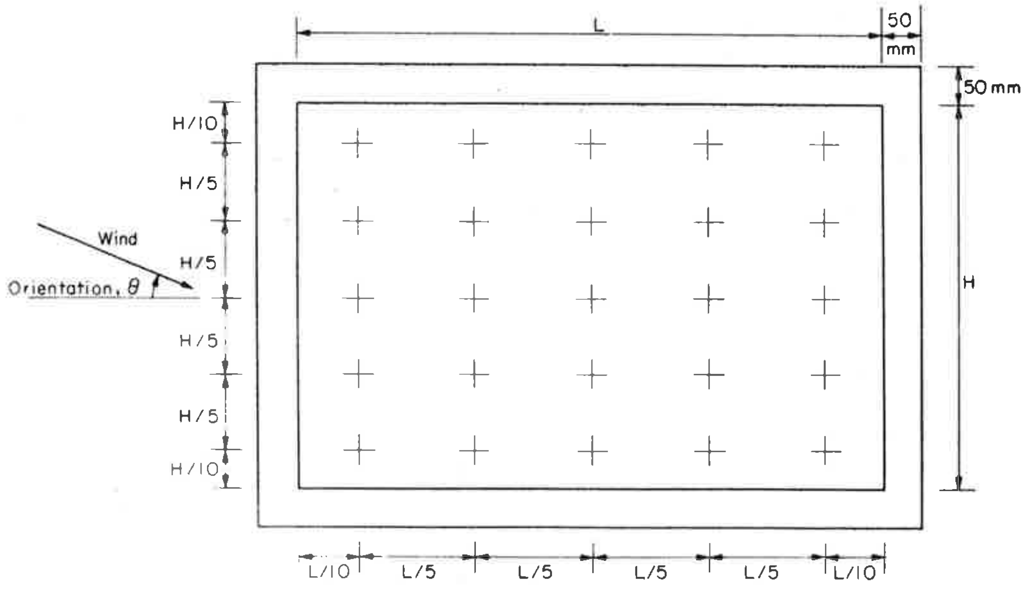

Fig. 1. Sketch of a model enclosure and the grid of measuring points.

**Table 1.** The average wind speed within rectangular enclosures of different sizes and orientations expressed as a percentage of the wind speed

| Length to height ratio, $L/H$ | Width to height ratio, $W/H$ | Orientation, $\theta$ 0° | 30° | 60° | 90° |
|---|---|---|---|---|---|
| 1.0 | 1.0 | 37.2 | | | 37.2 |
| 1.0 | 2.0 | 41.3 | 40.8 | 38.1 | 42.1 |
| 1.0 | 3.0 | 43.1 | 46.1 | 41.5 | 41.0 |
| 1.0 | 4.0 | 45.5 | 44.1 | 59.0 | 35.8 |
| 2.0 | 1.0 | 42.1 | 38.1 | 40.8 | 41.3 |
| 2.0 | 2.0 | 44.3 | 47.2 | 47.2 | 44.3 |
| 2.0 | 4.0 | 48.6 | 49.2 | 45.0 | 37.2 |
| 2.0 | 6.0 | 49.1 | 56.2 | 60.2 | 39.8 |
| 2.0 | 8.0 | 49.8 | 71.0 | 85.0 | 51.1 |
| 3.0 | 1.0 | 41.0 | 41.5 | 46.1 | 43.1 |
| 3.0 | 3.0 | 43.4 | | | 43.4 |
| 4.0 | 1.0 | 35.8 | 59.0 | 44.1 | 45.5 |
| 4.0 | 2.0 | 37.2 | 45.0 | 49.3 | 48.6 |
| 4.0 | 4.0 | 40.7 | 48.7 | 48.7 | 40.7 |
| 4.0 | 8.0 | 42.1 | 57.4 | 59.5 | 39.6 |
| 6.0 | 2.0 | 39.8 | 60.2 | 56.2 | 49.1 |
| 8.0 | 2.0 | 51.1 | 85.2 | 71.0 | 49.8 |
| 8.0 | 4.0 | 39.6 | 59.5 | 57.4 | 42.1 |
| 8.0 | 8.0 | 35.9 | 51.1 | 51.1 | 35.9 |
| 10.0 | 10.0 | 71.6 | | | 71.6 |

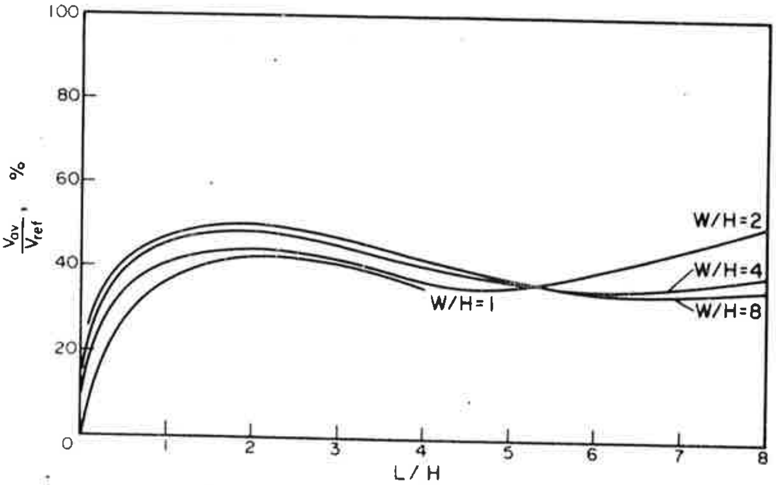

Fig. 2. The effect of length on the average speed in an enclosure at zero orientation.

wise walls of the enclosure in the case when the oncoming flow is parallel to them. Results are plotted for several enclosure widths.

In this figure, as in all the others, the dimensions of the enclosed space are given in terms of multiples of the wall height, $H$.

The curves exhibit several noteworthy features, the most important being the existence of optimal proportions for enclosures of moderate size. It will be seen that, as the length increases, the average velocity within the enclosure first climbs to a local maximum and then drops significantly before finally increasing again at large spacings. This runs contrary to what might have been anticipated intuitively. It might reasonably have been expected that increasing the enclosure's length would have given the wind a progressively greater opportunity to enter the space and that this would have led to correspondingly larger velocities within it. Had this been the case, the degree of shelter afforded by the enclosure could only have been improved by reducing its dimensions. In fact, the data show that, over a considerable range of sizes, shelter can only be increased by enlarging the space. In this sense, the figure shows that the design of enclosures of moderate size, of the kind and in the surroundings investigated, can be optimised with respect to the degree of protection they afford from the wind.

A second point of interest is the way in which the enclosure's width combines with its length to affect the flow. The figure shows that, for $L/H$ greater than about 2, increasing the width tends to stretch out the curves so that a given condition will occur at progressively larger lengths. In particular, the optimum length to height ratio (i.e. the value of $L/H$ at which the average velocity takes its local minimum) increases from 4.6 to 6.0 to 7.5 as $W/H$ is increased from 2 to 4 to 8 respectively. For the designer, perhaps even more important than the change in the optimal condition itself is the change in the enclosure's performance at near optimal dimensions. As the enclosure's width is increased, the stretching results in much flatter curves although the velocity at the optimum is little different. Thus a wide enclosure is able to provide good protection from the wind over a larger range of lengths than a narrower one. It is interesting to note, however, that no matter how wide an enclosure may be, it still produces relatively windy conditions when it is about twice as long as it is high.

Finally, it should be noted that for $L/H$ less than about 5.5, a narrow enclosure affords better protection than a wider one, whilst for longer enclosures the reverse is true.

It is instructive to interpret these results in terms of the flow patterns which produced them. This will be done with reference to Figs. 3–7. Discussion is facilitated by first considering the flows which obtain at very small and very large streamwise spacings and then by working inwards to intermediate lengths.

Figure 3 shows the flow at small spacings. The momentum of the flow passing over the upstream wall is sufficient to carry most of it over the intervening gap and over the downstream wall so that little of it enters the enclosure. By means of friction and the convective transfer of momentum, the external flow is able to endow the air within the enclosure with a recirculating motion of the type sketched in the figure. Of course, a full picture of the motion at small spacings will be more complicated than that outlined above—for example, the friction forces generated at the internal surfaces of the enclosure will undoubtedly affect the nature of the flow as will the presence of the streamwise walls—but it appears to explain the main features of the observed behaviour. In order to test this hypothesis and to investigate the properties of the flow, the simple theoretical model illustrated in Fig. 4 was constructed. The model consisted of an infinite array of vortices, each spaced a distance $L$ from its neighbour in the $x$ direction and $H$ in the $y$ direction. Each vortex had the same strength but the opposite sense of rotation to the one adjoining it. Under these circumstances it is easy to show that the rectangle marked in the figure is a streamline so that the flow within it is that of a vortex which is constrained to move within a box of length $L$ and height $H$. To complete the model, it was assumed that the velocity, $U'$, at the point $(0, H/2)$ (the centre of the top of the rectangle) was invariant of $L$ and that the average speed along the bottom of the rectangle could be taken as being representative of that at any small height above it. The two latter assumptions, which were made to simplify computation, were tested by means of some subsidiary calculations and were found to be sensibly true at all but the smallest values of $L$. The results of calculation with the model using several values of $L/H$ are given in Fig. 5. It will be seen that, despite the gross oversimplification, the results from the model exhibit the same characteristics as those found by experiment in that the average velocity first increases very rapidly with $L/H$ and then begins to fall but this time at a much slower rate. On the basis of this general agreement between the theoretical and experimental curves, it is not unreasonable to assume that the single vortex model explains the measured results for $L/H$ less than about 4.0.

At the other extreme, when the enclosure's length is very much greater than its height, the flow will look very much like that sketched in Fig. 6. If the two walls are sufficiently far apart, the flow between them will be able to settle to a state close to that which it had far upstream of the enclosure and thus will render the flow due to one wall independent of that due to the other. Reference to the literature (see, for example, the *Architects' Journal*[7]) shows that the flow adjoining each wall will then comprise a recirculation zone to the forward face and a somewhat longer wake to the rearward face. Thus, on starting from the rear face of the upstream wall and moving in the direction of the wind, one would first encounter a region of comparative shelter due to the first wall's wake, followed by a region of unabated wind speeds and finally another region of shelter due to the second wall's recirculation zone. Since the flows close to the two walls are mutually independent at large spacings, the dimensions of the zones of shelter are entirely fixed by those of the

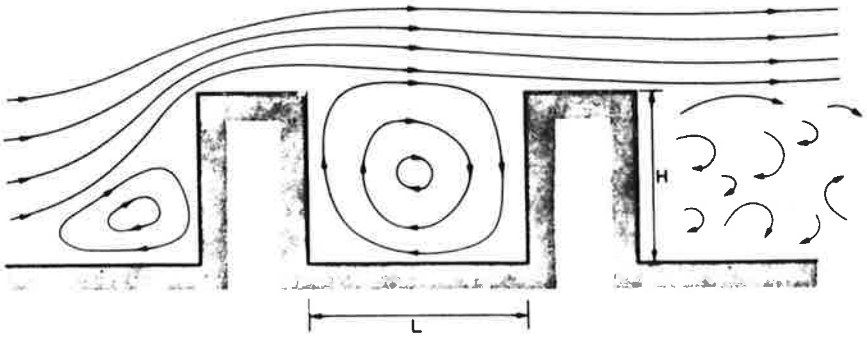

Fig. 3. The flow within enclosures at small length to height ratios.

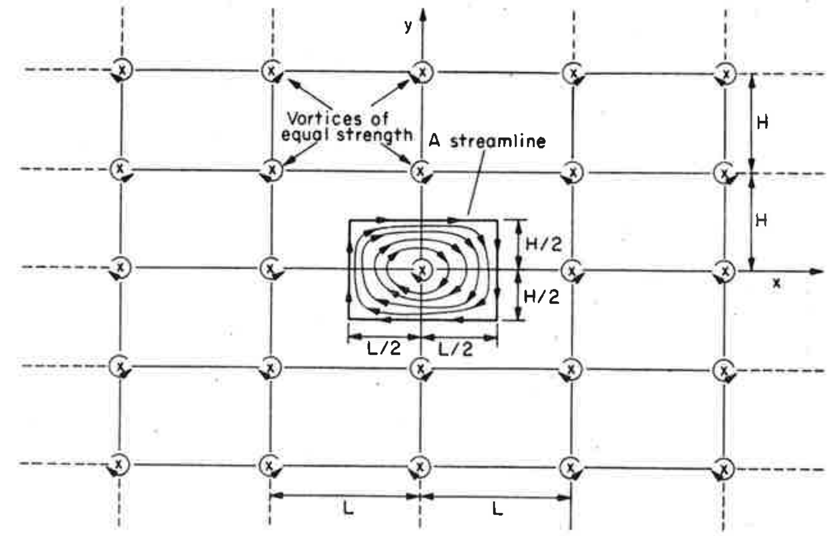

Fig. 4. A theoretical model of the flow at small spacings.

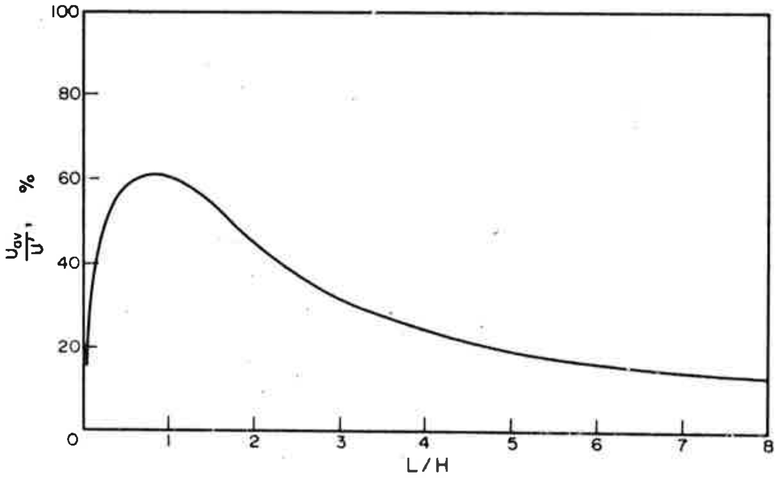

Fig. 5. The effect of length on the average speed on the floor of a box containing a vortex. (Two dimensional, inviscid flow.)

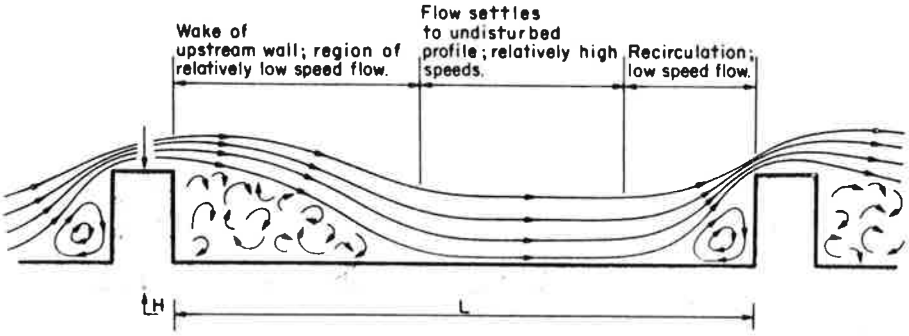

Fig. 6. The flow within enclosures at high length to height ratios.

walls and so any increase in the enclosure's length would simply enlarge the region of high wind speeds and would consequently increase the average speed. By estimating the average speeds within each of the three flow zones, it may be shown that the curve of average speed against $L/H$ slopes upwards but does so at an angle which decreases with increasing length. Unfortunately, the present data do not extend to large enough sizes to show this convincingly.

The flow at intermediate spacings is best understood by considering the events which occur as a large enclosure is progressively reduced in length. At first, a reduction in size will simply result in a contraction of the region of high flow speeds and thus will lead to a reduction of the average velocity. Eventually, however, this region will disappear so that the flows due to the two walls will impinge and become interdependent. Inspection of Fig. 7 shows that their meeting will provide just the conditions needed for the flow to transform itself into one large vortex. Consider the conditions along the line $X$–$X$ where the two zones meet. The opposing motions will tend to cancel each other out so that the speeds found at the interface will be generally much lower than found elsewhere. It is then just a small step for the tops and bottoms of the two vortices to join up with each other to produce the single vortex typical of the flow found at small spacings. It is not difficult to imagine that the cancellation of velocities which produces the change in flow pattern proceeds progressively as the length is reduced so that the transition from one regime to the other is a continuous process. This would then explain why the velocity against length curve passes smoothly from the shape typical of small enclosures to that typical of large ones.

It will be noticed that the foregoing model of the flow is a strictly two-dimensional one and in view of this it is hardly surprising that it could give no indication of the way in which the enclosure's width could combine with the length to influence the flow. In the absence of more detailed experimental data, all that can be done is to hypothesize that the affects of the streamwise walls are limited to within a small distance of them so that, as the enclosure becomes very wide, they play a rapidly diminishing role in the flow as a whole. This hypothesis can be tested with reference to Fig. 8.

*Variation of average speed with width* (*Fig.* 8)

Figure 8 shows the variation of the average speed within an enclosure with its width for several cases where the length is held constant. The curves confirm the foregoing hypothesis in as much as the velocity varies little once the enclosure's width is more than about four times its height.

*Variation of average speed with orientation* (*Figs.* 9 *and* 10)

So far the discussion has centred on the special cases where the wind blows parallel to one pair or other of the

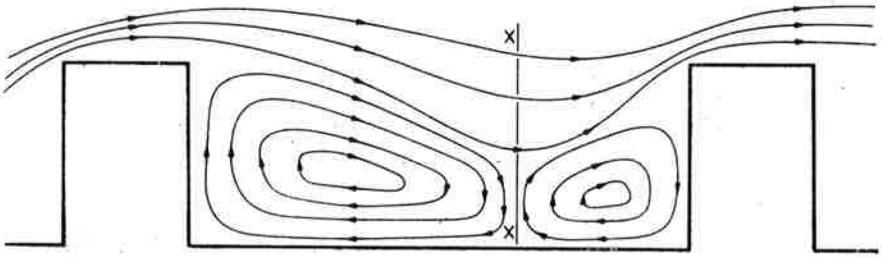

Fig. 7. Diagram of the flow at moderate spacings.

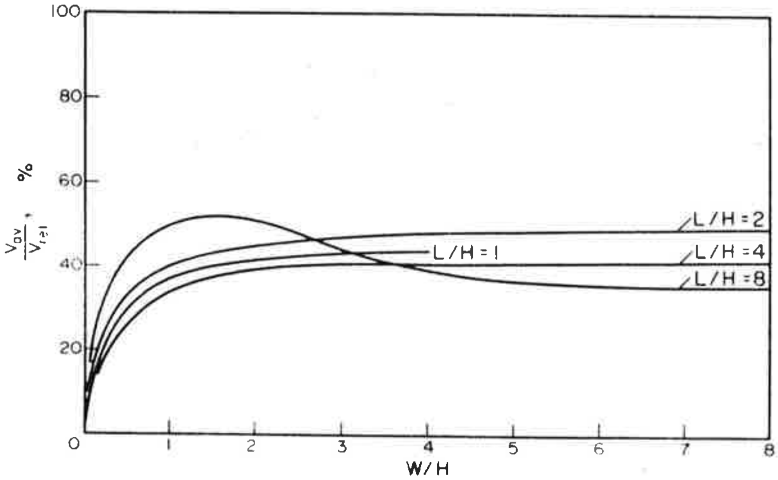

Fig. 8. The effect of width on the average speed in an enclosure at zero orientation.

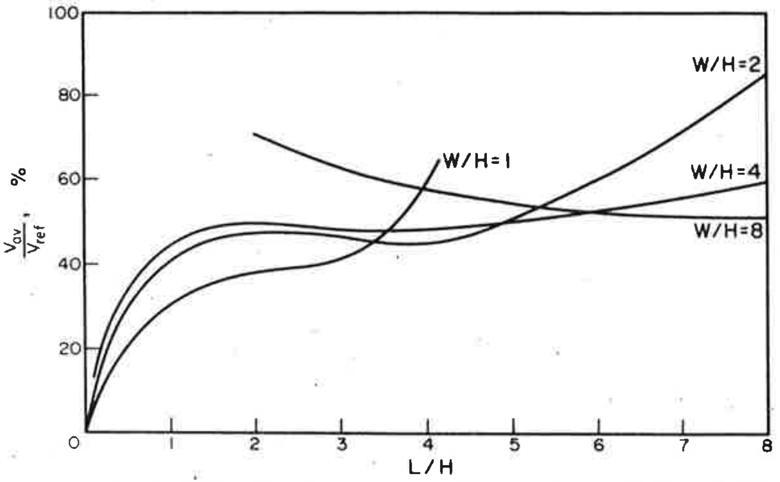

Fig. 9. The effect of length on the average speed in an enclosure at 30° orientation.

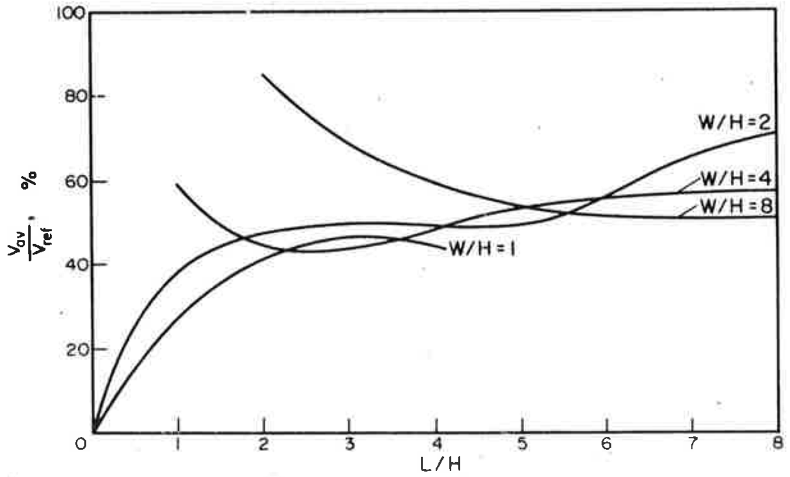

Fig. 10. The effect of length on the average speed in an enclosure at 60° orientation.

enclosure's walls. It will now be widened to include cases where the wind approaches from other directions, specifically from 30° and 60° orientations. Although the change in orientation between one set of data and another is rather large, it will be seen that the results shed light on the nature of the flow at other angles.

In order to understand the orientation's influence on the flow, it is useful to plot the data in the same manner as was used for the previous case—that is, as curves of average velocity against length for a series of widths—and also to consider the 30 and 60 degree cases together. Inspection of Figs. 9 and 10 shows the advantage of such a procedure. It will be noticed that, in both cases, the curves corresponding to the smaller widths bear a marked resemblance to those which were obtained for the zero orientation case. An apparently new but systematic form of behaviour is recorded for the wider enclosures. The key to understanding these curves lies with some flow visualisation tests which were made using a probe mounted wool tuft. It was found that, whatever the orientation of the wind, the flow within the enclosure had a strong tendency to align itself with the direction of the walls and to maintain the kind of vortex motions discussed above. Further, it was found that the flow had a preference for moving in a direction roughly parallel to whichever of the walls was longest.

Equipped with these observations, it is possible to interpret the figures. Because the flow adopts a motion like that of the zero orientation case and because of its preference for running parallel to the longest wall, it is not surprising that the curves for narrow enclosures look like those of the zero orientation case. Comparison of the figures shows some differences between the values of the average velocity for the same lengths and widths but these are to be expected since the wind approaches the enclosure from quite different angles. What is very noticeable, however, is that the general shape of the curves are the same and from this we may conclude that the flow in rotated enclosures reacts to changes in form in much the same way as it does in the simple case.

The observation that the flow tends to align itself with the direction of the longest wall also reconciles the curves obtained for large widths with the previous discussion. If the proportions of an enclosure are such that its width is generally greater than its length over a series of tests, the flow will tend to run across rather than along it so that the effects of length and width will be reversed. The graph of the enclosure's performance will then look like Fig. 2 except with the labels $L/H$ and $W/H$ reversed. Replotting the curves for large $W/H$ in the usual manner—that is with each curve being for a fixed value of $W/H$ and letting $L/H$ increase along the abscissa—will produce results much like those shown in Figs. 4 and 5 for large values of $W/H$. This is shown schematically in Fig. 11.

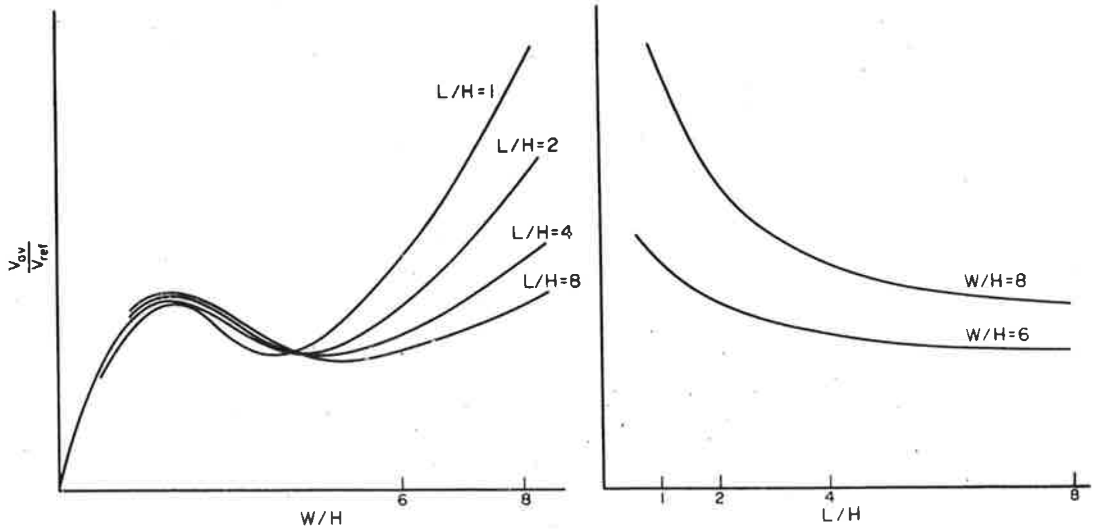

Fig. 11. The relationship between average velocity and length when the flow runs across the enclosure.

Whether the flow aligns itself with the enclosure's length or width will be influenced by the wind's angle of approach as well as by the walls' relative dimensions. It is reasonable to expect that the closer the wind comes to blowing in the direction of the enclosure's width, the more the flow will be inclined to run parallel to it irrespective of its dimension. This is borne out by the experimental data. At 30° orientation the flow runs across the enclosure for only the largest width ($W/H = 8$) whilst at 60° it does so for both $W/H = 8$ and also $W/H = 4$.

Comparison between Figs. 9 and 10 and Figs. 2 and 8 disclose that much higher velocities may be found in enclosures which are rotated to the oncoming flow than in those which face directly into it. Detailed examination of the data shows that, in certain cases, the velocity within some parts of the enclosure may exceed the undisturbed wind speed. The high average speeds recorded for these cases serves as a warning against the use of those combinations of proportion and orientation.

## EXTENSIONS OF THE WORK

As discussed above, the dip in the curves of average speed against length is the result of a transition from one flow regime to another—in particular, it is due to the interaction between a pair of contra-rotating vortices. Since the arguments used in the derivation of this flow model made no special reference to the detailed structure of the approaching wind or of the enclosures or of their surroundings, it is reasonable to assume that the model describes the essential character of the flow over wide ranges of those parameters, their effects being limited to such details as the strength of the interaction. This is confirmed by some current, unpublished work performed at the Building Research Establishment on a set of forms which were similar to the present ones but which were surrounded by roughness. The data suggests that roughness causes the dip to be replaced by a plateau or flattening of the curves, the overall shape remaining much the same. The degree of flattening, whether or not it is sufficient to produce a plateau or a dip, the relationship between these phenomena and the degree of roughness, and the correlation between the roughness used in the tests and the nature of the enclosure's surroundings at full scale are all unknown and would need to be deduced by parametric testing. Nevertheless, the data presented here demonstrate quite clearly the value of the present approach in as much as an unexpected pattern of behaviour has been found in the form/performance relationship which could only be discovered by a parametric investigation.

**Acknowledgements**—We would like to thank Dr. J. Morgan of the Department of Civil Engineering and Building Science, University of Edinburgh, for his invaluable help with the wind tunnel and its electronics.

The work was carried out under the terms of a contract on "The Optimisation of Micro-climate" with the Scottish Development Department.

## REFERENCES

1. A. D. Penwarden & A. F. E. Wise, Wind environment around buildings. *Building Research Establishment, HMSO* (1975).
2. A. F. E. Wise. Wind effects due to groups of buildings. *Phil. Trans. Roy. Soc.* **A269,** 469–485 (1971).
3. S. S. Hassan, The morphology of wind flow and built form. Ph.D. Thesis, University of Edinburgh (1974).
4. P. M. Jones, M. A. B. de Larrinaga & C. B. Wilson, The urban wind velocity profile. *Atmospheric Environ.* **5,** 89–102 (1971).
5. A. D. Penwarden, Acceptable wind speeds in towns. *Build. Sci.* **8,** 259–267 (1973).
6. J. C. R. Hunt, E. C. Poulton & J. C. Mumford, The effects of wind on people; new criteria based on wind tunnel experiments. *Build. Environ* **11,** 15–28 (1976).
7. T. V. Lawson, Air movement and natural ventilation. *Architects' Journal Information Library*, Sect. 3, para. 1.01. (11 December 1968).