THE FEASIBILITY OF USING MODELS FOR PREDETERMINING NATURAL VENTILATION

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Introduction

The advantages of utilizing the natural wind to ventilate buildings have long been recognized, particularly in the milder climates. However, little work has been done to establish methods for predetermining the natural air flow patterns for ventilating proposed buildings. The development of such methods is the objective here.

In order to develop the methods which are to be utilized in predetermining ventilation characteristics, it is natural to turn to the field of aerodynamics.[1,2,3] Unfortunately, few studies in aerodynamics are useful in this study. Since the use of models is very important in any aerodynamical study, the possibility of utilizing models in the study of ventilation characteristics should be investigated completely. Most of the early work which was done on the problem of determining air flow patterns by the use of models employed simple geometric shapes such as spheres, cylinders, and rectangular parallelepipeds. With the advent of the airplane, aerodynamicists turned their attention to the host of problems which this medium of transportation raised. Thus, most of the models used were sections of airplanes or complete airplanes, and the air speeds employed were much higher than those found in natural ventilation. Therefore most of the work done with models in aerodynamics is of such a nature that it gives little information concerning their use in the study of natural ventilation. It is the purpose of this report to give an abbreviated summary of the theoretical basis for the use of models in aerodynamics and to describe the results of a series of experiments which indicate that the use of models in the study of natural ventilation is feasible.

Since only the ventilation patterns due to the natural wind are to be investigated, it is necessary to confine this study to buildings of moderate ceiling heights in order that the effects of thermal convection may be negligible. This should be kept in mind throughout the following discussion.

[1] Numbers refer to Bibliography at end of report.

T H E   W I N D   T A B L E   M E T H O D

In order to study natural ventilation by the use of models, a means of producing an artificial wind must be used. The device which is used for this purpose at the Texas Engineering Experiment Station is the Air Flow Chamber, which is essentially an open throat, closed circuit wind tunnel[4,5,6] including a wind table 8 feet wide and 12 feet long upon which models are tested. See illustrations on following page.

The inlet is specially designed with eggcrate louvers, and cheese-cloth screens to insure uniform air movement immediately above the top of the wind table. An attic fan in the opposite wall exhausts the air from the chamber through the air washer, and into the return air circuit. The air washer, consisting of water sprays and an excelsior mat, serves to remove most of the undesirable effects from the air caused by the use of titanium tetrachloride in the chamber.

In using the wind table for testing, models are placed upon the table in the air stream and the resulting air flow patterns observed by the use of titanium tetrachloride smoke.

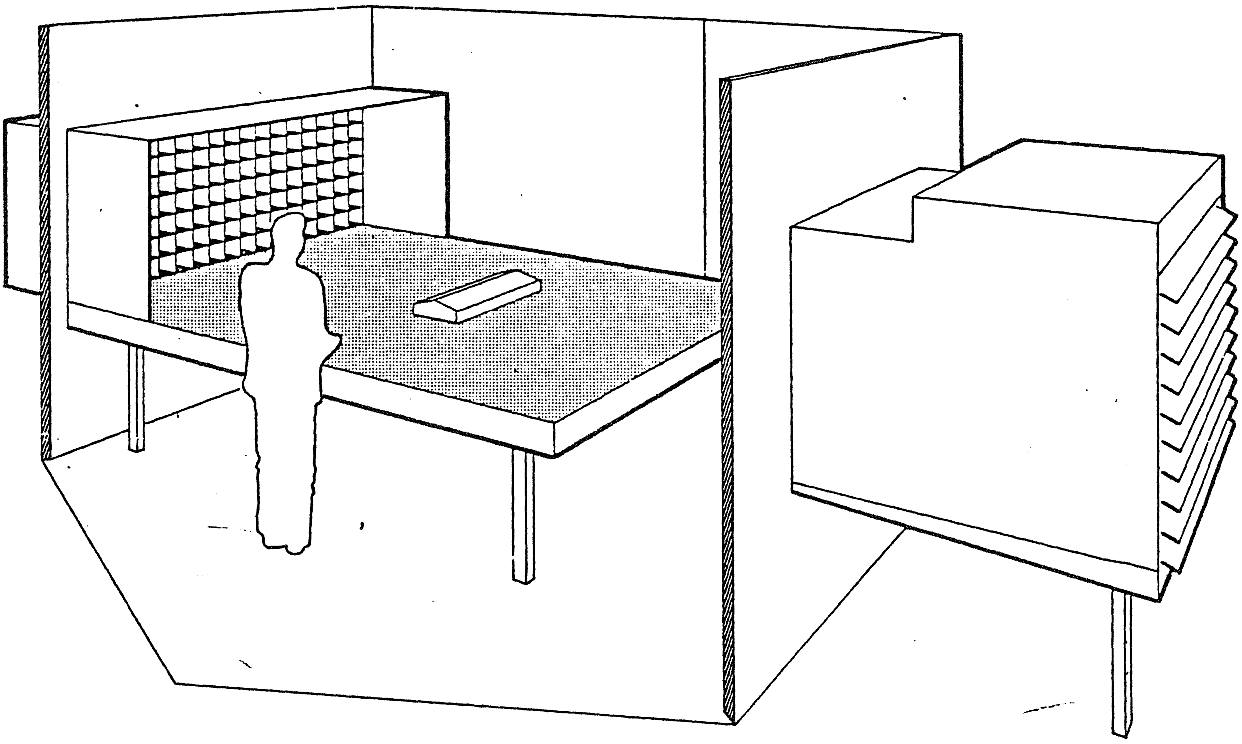
Before models can be used with confidence for predetermining the natural air flow in a proposed building, information concerning each of the following topics must be available:

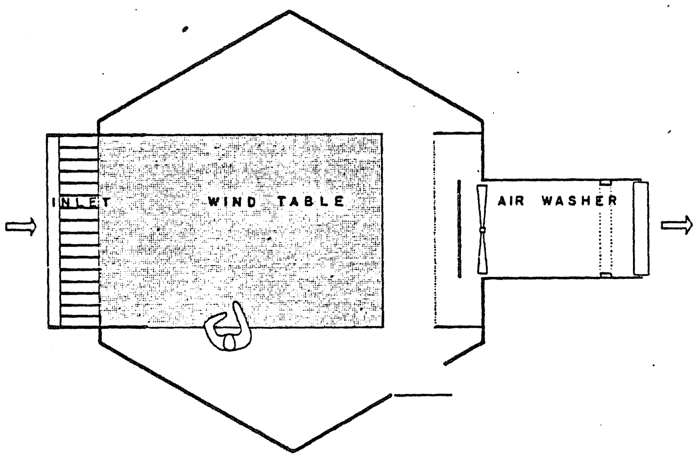
1. Sizes of models and corresponding air speeds, necessary for giving accurate predictions of air flow patterns and relative air speeds.

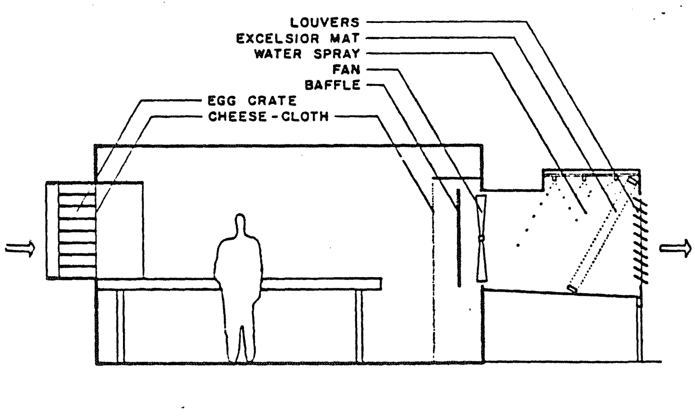
2. Methods which can be used to determine air flow patterns in and around models.

3. Methods which can be used to measure air speeds in and around models.

A series of experiments was conducted to test the reliability of the information which is obtained by the Wind Table Method. Accounts of the experiments concerning the above topics are brought forth in the following sections.







AIR FLOW CHAMBER

THE AERODYNAMICAL BASIS FOR THE USE OF MODELS

According to accepted aerodynamic theory,[7,8] a model should give the same air flow pattern as a full-sized building if the following condition is satisfied:

> That Reynold's Number is the same for the model as for the full-sized building. Reynold's Number, $R = \frac{vh\rho}{\mu}$, is the product of the air speed, some dimension, and the density of the air all divided by the viscosity of the air.

It may be observed that if the density and viscosity of the air remain constant, the smaller the model, the higher the air speed which must be used to test it. Thus, if a model 6 inches high is to be used to predict the performance of a building 14 feet (168 inches) high, when the speed of the wind is $2\frac{1}{2}$ miles per hour, the relation must satisfy

(Air speed for model)(Height of model) =
(Air speed for building)(Height of building) (1)

$(v)(6) = (2\frac{1}{2})(168)$ (2)

$v = 70$ miles per hour, or slightly over 6,000 feet per minute.* (3)

At this or lower air speeds, changes in the density and viscosity of the air are very small, thus the assumption that the density and viscosity are constant is justified.

A serious objection to the use of very high air speeds is that comparatively strong expensive models must be employed. There are also two objections to the use of very small models. First, the air flow patterns are difficult to observe, and second, air speed measurements inside a very small model are almost impossible to make.

In order to make possible the use of very cheap models, it is desirable to work with air speeds which are too slow to satisfy the relation that the product of the height of the building by the wind speed expected shall equal the product of the height of the model by the air speed used in testing it. There is, however, a very definite possibility that the patterns may not change appreciably over a considerable range of the product of the air speed by the height. To test this, two series of tests were run. The first series of tests was on interior air flow patterns, and the second series was on exterior air flow patterns.

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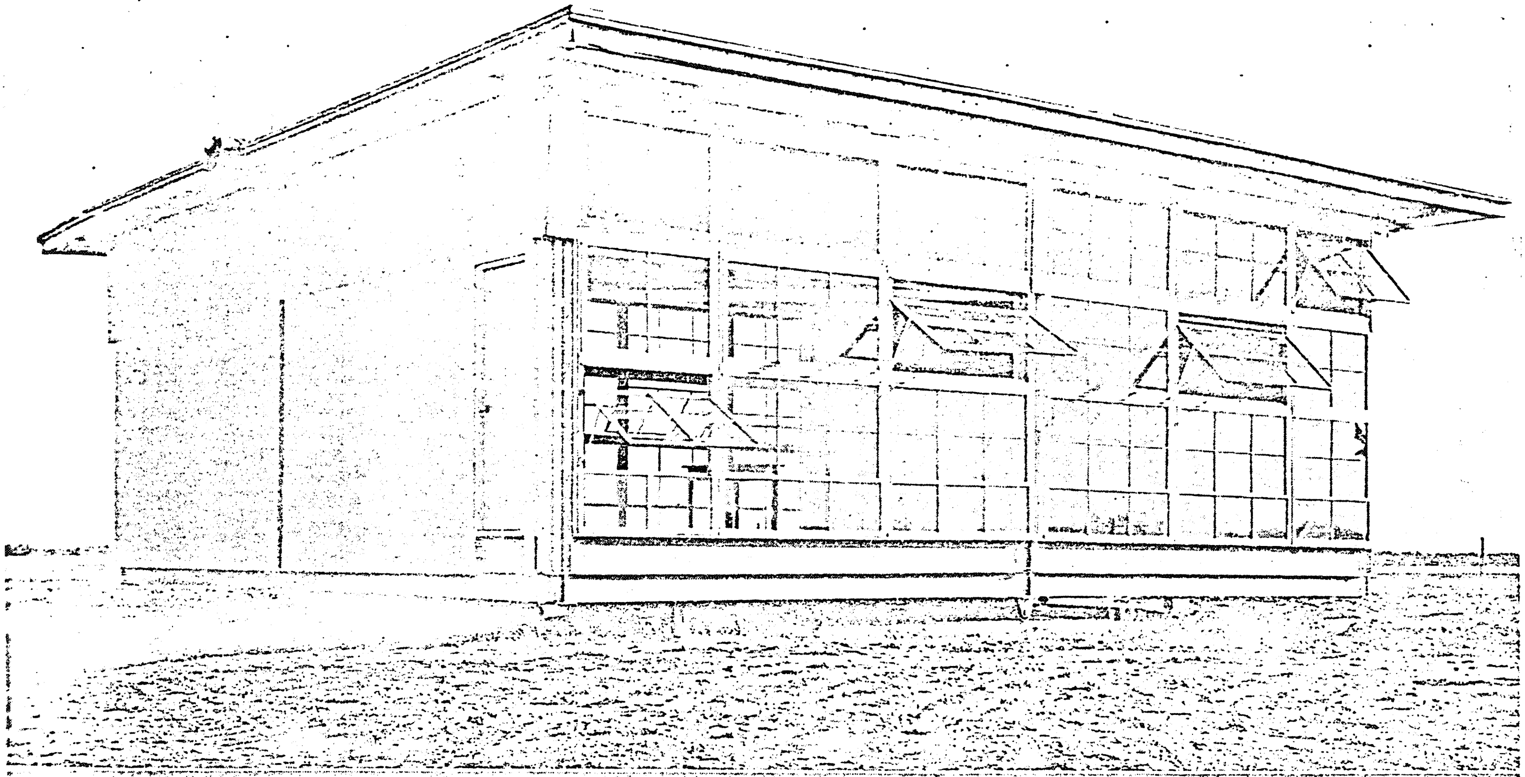
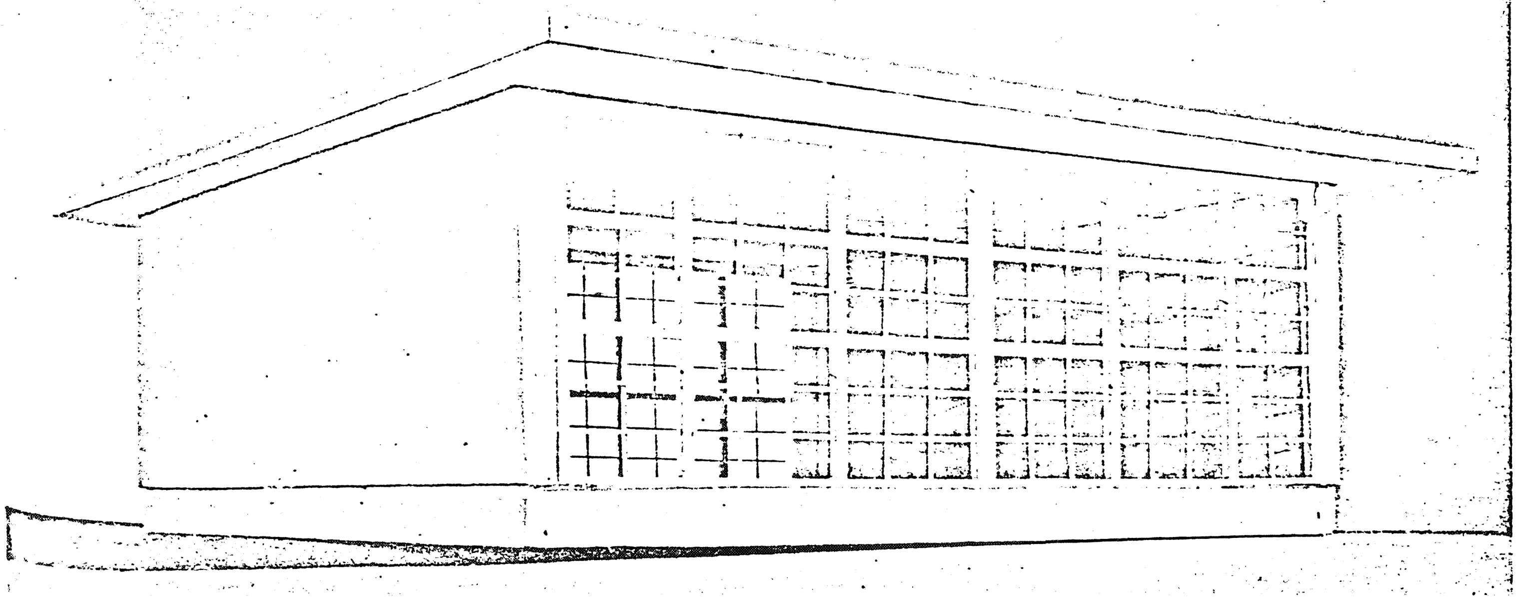
* 1 mile per hour = 88 feet per minute.

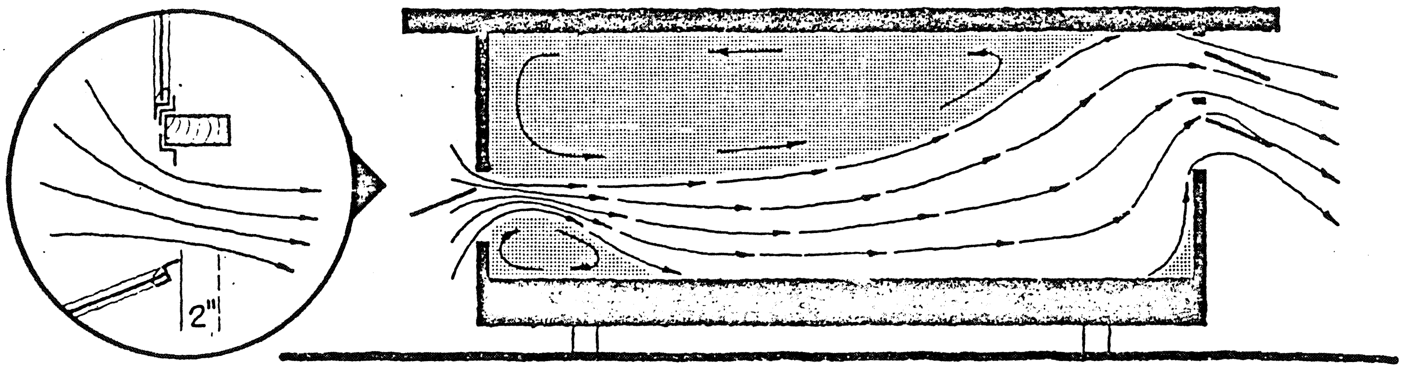
The first tests of this series were run in a full-sized building. This building, 30 feet long by 30 feet wide by 14 feet high, was built on an open plain and constructed so that the fenestration could be changed rather easily. It was also mounted on wheels which ran on a circular track. This latter arrangement permitted the orientation of the building to be changed at will so that the wind could be made to blow past it in any desired direction. This rotatable building is usually referred to as the "Experimental Building" and will be so called in this report. After a number of different fenestrations had been tested in the Experimental Building, the same fenestrations were then tested in a model which was built to a scale of 3/4 inch equals 1 foot, or on a scale of 1/16 of actual size. This gave a model which was about 2 feet wide. See photographs of the Experimental Building and its model on the following page.

EXPERIMENTAL BUILDING

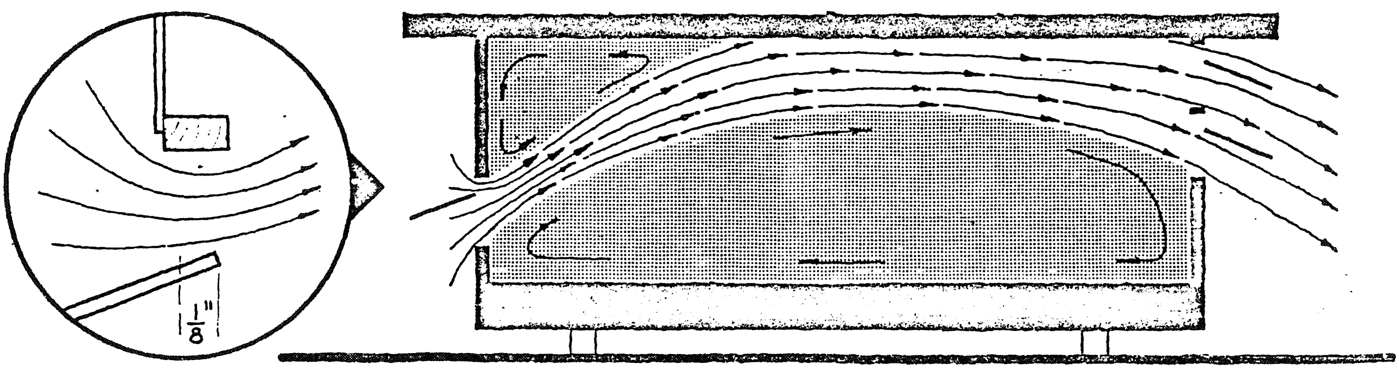
5'0" BUILDING ABOVE
2" MODEL BELOW







FULL SIZE BUILDING



MODEL

Most of the fenestration patterns gave the same air flow pattern in the model that they had given in the Experimental Building, but there was one notable exception. The upper drawing on the opposite page shows the air flow pattern which was obtained in the Experimental Building, and the lower drawing shows the air flow pattern which was obtained in the model for a fenestration arrangement which was intended to be the same. Since there was a very definite possibility that the change in pattern in this isolated case might have been caused by something other than the change in magnitude of the product of the air speed by the height of the building or model, a careful search for possible causes of the variation was made. Finally, it was noticed that the inner edges of the windows projected a little farther inside the wall of the model than they did in the wall of the Experimental Building. Since the model was made of balsa wood and cardboard fastened together by means of a minimum amount of model airplane glue and many common pins, it was very easy to change it so that it reproduced the arrangement of the Experimental Building more accurately. The required change involved moving the windows horizontally less than 1/8 of an inch, but when this small change was made, the model gave the same pattern that had been obtained in the Experimental Building.

This experience called attention very sharply to the fact that small changes in a structure may cause large changes in the air flow pattern. In the case just described, a small change in window design altered the air flow pattern from a poor one in which the air flow was all near the ceiling where it would not blow upon the occupants of the room to a good one which produced the maximum air movement down near the floor where it was effective in increasing comfort.

These results immediately raised the question as to whether a slight vertical movement of the window sash and pane might cause an important change in the air flow pattern. This was tested in the same model by moving the cardboard rectangles, which represented the window frames and panes, vertically without rotation. It was found that a change of position of as little as 1/16 inch could change the direction of influx of the air into the model from inclining toward the ceiling to inclining toward the floor.

The conclusion to be drawn is obvious. No matter what else may be important, it is essential to make the models large enough and flexible enough in details of construction so that the effects of small changes in the design of the building upon air flow patterns can be tested. This means that models should consist of structural frames of balsa wood to which cardboard or acetate sheets may be attached by means of pins or glue, whichever is more practical. This rules out the use of air speeds which exceed 1200 feet per minute and indicates that speeds below 600 feet per minute are desirable.

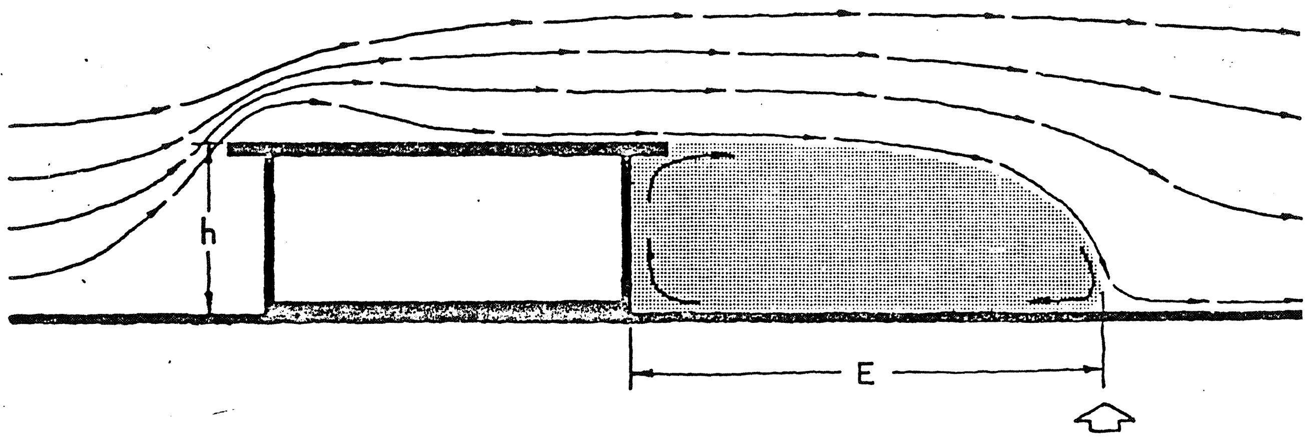
The tests described so far were run at air speeds which ranged from 60 feet per minute to 120 feet per minute measured outside the model, and they gave no indication that the very low values of the product of the height of the model by the air speed caused any important changes in the air flow pattern. However, as will be shown later, the tests so far described involved effects which depended almost entirely upon the geometry, or shape, of the model and could not very well be affected greatly by either size or air speed.

The Necessity For A Criterion Which Makes Different Shapes Roughly Comparable

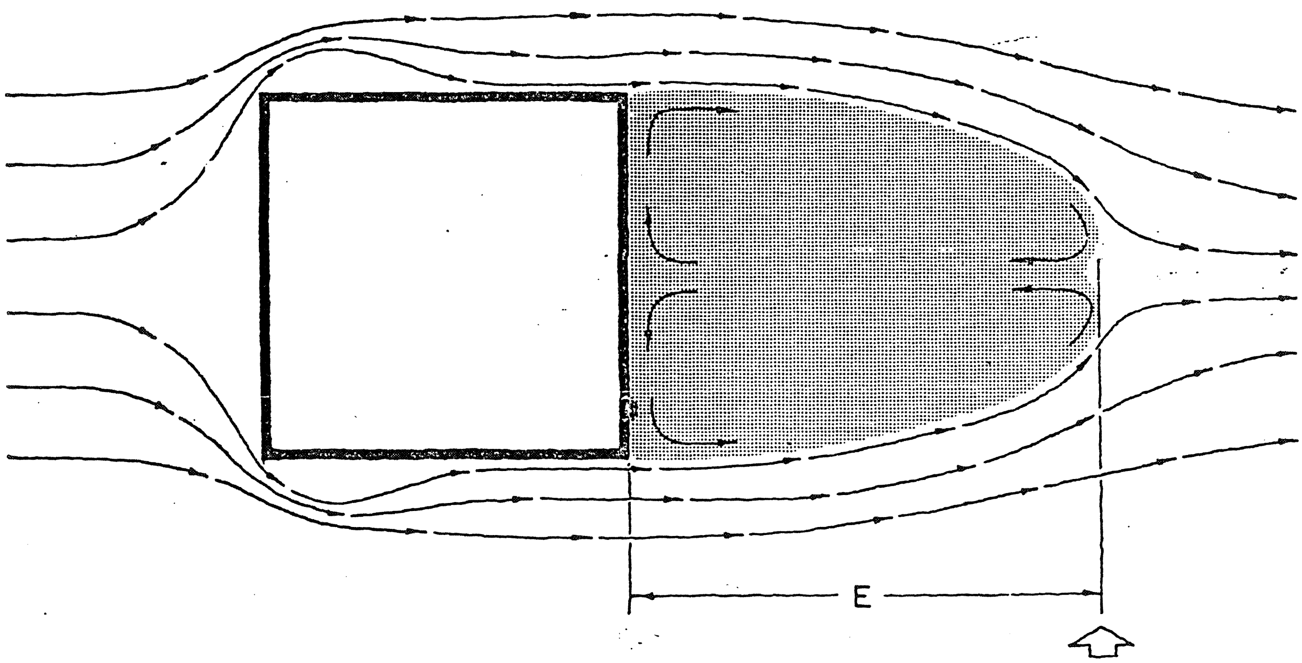
In order to determine the limits within which the product of the height of the model by the air speed may vary without introducing serious possibility of error, it is necessary to run a large number of tests on models of various shapes using a test which depends more upon size and air speed than upon geometry.

An important pattern which can be altered considerably by changing either the air speed or the size of the model is to be found on the lee side of a building or model as shown in the drawings on the following page. A good way to test such a pattern which is to be compared to another of the same geometry, but having a different size and air speed, is to locate the point on the ground in the lee of the building where the air is at rest. When this has been done for models of various sizes at various air speeds, the ratio of the distance E to the distance h may be used as a criterion to determine whether or not the pattern has changed. If the ratio E/h shows no tendency to change in a definite manner as the size and air speed are increased or decreased, and if its irregular variations are of the order of 10% or less, there has probably been no important change in the pattern.

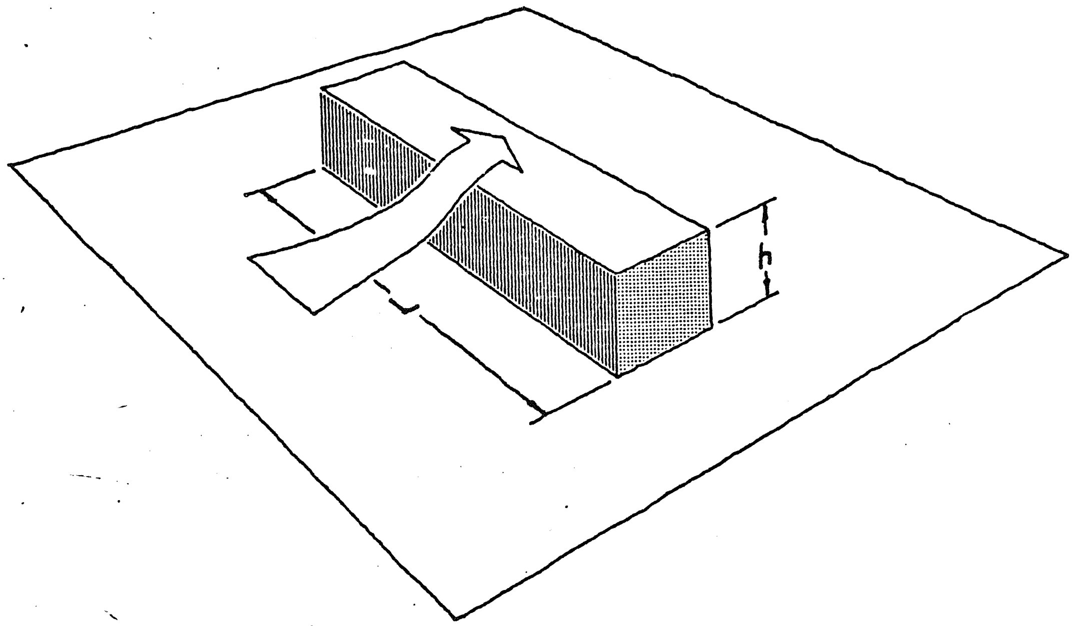
In addition to having a criterion for determining whether or not the pattern has changed, it is highly desirable to find an abscissa against which to plot the ratio E/h in such a manner that any critical values of E/h will come at about the same abscissa on the graphs for various shapes.

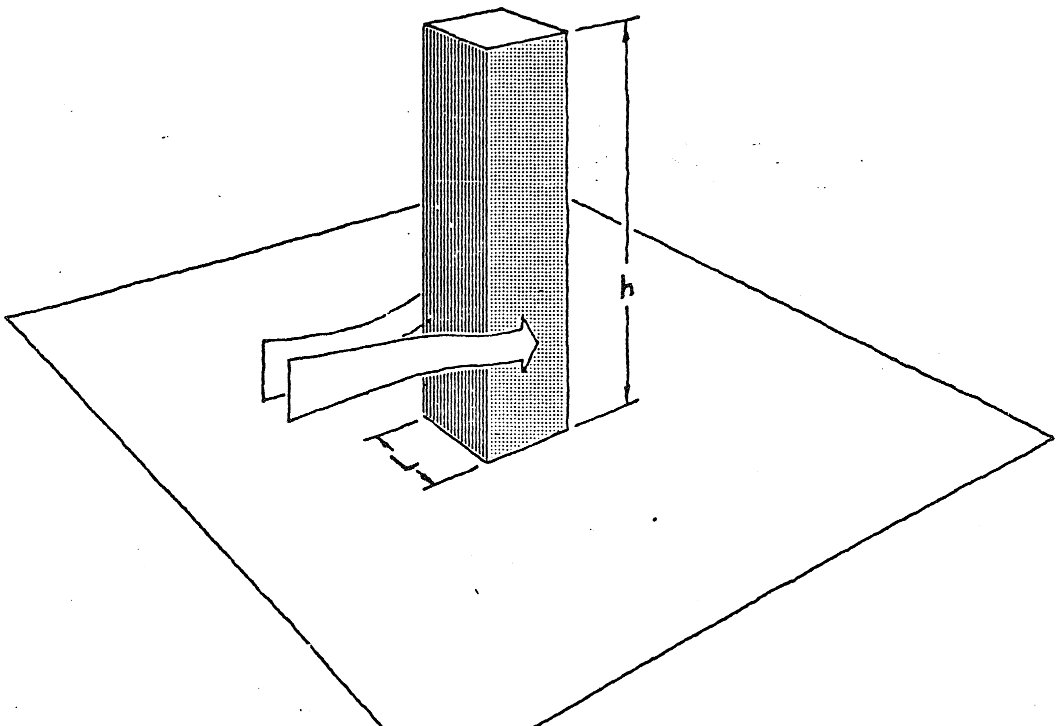


SECTION



PLAN


h
L


h
L

The product hv, which represents the product of the height of the model and the air speed is not a good quantity to use as the abscissa because it does not give comparable results for such different arrangements as shown on the opposite page. If the two ultra simple models which are depicted in these drawings are tested at an air speed of 600 feet per minute for the point where the air is at rest, and the blocks used are about 10 inches square, the location for zero air speed is found to be at a distance equal to about 2h back of the block in the upper drawing, and at a distance roughly equal to L behind the block in the lower drawing. Evidently, a quantity which reduces to approximately 2h for the upper block and to approximately L for the lower block would be very advantageous as a substitute for h in the product hv. Fortunately it is not difficult to devise a quantity which has these characteristics. The desired quantity is two times the projected area normal to the air flow divided by the perimeter past which the air flows. If it is decided to call this quantity the aerodynamic radius and represent it by r_a, the defining equation becomes

$$r_a = \frac{2A}{P}. \tag{4}$$

The name aerodynamic radius is appropriate for this quantity because it reduces to the radius for a sphere placed in the air stream. That is, for a sphere

$$r_a = \frac{2A}{P} = \frac{2(\pi r^2)}{2\pi r} = r. \tag{5}$$

To see that r_a reduces to approximately 2h for the upper block, note that for this block

$$A = hL \tag{6}$$

and

$$P = 2h + L. \tag{7}$$

When equations (6) and (7) are substituted into equation (4), the result is

$$r_a = \frac{2(hL)}{2h + L} = \frac{2h}{\frac{2h}{L} + 1}. \tag{8}$$

Now in the upper drawing, h is very small compared to L so that the quantity 2h/L is small compared to unity and can, therefore, be neglected. Under these circumstances, equation (8) may be replaced by the approximation

$$r_a \approx 2h \tag{9}$$

In a similar manner, by looking at the lower block it may be seen that for the tall model

$$A = hL \tag{10}$$

and

$$P = 2h + L, \tag{11}$$

when equations (10) and (11) are substituted into equation (4), the result is

$$r_a = \frac{2(hL)}{2h + L} = \frac{L}{1 + \frac{L}{2h}} \tag{12}$$

In this case L is very small compared to h, so that the quantity L/2h can be neglected in comparison to unity. Equation (12) can, therefore, be replaced by the approximation

$$r_a \approx L. \tag{13}$$

Equations (9) and (13) indicate that a good abscissa to use in connection with the criterion E/h is

$$r_a v, \tag{14}$$

which may be written in full as

$$\frac{2A}{P} v. \tag{15}$$

EXPERIMENTAL TESTS TO DETERMINE WHICH VALUES OF $\frac{2A}{P}v$ GIVE THE MOST RELIABLE RESULTS

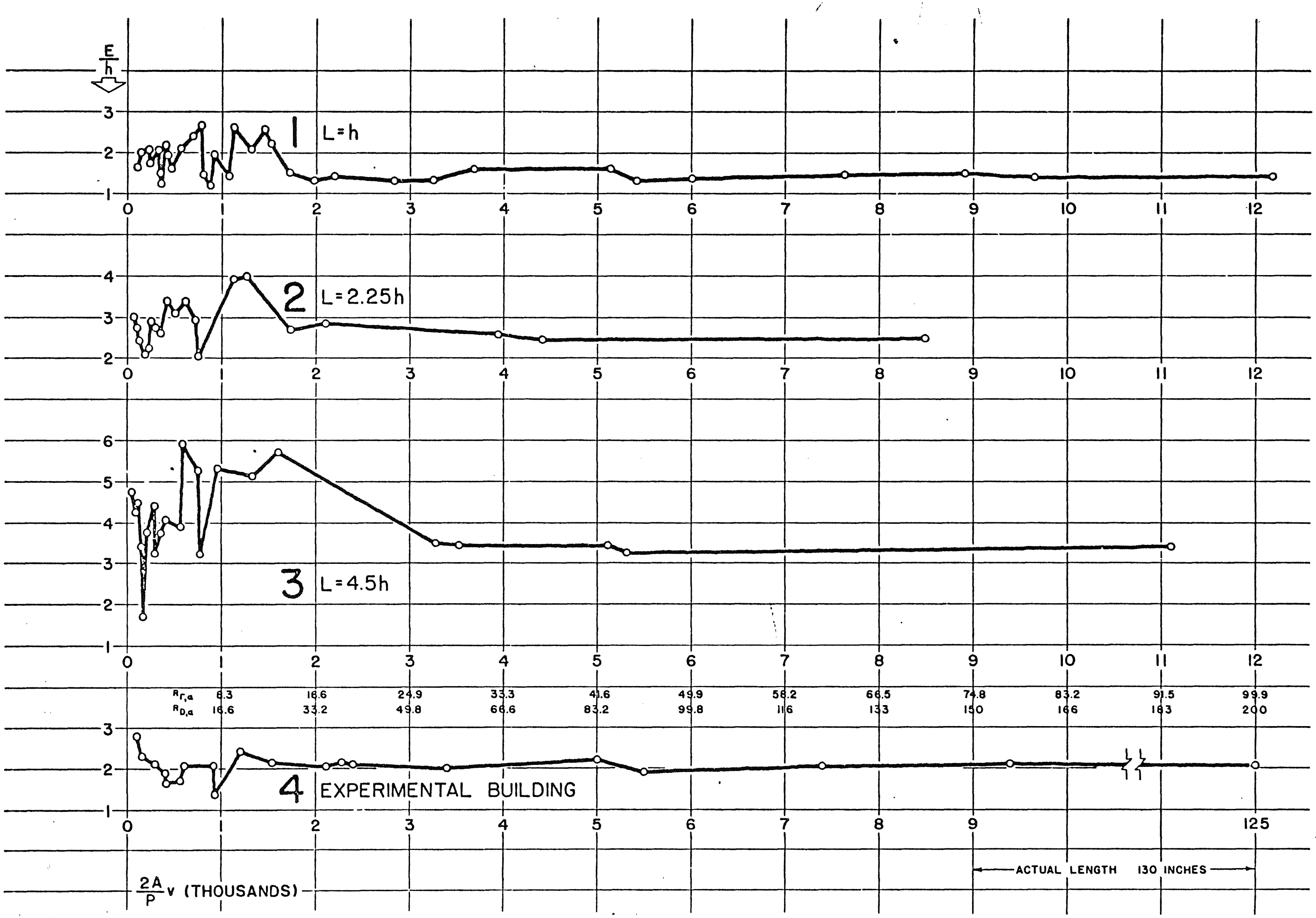
In working with models of buildings, it is most convenient to express area, A, in square inches, perimeter, P, in inches, and speed, v, in feet per minute. Accordingly, in all the tests to be described, the results are expressed in the above units.

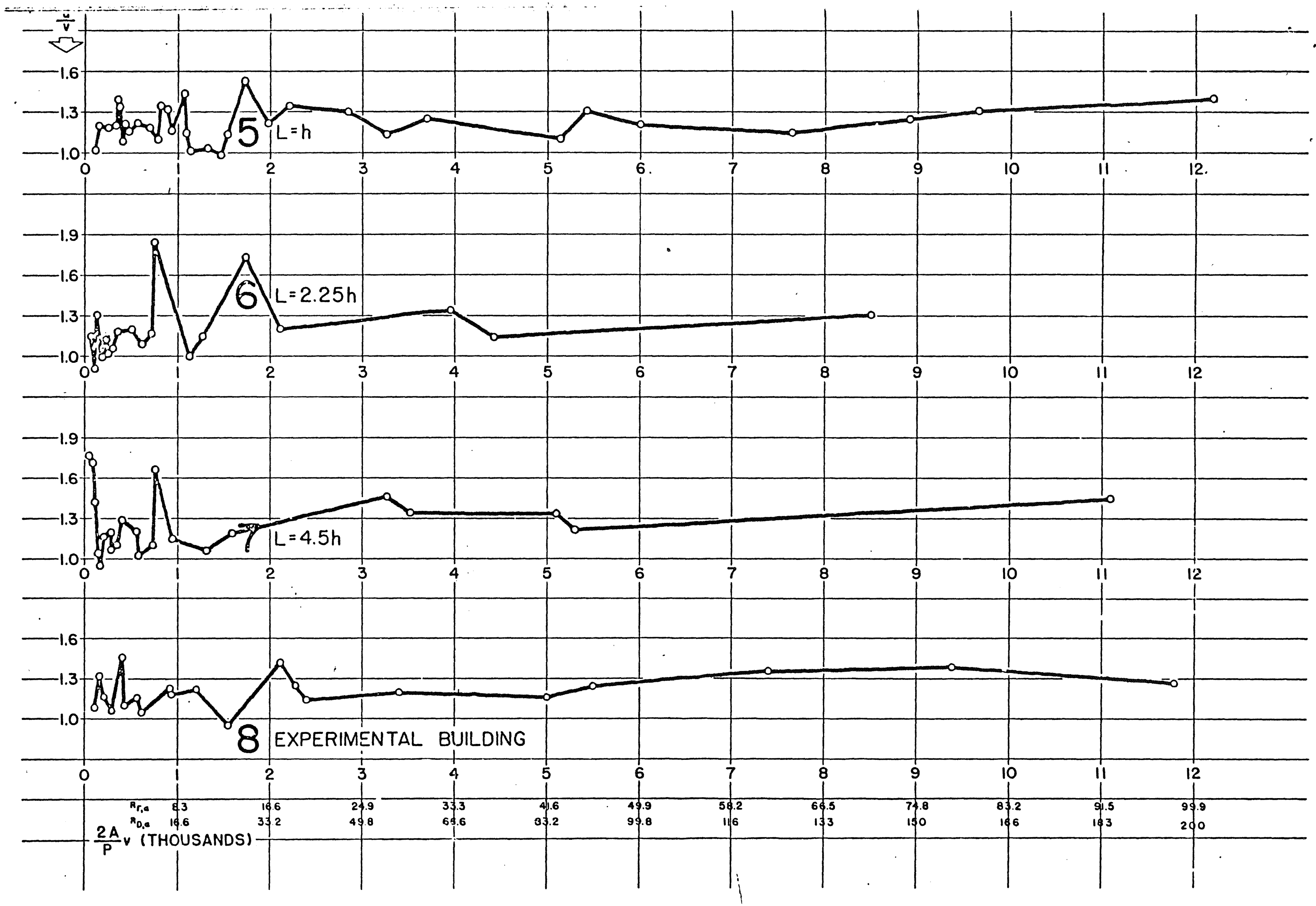
One of the simplest shapes which can be tested is a cube. Graph 1 on the following page shows the results of a series of tests run on cubes. The cubes which were used ranged in height from 3 inches to 18 inches. The lowest air speed used was about 40 feet per minute, and the highest used was about 1000 feet per minute. The graph shows that for values of $\frac{2A}{P}v$ below 1500, the results were both highly variable and inconsistent with the results obtained for higher speeds. Graph 2 shows almost identical results for a square ended block whose length, L, was 2.25 times its height, h. Note that for the cube, $L/h = 1$, and for the second block $L/h = 2.25$. The results for a third block having $L/h = 4.5$ are shown in Graph 3. The results are again consistent for values of $\frac{2A}{P}v$ in the neighborhood of 1800 and higher.

Although the tests just described indicate that there is a region of great consistency for values of $\frac{2A}{P}v$ between 2000 and 12,000 there is no certainty that this consistency continues to the values of $\frac{2A}{P}v$ which are encountered when the natural ventilation of a full-scale building is being considered.

In order to determine whether this uniformity of pattern held for full-sized buildings, models of the Experimental Building were constructed, and tests were run on both the models and the full-scale building. This series of tests was run with the roof arranged to be flat, as shown in the photographs on page 6. The results of these tests, as shown by Graph 4, indicate that the results obtained for values of $\frac{2A}{P}v$ between 2000 and 12,000 are valid for conditions described by $\frac{2A}{P}v = 125,000$.

That is, for models tested, having values of $\frac{2A}{P}v$ between 2000 and 12,000, the results were consistent with those obtained from the full-scale structure for a value of $\frac{2A}{P}v$ of 125,000. These data seem to indicate that the <u>workable range of values for $\frac{2A}{P}v$ is from 2000 to 125,000</u>. Since these models were tested in two tunnels and the degree of turbulence between the two tunnels was not definitely known, it is very possible that the lower limit of the valid range may be extended even lower by considering this factor. Also, there is no reason to expect any variation for values which are greater than 125,000.


E/h
1 L=h
2 L=2.25h
3 L=4.5h
4 EXPERIMENTAL BUILDING
$R_{r,a}$ 8.3 16.6 24.9 33.3 41.6 49.9 58.2 66.5 74.8 83.2 91.5 99.9
$R_{D,a}$ 16.6 33.2 49.8 66.6 83.2 99.8 116 133 150 166 183 200
125
ACTUAL LENGTH 130 INCHES
$\frac{2A}{P}v$ (THOUSANDS)



u/v
1.6
1.3
1.0
5 L=h
1.9
6 L=2.25h
7 L=4.5h
8 EXPERIMENTAL BUILDING
0 1 2 3 4 5 6 7 8 9 10 11 12
$R_{r,a}$ 8.3 16.6 24.9 33.3 41.6 49.9 58.2 66.5 74.8 83.2 91.5 99.9
$R_{D,a}$ 16.6 33.2 49.8 66.6 83.2 99.8 116 133 150 166 183 200
$\frac{2A}{P}v$ (THOUSANDS)

Furthermore, not only is the pattern essentially independent of the values for $\frac{2A}{P}v$ above 2000, but the same is also true for the speed ratios. Graphs 5, 6, 7, and 8 on the opposite page give the plot of the ratios of the speed at a point above the leading edge of the models of graphs 1, 2, 3, and 4 respectively to the undisturbed air speed in front of the models. While the variation is somewhat greater than in the tests for the flow patterns, useful information concerning the air speeds at various points of the full-scale structure may be determined within a reasonable percentage of accuracy. It seems probable that most of this variation is due to the inaccuracy of the anemometers which were used to make these measurements.

As an example to determine the minimum speed of air flow for testing a typical rectangular model, assume a model having a windward side dimension of 24 inches by 9 inches:

$$\text{Since } \frac{2A}{P}v \geqq 2000,$$

$$\text{then } \frac{2(24 \times 9)}{(9 + 24 + 9)}v \geqq 2000,$$

$$\text{or } v \geqq 194 \text{ feet per minute.}$$

Therefore, tests for a model of this size should be conducted in a flow of air having a speed greater than 200 feet per minute.

No tests have been run on models with rounded surfaces, such as a Quonset hut; therefore, it is not possible to indicate whether or not there should be variations in the pattern of this type of structure with an increase in size or an increase in wind speed.

ADDITIONAL REMARKS FOR COMPARING THESE RESULTS WITH OTHER AERODYNAMIC DATA

For those interested only in the feasibility of using models for predetermining natural ventilation, the previous discussion will be adequate. Those who have an interest in either aerodynamics or hydrodynamics will want to convert the quantity $\frac{2A}{P}v$ to consistent units and multiply it by the quotient of the density of the air by its viscosity to obtain Reynold's Number. Thus, if ρ = the density of air, and μ = the viscosity of air, Reynold's Number, based upon the aerodynamic radius, is then:

$$R = \frac{2A}{P} v \frac{\rho}{\mu} \tag{16}$$

By referring to equation (5), it can be seen that equation (16) gives a Reynold's Number for which the length involved reduces to the radius for a sphere. Sometimes it may be desirable to compare these data with other data for which Reynold's Number for a sphere is computed by using the diameter of the sphere. In this case let the

aerodynamic diameter D_a (17)
be defined by the equation

$$D_a = \frac{4A}{P}. \tag{18}$$

For convenience in relating the graphs of this report with various other experimental data, all the graphs have three sets of abscissas - $\frac{2A}{P}v$, Reynold's Number based upon the aerodynamic radius, $R_{r,a}$, and Reynold's Number based upon the aerodynamic diameter, $R_{D,a}$.

METHODS BY WHICH AIR FLOW PATTERNS CAN BE MADE VISIBLE

Probably the most satisfactory way of determining an air flow pattern at low speeds is by introducing a dense smoke into the air stream so as to make the pattern visible.[9,10,11] When proper precautions are taken for washing and filtering the air, titanium tetrachloride smoke is a very satisfactory substance to use for this purpose.

Since the smoke produced by the use of titanium tetrachloride is white, it can best be observed against a background which is rough and painted a very flat black. The irregularities of the surface which cause its roughness must, of course, be small in order not to affect the air flow pattern. In the case of the model, as distinguished from its surroundings, the wall nearest the observer should be transparent in order to permit the pattern to be observed. The most satisfactory material found for making the transparent wall is a sheet of acetate, because it can be easily cut and glued or fastened with pins. A strong light at right angles to the line of sight of the observer is also very desirable, but care should be exercised to avoid any arrangement which might produce convection currents strong enough to alter the air flow pattern appreciably. If it is necessary to take photographs of the pattern, a much stronger light is needed. Some information concerning techniques for photographing smoke patterns can be found in references 12, 13, and 14 of the bibliography.

In the determination of the air flow pattern in or around a model there are two principal features to observe - the actual air streams, and the eddies bounded by the air streams.

If the interior flow pattern of a model is to be observed, two techniques may be employed. The first is referred to as the main-stream technique. In this method, a stick which has been dipped into a bottle of titanium tetrachloride is placed in the air stream slightly windward of the region for which the pattern is desired.

The smoke from the stick flows with the air through the model and defines the region of air flow. The second, or eddy, technique is not only useful in observing the flow streams, but also in outlining the eddies in the pattern. In this method, the smoke stick is placed in an eddying region until the eddy has filled with smoke. The stick is then removed. The flow streams are quickly cleared of smoke while the eddy remains filled with smoke. Since the background is black, the clear air stream then appears black while the eddy appears white. By careful observation it is possible to detect the flow within the eddy itself.

In observing exterior flow patterns, as in the case of interior patterns, it is only possible to use the eddy technique to advantage to observe eddies. Therefore, both techniques must be used. To locate the lee point of a building, the point where the air is at rest, a modification of the main stream technique is used. This is done by placing a heavily smoking stick close to the ground, or wind table, and at a considerable distance from the building on the lee side. If the distance from the building to the smoking stick is not too small, the smoke drifts away from the building. The smoking stick is then moved slowly closer to the building while keeping it close to the ground. When some of the smoke begins to show a tendency to drift toward the building, the position of the stick is noted. After the titanium tetrachloride on the stick has been replenished, the stick is placed close to the ground and near enough to the building so that the smoke drifts toward the building. The stick is then moved slowly away from the building. When some of the smoke begins to show a tendency to drift away from the building, the position of the stick is again noted. The mean of the two recorded stick positions is taken as the place where the air is at rest.

For special cases other modifications of the above techniques can be used. With a little experimentation, the observer will find which of the above techniques or modifications will give the most information about a particular flow pattern.

The only instruments known to the authors which have probes small enough to be used inside a model of a building are hot wire anemometers,[15,16] more properly called resistance thermometer anemometers, and thermocouple anemometers.[15, 16] These instruments are equipped with T-probes, which have fair directional characteristics and may be placed at the point where the air speed is desired without changing the flow pattern appreciably. Most of the instruments of this type have meters reading directly in air speed, usually in feet per minute. These instruments can be calibrated reliably at low air speeds by using the titanium tetrachloride methods described in references. Instruments to be used for measuring low air speeds should always be calibrated to avoid large errors.

Both paddlewheel and deflecting vane anemometers[17] give reliable air speed measurements in and around full-scale buildings. When using paddlewheel anemometers, the electrical contactor type is usually preferred to the direct reading type because by using several of these instruments, continuous records of the air speeds at several different points can be made.

S U M M A R Y

1. The criterion of aerodynamic theory, that the product of the undisturbed air speed and some typical dimension must be constant in order that the same air flow pattern will be observed in a model and in the full-scale structure, is not a necessary condition. It has been found by a series of experiments that if this product is above a certain critical value, the observed patterns are essentially independent of the value of the product. This result makes possible the use of convenient size models and convenient air speeds to predetermine the natural ventilation characteristics of proposed buildings. It must be remembered that these results were obtained from straight edged models and caution must be used in interpreting the patterns of models with smooth rounded surfaces.

2. In applying this method of using models, the following conditions must be observed.

   A. The changes in the density and viscosity of the air must be negligible.

   B. The effects of thermal convection must be negligible, or other methods must be used.

   Condition "B" is of special importance if the flow patterns of certain types of buildings are to be determined. In many industrial buildings and in any tall, heated building, thermal effects are the major factor in the observed flow patterns; therefore, the results of the experiments in this report are not applicable.

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