WIND EFFECT ON THE AIR MOVEMENT INSIDE BUILDINGS

L'EFFET DU VENT SUR LA CIRCULATION DE L'AIR DANS LES BATIMENTS

by
H.K. MALINOWSKI*

SUMMARY

The wind effect on air exchange in buildings through small openings or through porous walls is an important factor in the study of the penetration of polluted air into a building or the removal of the contaminated air.

The results of tests, on models demonstrates that air change is the result of: through flow, pulsation, turbulence and diffusion. The effect of the wind velocity, and turbulence on the ventilation for different configurations is presented in the form of graphs.

The feasibility of estimating the rate of air change, based on the concentration distribution, by a hyperbolic function is discussed, but more tests are needed for practical recommendations.

INTRODUCTION

The problems of the efficiency of the air exchange and the air motion in a closed compartment have been discussed in many papers. Most of these papers however, are concerned with forced ventilation; some works also have been published on the wind effect on internal pressure, as a result of wind action, (5).

The primary objective of this paper is the study of air exchange, between outside and inside of buildings, caused by the external air flow.

It has been observed that very small openings, or imperfections of tightness could cause considerable amounts of air change in a building and the rate of change for particular configurations primarily depends on the velocity, direction and turbulence of the wind.

Knowledge of internal air circulation, due to a combination of openings, or due to a porous wall, as a result of wind, is far from being adequate.

The importance of the problem is emphasized by the following considerations:

1. Modern large buildings are usually, completely air conditioned, but small new, as well as majority of existing buildings rely on the "natural" air ventilation only.

2. In case of some sort of disaster, which could cause a power failure, like earthquake, fire, tornadoes, snow storm. Only natural air circulation will be available. This is particularly

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important for animal housing with large numbers of animals, when evacuation is difficult or impossible.

3. The rapid growth of air pollution makes urgent the need for a better understanding of the phenomena concerning the penetration of polluted air into a building or removal of the contaminated air.

Each of these reasons is enough to justify study in this field, and gives rise to the urgent need of a better understanding of this phenomena.

This paper presents the result of a series of tests conducted on models in a water flume, and in a wind tunnel with the objective of establishing criterions, to evaluate the rate of exchange.

FULL-SCALE CONDITIONS AND OBSERVATIONS

In an actual building the internal air exchange depends on a large number of parameters, and the study of the phenomena requires some assumptions, which could lead to an uncertain result, since the assumptions contain many simplifications, which have not been adequately supported by experimental data.

Some of the more important parameters are:

a) Pressure distribution on a building, which is a result of shape and size of the building, environmental conditions, and direction and nature of the wind.

b) Location, shape, area and number of openings or permeability of walls.

c) Internal partitions and interconnection between internal compartments.

d) Temperature gradients.

Observations on a building, confirmed by test, that the process of air exchange could be considered as a resultant of the following four factors:

First; the air flow through the compartment
Second; pulsating flow
Third; the penetration of eddies (turbulence)
and Fourth; static or molecular diffusion, (including thermo and chemical processes)

The air exchange by the flow through a compartment, presented in Fig. 1 occurs when openings are located in areas of different pressure, (16). The phenomena is very similar to forced ventilation, the only difference being that the flow is not steady, and depends on the external conditions.

Pulsating flow takes place when all the holes are located in an area of the same external pressure, or when the pressure difference is very small, but variation of the pressure in time predominates. This process is demonstrated in Fig. 2a. Another type of pulsation flow exists when the external pressure changes between two or more holes are in such a way that the flow periodically changes direction, Fig. 2b.

The difference between unsteady continuous flow and pulsating flow is distinguished as follows: continuous flow is, when inflow and outflow of mixture is through different openings, and pulsation, when inflow and outflow is through the same, one or more openings, or by reversed flow direction.

If the external flow is turbulent, or potential turbulence is created in the vicinity of the hole then eddies, by penetration into the building are carrier vehicles for the conveyance of external air into the building and for the removal of the internal mixture of air to the outside. This phenomena is illustrated in Fig. 3.

Finally, static, molecular, or thermal diffusion, (7), (9). Thermal or chemical diffusion effect have not been investigated in this work. Molecular diffusion is a very slow process, and while it accompanies any other mode, its relative contribution to total air exchange through the holes is very small. This is illustrated on the Graph Fig. 4, where slope of the curve $V = 0$ represents rate of air exchange mainly by diffusion.

For the porous wall, with low permeability of the air the contribution of molecular diffusion is of the same order as external velocity effect and should not be neglected. As can be seen on Fig. 5, the difference in slope of curve $V = 0$ and $V \neq 0$ is much smaller than that for two holes on Fig. 4.

TESTS

A series of tests have been conducted at the University of Guelph with the following objectives:

1. To develop a testing technique, to study the effect of the external air flow in the internal air circulation.

2. To obtain information for a better understanding of the mass transfer phenomena through limited openings, or through a porous wall and

3. To investigate the feasibility of developing methods to predict the rate of air exchange, in a building.

In order to achieve these objectives some tests were conducted in a water flume, and some in a wind tunnel.

<u>Water Flume Testing</u> provided qualitative information regarding the movement of fluid in the vicinity of holes interconnecting a closed compartment with the external stream, and also some information regarding the concentration distribution of the mixture.

The two-dimensional flow has been studied in two different arrangements: first; when the compartment was filled with clear water, and external wind was simulated by water with aluminium powder. These tests provided information regarding the mixing processes, and the density gradients, on a time base.

The second series of tests was designed to study the motion inside the compartment with suspended aluminium powder was introduced to the flow outside and also inside of the compartment. In both cases, motion pictures with increased speed were taken and viewed at reduced speed to allow detailed study.

Tests In The Wind Tunnel were mainly quantitative. In order to eliminate the effect of the shape of the building the rectangular compartment was attached to the testing section of the wind tunnel, with one side matching with the internal surface of the testing area. The whole box was outside the tunnel. Each test started with the compartment filled with either carbon dioxide or nitrogen. The only opening into the box was through the side attached to the tunnel.

The percentage of oxygen in the compartment was recorded at regular time intervals while a controlled air flow was provided in the tunnel.

From these records rate of air exchange in the box was calculated, for different external flow rates, and for different testing conditions.

Results Of The Tests

The model used for test was a box of internal dimensions of 2 x 10 x 15 inches, made from the plexiglass. The wall 2 x 15 inches and 0.25 inches thick was subjected to the external air flow, along the longest side (15 inches)

For each test, the concentration of either Nitrogen or Carbon Dioxide against time, was plotted in a semilogarithmic form.

Typical examples of these graphs, for the holes 10 inches apart and for porous material are shown on Fig. 4 and 5 respectively.

These graphs prove that an exponential function very close represents the actual phenomena of the air exchange.

$$C = C_o e^{-Rt} \qquad \text{(a)}$$

Where:

C = concentration inside the box after time t
C_o = initial concentration
$R = \frac{Q_e}{V}$ number of air changes per unit time
Q_e = effective flow
V = volume of the box
t = time

Originally this equation was developed, with the assumption of perfect mixing in the box.

Good agreement with the tests however, indicates that the sample of gas represents an average concentration, or that the method of sampling records the conditions at one particular point in the box.

In both cases it is justified to use an exponential function, to estimate the rate of air exchange 'R'.

From the diagrams similar to Fig. 4 and 5 the rate of the air exchange 'R' was determined as the slope of the curve corresponding to the particular velocity.

The effect of the location of two holes of the 0.125 inches diameter, symmetrically located along the tested side of the box is presented on Fig. 6.

The extreme case of the reduction of the distance, between holes is also presented on the same figure, when only one hole in the center of 0.177 in diameter, is used. The cross-sectional area of one hole corresponds to the total area of two holes of 0.125 in. diameter.

Following the same procedure the effect of turbulent flow and thickness of the wall are shown on Fig. 7 and Fig. 8 respectively.

The ventilation efficiency through the porous wall was determined by replacing the tested side of the box (2 x 15 inches) by porous material.

The result of the tests for three different porous materials are presented on Fig. 9.

Feasibility of being able to predict rate of air changes

The study of the rate of air change in buildings is closely related to the mass-transfer process.

The discussion is limited to the binary system only. Further it was assumed that pressure and temperature are uniform and constant in time.

The diffusion process could be considered as equimass when Nitrogen is used since the properties of Nitrogen are very close to the air properties as shown on Table 1.

A number of tests have been repeated in the same conditions using Nitrogen and Carbon Dioxide. The results of the tests were practically the same. The difference in properties between CO_2 and air have negligible effects on the test results.

Table 1

Property Values for air, nitrogen and carbon dioxide at atmospheric pressure and 80°F (17).

	g lb/ft^3	Cp Btu/UF°	μ lb/sec. ft.
air	0.0735	0.2402	12.41×10^{-6}
N_2	0.0713	0.2486	11.99×10^{-6}
CO_2	0.1122	0.2080	10.05×10^{-6}

The rate of air change in each compartment in a building is a function of a number of independent parameters.

This discussion covers only mass transfer process as effected by the gradient of concentration in time. It is assumed that external pressure distribution, as a result of the nature of the wind is estimated by statistical analysis, and that air leakage value, or discharge coefficients for windows, doors and other external or internal components of a building are known (1), (10), (11).

From this information the pressure gradient, as a function of time across each opening (cracks of porous components) could be calculated and consequently the air flow or pulsation estimated, analytically, or by electrical model. This procedure gives total actual flow Q_a through each external component, and across partitions inside.

To predict rate of air changes R, the effective value for flow (Q_e) should be used, as indicated in equation (a).

The importance of distinguishing between actual value of flow (Q_a) and effective (Q_e) is not always fully recognized. It is probably because the method of tracer gas is used for experimental measurement of the rate of air change, to determine heat losses, when practically perfect mixing takes place.

In this discussion when an attempt is made to estimate the value of effective flow Q_e by calculation the coefficient of mixing efficiency K is used in euqation

$$Q_e = K\,Q_a$$

The mixing coefficient K has been determined experimentally for the model described before, for one hole of 0.125 in. diameter, and wind velocity 32 ft./sec. The actual flow Q_a measured by a sensitive hot wire anemometer, and effective value of flow Q_e by measuring gas concentration. From this test the average value of K is 0.845. The pulsation mode was predominant in this test, the effect of convection by eddies has been reduced by increase length of hole to one inch. The mixing coefficient K, for the same condition as tested, was also determined by calculation. A square wave of the predominant frequency and average amplitude as recorded was used, and amount of air remaining in the box after each pulse was calculated as effective flow. This calculation gives value for K = 0.879, and was based on a simple assumption that the out-flow is composed of the mixture in the semi-sphere with the centre located in the center of the hole inside the box. The volume of the semi-sphere is equal to the volume of the inflow quantity per impulse.

The calculated value of the coefficient K for pulsating flow for different hole diameter, and different average flow per cycle is illustrated on Fig. 10. This simplified assumption works satisfactorily for a pulsating flow. For the other type of air changes when through flow is predominant it is necessary to estimate the gradient of concentration as a function of time.

The author suggests to use the following hyperbolic function:

$$C_x = \frac{C_B}{2}\left(\tanh \alpha\frac{x-ut}{\beta t} + 1\right)$$

Where:

C_x = concentration at distance x
C_B = concentration inside compartment
x = distance from initial interface between two gases
u = velocity of flow
t = time
α = coefficient controlling model of flow
β = coefficient depended on the rate of diffusion

This equation gives concentration distribution as a function of time along the normal to the surface of constant concentration in the concentration field.

Figure 11, illustrates the concentration distribution for U = 0, C_B = 100, α = 1, β = 0.1 for the time intervals of 1, 2, 10 and 30 seconds, and Fig. 12 for concentrations; C_B = 100, 90, 80 and 70 percent, α = 1, β = 0.1, and velocity U = 0.2 cm/sec for time 0, 1, 2 and 4 seconds.

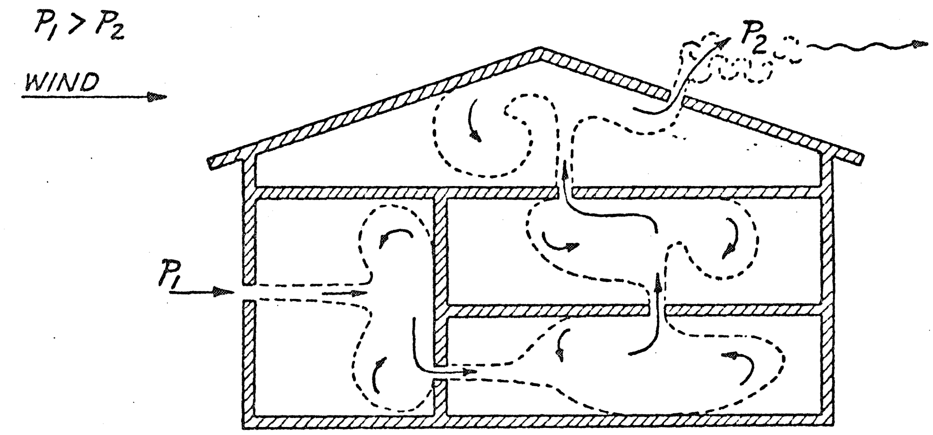

FIG. 1 - THROUGH FLOW $P_1 > P_2$

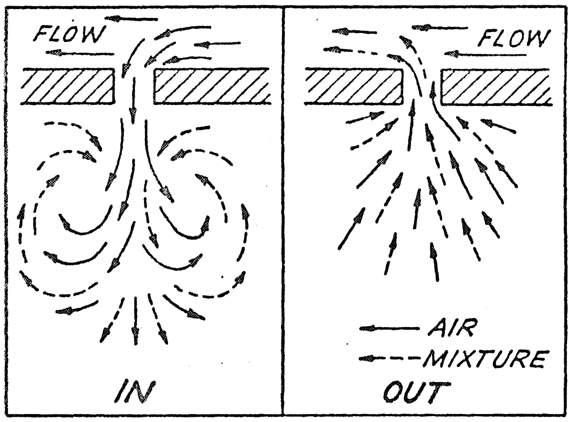

FIG. 2A - PULSATION. ONE HOLE

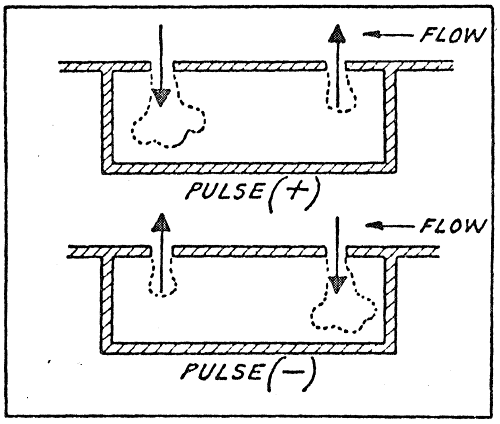

FIG. 2B - PULSATION. TWO HOLES

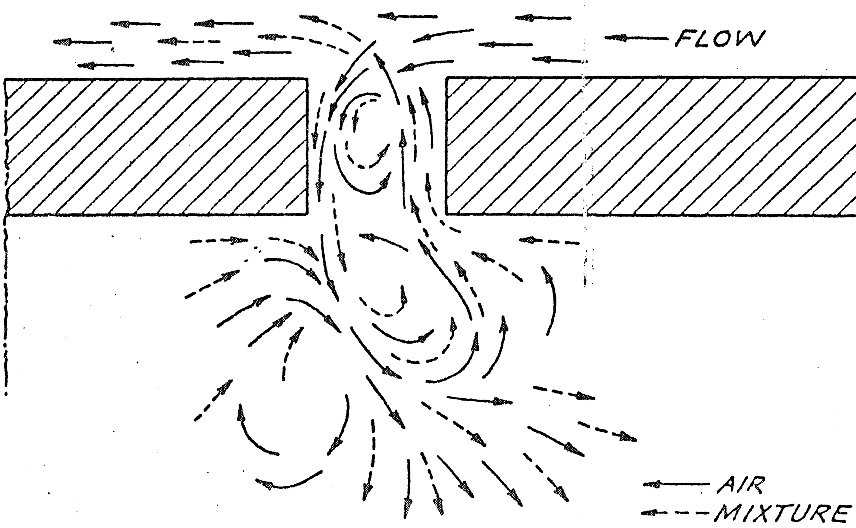

FIG. 3 - AIR EXCHANGE BY PENETRATION OF EDDIES

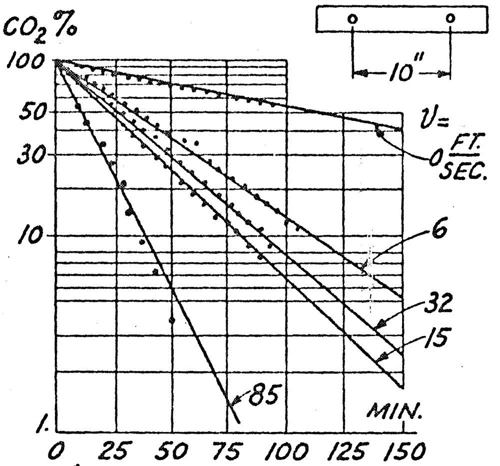

FIG. 4 - CO_2 CONCENTRATION FOR TWO HOLES

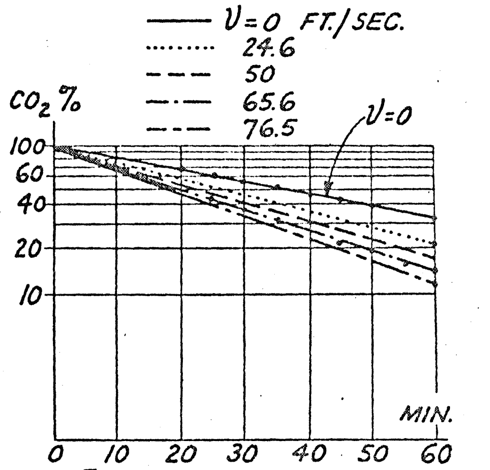

FIG. 5 - CO_2 CONCENTRATION FOR POROUS MATERIAL

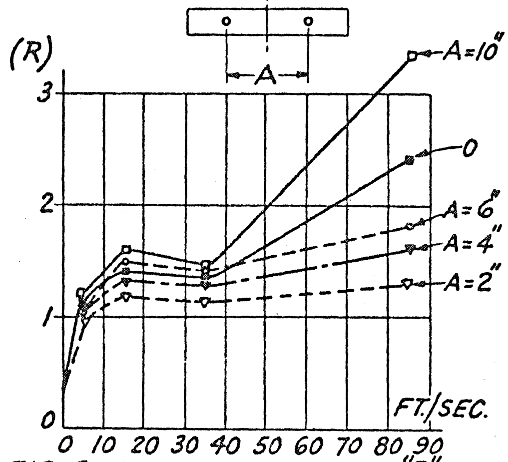

FIG. 6 - RATE OF AIR CHANGE "R" FOR DIFFERENT DISTANCES BETWEEN HOLES

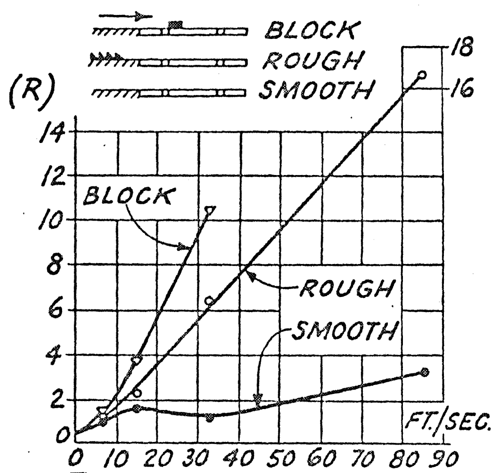

FIG. 7 - EFFECT OF TURBULENCE ON THE RATE OF AIR CHANGE "R"

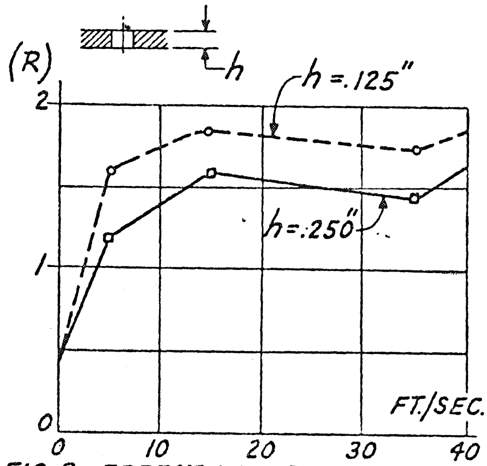

FIG. 8 - EFFECT OF THE THICKNESS OF WALL ON THE RATE OF AIR CHANGE

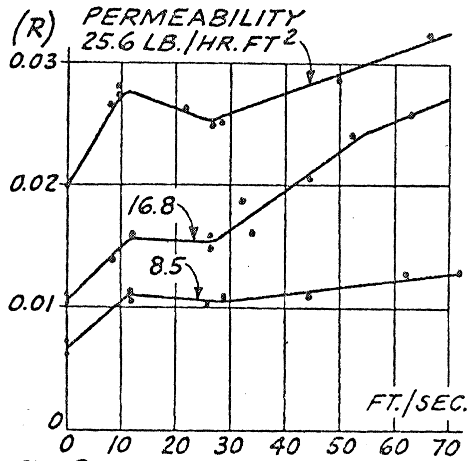

FIG. 9 - PERMEABILITY EFFECT ON THE RATE OF AIR CHANGE "R"

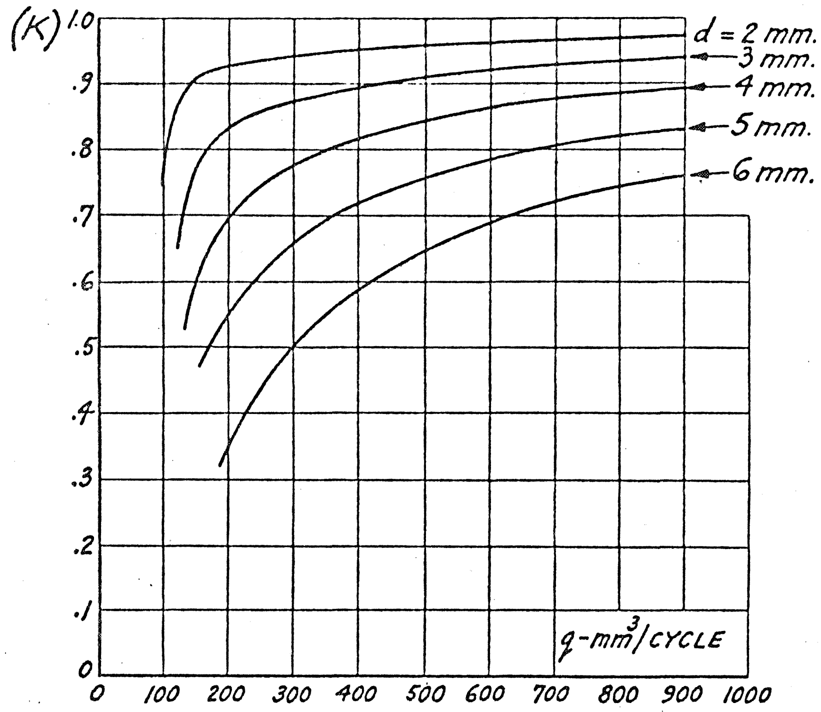

FIG. 10 - COEFFICIENT MIXING EFFICIENCY K FOR PULSATING FLOW (THEORETICAL VALUE)

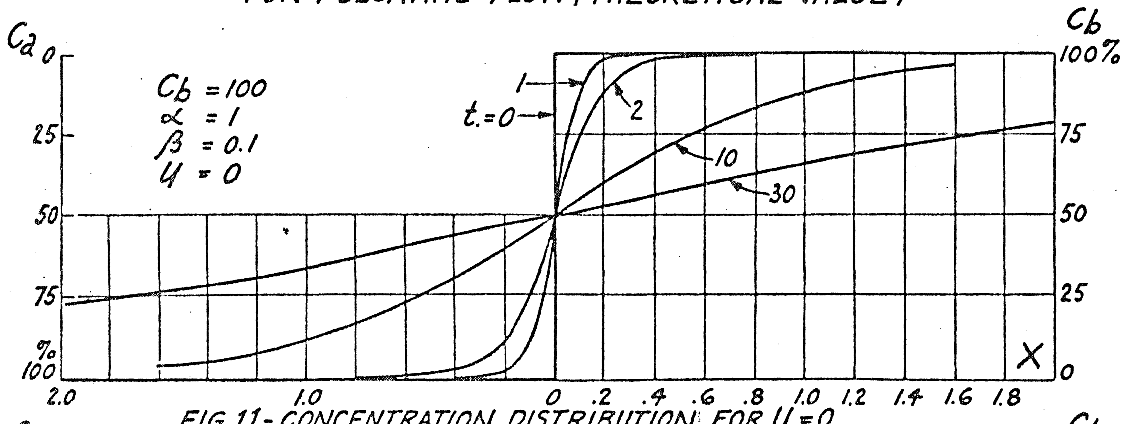

FIG. 11 - CONCENTRATION DISTRIBUTION FOR U = 0

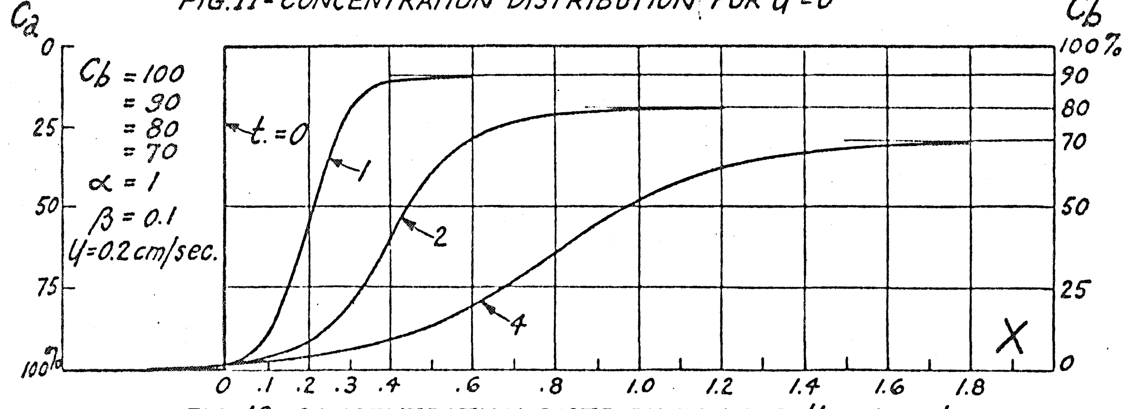

FIG. 12 - CONCENTRATION DISTRIBUTION FOR U = 0.2 cm/sec.

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Comment by T. A. Wyatt

Professor Mackey had asked for some clarification of the difference between the criteria suggested by the authors and the much lower value of 5 m/s at 3 m above ground that has been used to assess projects in the U. K..

Mr. Eaton has commented on the use of the 5 m/s criterion at the Building Research Station and pointed out that this is a comfort criterion.

I would like to emphasise that I feel strongly that if open spaces between buildings are to be regarded as an amenity they must be comfortable to a pedestrian--at least for most of the time, although I consider that "uncomfortable" conditions might be permissible say 5% of time, certainly more often than one could tolerate dangerous conditions.

The comfort condition is temperature dependant, and 5 m/s has been related to 10° c. This is perhaps particularly relevant to the United Kingdom climate. Higher speeds would be relevant to warmer regions, whereas in colder conditions pedestrians probably do not expect to be comfortable unless comprehensively protected by clothing.

The 5 m/s value may well be restrictive in design, but at least in the U. K. climate I believe some such limit must be set if the town is to remain a pleasant environment for the activities that we presently associate with it.

DISCUSSION OF PAPER I-13 BY H. K. MALINOWSKI

WIND EFFECT ON THE AIR MOVEMENT INSIDE BUILDING

Question by P. C. Chang

I would like to comment Prof. Malinowski's paper by reporting a similar study conducted in the University of Utah. We performed a simulation study on flow exchange through a spherical dome building in a laboratory water tunnel. It was mainly to study the urgent condition encountered in the incidence of a sudden rupture of a contaminent container, such as a nuclear reactor. The contaminent leakage within the building introduces the problems of expedient ventilation through the building for various outside meteorological conditions. The effluent with time-dependent sourse strength due to pollutant dilution inside the building will subsequently diffuse downstream into a building-distorted flowfield with a separation cavity and a turbulent wake.

The dilution rate of contaminent source inside the building due to the leakage excited dynamically by the external flow was found to follow an exponential decay as reported by Prof. Malinowski. The rate of exponential decay depends upon the configuration of hole openings and correlates remarkably with the pressure distribution around the sphere. This means Prof. Malinowski's first mode of air exchange is generally predominant if we have more than one opening. To account for the unsteady behavior of the effluent, we nondimensionalized the concentration profiles at various positions downstream in wake by the source strength at the time of observation. The effect of the distorted flowfield on the diffusion behavior is observed by comparing the experimental data with the simple Gaussian distribution or with the linearly-superimposed multiple Gaussian distribution. At a short distance downstream from the building, strong effect of the cavities embeded in the wake flow is observed from the significant deviation of the concentration profile from the Gaussian distribution. It indicates that the build-up and recirculation vicinity of building and thus creates an environmentally hazardous area. The contaminent is emitted from the cavity and the diffusion process approaches the normal distribution as the distance traveled downstream increases.

Author's reply

I thank you to Dr. P. C. Chang for his comments. The condition for the first mode (through flow) to be predominant, is not only, more than one opening, but also requirement that openings are located in areas of different pressure.

It seems natural that Gaussian solution do not give satisfactory answer, close to the building, and particularly for sudden impulse.

Our research is concerning effect of the natural wind, and do not include sudden impulse due to explosion.

DISCUSSION OF PAPER I-14 BY B. ETKIN

INTERACTION OF PRECIPITATION WITH COMPLEX FLOWS

Question by N. M. Standen

Have you made any estimate of the noise levels associated with the air curtain over a stadium? If such noise would be a problem, what means would you propose to alleviate it?

Author's reply

I have estimated the jet noise using Lighthill's theory and appropriate empirical data. It is not large enough, for the jet speeds used, to constitute a problem. This is because of the γ^8 law for jet noise. The major noise problem would, I think, come from the motors and blowers. These would have to be silenced by conventional acoustical techniques. This might be a major factor in the design and cost of the system.

DISCUSSION OF PAPER I-15 BY H. ISHIZAKI AND I. W. SUNG

INFLUENCE OF ADJACENT BUILDINGS TO WIND

Question by P. C. Chang

I would like to point out that there exists three distinct types of micro-circulation patterns in the gap between the two same size buildings in the shear flow. When the gap width to the building height is sufficiently large, the wind separates from the building block and reattaches to a point close to the next building block. This type of wake-interference flow is characterized by a strong shear or mixing layer along the separation streamline. This phenomenon is basically unsteady with a periodic "filling" and "emptying" of the cavity with fresh ambient fluid. If the gap width is close to the building height, there is a tendency to form a single, stable but slightly skewed vortex which is maintained through transmission of shear stress from the ambient fluid at the upper limbs. Still another type of flow is observed when the street width is much smaller than the building height, and multi-vortices rotate alternately in opposite directions inside the depression.

I would also like to know the detailed procedure the authors used to measure flow characteristics inside the gap. I feel the application of hot wire anemometer is not straight forward due to the appearance of large scale building-generated vortex motion which has unknown mean flow direction.

Reply by H. Ishizaki

Although the airflow in gap is turbulent, we made a measurement of the wind velocity in gap by a hot-wire anemometer. A hot-wire anemometer which was used in this study was suspended toward altitude and so we almost took away the characteristics of direction of them.