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Experimental studies on natural ventilation

by

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SYNOPSIS

Natural ventilation, or airation and infiltration, of buildings or rooms must be considered with respect to the kind, usage and construction of the structure concerned, taking account of its primary merit and demerit, that, while it replaces foul air with fresh one and lowers effective temperature in hot weather by removing excessive heat and moisture, it imposes, on the other hand, an increased burden on the appliances of artificial heating, air-conditioning or dehumidification, if these are employed.

Natural ventilation is caused by wind pressure on the exterior of structures and the difference of temperature in and outside of structures. The amount of ventilation, an important item in the problem of natural ventilation, depends not only upon these external forces but upon the locality, shape and size of windows or other openings through which air is interchanged. The distribution of temperature and of the velocity of inside air flow is also an important factor for judging interior environment.

Though many a valuable information on natural ventilation has been made public, these are mostly on some special cases or other and there are few that may be considered fundamental and comprehensive. The purpose of this research is to study the whole aspect of natural ventilation by a series of comprehensive experiments and thus to clarify the relation between the natural ventilation and the design or construction of buildings, furnishing a reasonable formula to estimate the amount of ventilation taking consideration of factors such as the ratio of outlet and inlet areas and the coefficient of discharge of openings or cracks.

Chapter 1 of this paper deals with the theoretical analysis of natural ventilation. As for ventilation due to temperature difference a fundamental formula of the amount of ventilation has been derived from the Bernouilli's theorem, considering buoyancy, and the physical meaning of friction loss and neutral zone has been explained. As for that due to wind, the coefficient of pressure distribution has been defined basing on the shape of buildings as well as the location of openings and introduced into the formula.

Thus for the amount of ventilation due to both temperature difference and wind, the author got:

$$Q = \varphi \left\{ 2gh\Delta T/T_0 + \Delta P/\rho_0 \right\}^{1/2} A_2,$$

$$\text{where } \varphi = \left\{ K_2 + (T_0/T_1)^2 m^2 K_1 + r \right\}^{-1/2}$$

$$\text{and } \Delta P/\rho_0 = (C_1 - C_2)V^2/2g;$$

denoting by Q the amount of ventilation; g: the acceleration of gravity; h: the vertical distance between inlet and outlet; ΔT: the temperature difference between inside and outside airs; T_1, T_0: the absolute temperatures of inside and outside airs; ΔP: the difference between the pressure in the vicinity of inlet and that of outlet; ρ_0: the density of outside air; A_2: the area of outlet; K_1, K_2: friction factors for inlet and outlet ($K = \alpha^{-2}$, in general, where α denotes the coefficient of discharge of the opening concerned); m: opening ratio, ratio of outlet area to inlet area; r: a factor for interior friction; C_1, C_2: the coefficients of pressure distribution at inlet and outlet; and V: wind velocity.

In Chapter 2 are discussed methods of measuring very slow air flow making reference to the development of an improved method with carbon-dioxide and the calibration of a modified electric Kata-thermometer.

The case treated in Chapter 3 is the case when the inside temperature is higher than the outside one. Described are the results of experiments on the amount of ventilation carried out at various temperature differences using model structures with inlets and outlets of various types and opening ratios; accounts are also given of the mean inside temperature, the neutral zone and the coefficient of discharge.

In Chapter 4 are described the results of model experiments of the case when the inside temperature is lower than the outside one. In this case, however, experiments were carried out, instead of under actual temperature differences, by mixing the inside air with carbon-dioxide gas and thus making the density of the inside air as much higher than that of the outside air so as the density differences correspond to the intended temperature differences.

Chapter 5 deals with the coefficient of discharge, measured for circular openings and some typical cracks of windows or doors. The measurement of the coefficients has been extended into a range of small Reynolds' number, a range that had so far been passed by unnoticed.

For the measurement of air flow in the experiment of airation, carried out with a three-storied model structure resembling apartment-houses or school houses and described in Chapter 6, a modified electric Kata-thermometer of the author's invention was used. By this experiment, the effects of the direction of wind, the locality of a set of rooms and the arrangement of openings of various sizes on the exterior as well as the interior walls have been clarified. The results obtained by experiments were compared to those calculated by the formula.

If we consider proper shape factors and Reynolds' number, the results of this research may be applied to actual structures as a physical phenomena and the quantitative estimation of ventilation may be approached by the calculation formula. However, it must be borne in mind that since there are many complicated factors in the case of actual structures, concerning the external forces and the structure itself, the question is not so simple as in model experiments. It is, therefore, necessary for the estimation of the amount of ventilation to integrate practical experiences and further researches.

EXPERIMENTAL STUDIES ON NATURAL VENTILATION

By Takashi Shoda

(MS received June 12, 1950)

CONTENTS

INTRODUCTION

The condition of the air in buildings or rooms can be artificially regulated by means of heating or cooling and ventilating arrangements, the rooms being kept comfortable and hygienic and made suitable for manufacture, working or storage. The important thing is that the design and construction of the buildings or rooms should not conflict with such arrangements. It is true that air conditioning equipment is indispensable to large commercial and industrial buildings, but it is not an easy undertaking to apply such plans to small structures - particularly in Japan. Herein comes the need for natural ventilation; in fact, in such a case it is better to exploit natural ventilation architecturally than to rely upon unsatisfactory air conditioning equipment.

There seems to have been no important work in the U.S.A. on natural ventilation since Randall wrote on the subject in 1931. (Ref. 1). In Great Britain experiments have been carried out on a large scale into ventilation applied to two-storied dwellings. (1948) (Ref. 2).

The effect of natural ventilation on heat loss, infiltration of humidity (Ref. 3), etc., is large, but hitherto these aspects of natural ventilation have never been investigated quantitatively in detail. The writer hopes that in this paper he has clarified to some extent the basic nature of the formulae concerning the amount of ventilation.

To calculate the amount of ventilation by the use of CO_2 is a simple and good method, but the writer had not previously been particularly interested in the distribution of CO_2 in a room, or the density of air mixed with CO_2. In the present study, therefore, he examined these questions, and from these points of view experiments were carried out with rooms at low temperature. Further, the writer made an improvement on the carbon dioxide method hitherto in use, and found it a useful method for measuring air flow, particularly slow air flow or wind velocity below 1 m/sec. He also applied this method to the path of flow when the coefficient of discharge was measured, and was able to find out the properties of openings and cracks which no other methods had succeeded in obtaining. In the writer's opinion we may be able to obtain a satisfactory method for testing various kinds of sashes by further improving the CO_2 method.

In the case of both natural and artificial ventilation it may be said that the velocity of air flow in a room is small; and further, the direction of flow varies with localities; the temperature, too, sometimes varies. There may be no method of measurement which suits all these conditions perfectly. In the present research the writer employed a new katathermometer of his own design, but he realises that further study is necessary in this direction.

In all the experiments, factors important in architectural technique, particularly the positions and forms of windows, openings for ventilation, cracks, etc., were dealt with under specific conditions so that useful features found in these experiments might be applied to architectural designs with little modification.

CHAPTER 1

FORMULAE FOR NATURAL VENTILATION

The formulae for natural ventilation of buildings or rooms, by temperature difference or wind, which have been published so far (Refs. 4 - 9) are described part-theoretically and part-experimentally.

Regarding ventilation by temperature difference, the writer derived a formula for the amount of ventilation from Bernouilli's theorem, as one of its applications (Ref. 11), taking buoyancy (Ref. 10) into consideration; and in this way he was able to explain the physical meaning of friction loss and of the neutral zone.

Ref. 1. W. G. Randall and E. W. Conover: Journ. H.P. & A.C. (Jan. 1931).
Ref. 2. Cyril Tasker: Heating and Ventilation, p.75 (Sep. 1949).
Ref. 3. Max. F. Mueller: Heating and Ventilation, p.63 (Aug. 1949).
Ref. 4. Watanabe: Principles of planning - Higher Architecture, part 23, pp. 47 - 57, (1937).
Ref. 5. Hirayama: Theories of designs in Architecture, pp. 133-145, (1948).
Ref. 6. Sato: Studies in buildings and their environs, pp. 101-105, (1948).
Ref. 7. K. E. Kunze: Gasschutz u. Luftschutz, (Juli, 1938).
Ref. 8. W. Matschinsky: Gesundheit-Ing., Nr. 31, S.361, (1933).
Ref. 9. Niitsu: Journal of Sanitary Engineering, (Jan.-Feb., 1950).
Ref. 10. Arakawa: Meteorological Thermodynamics, p. 51, (1941).
Ref. 11. Den: Chemical Engineering, pp. 1-81, (1944).

As for ventilation by wind, he considered relationships between the amount of ventilation and the shape of buildings and position of rooms through the coefficient of pressure distribution. He thus sought to combine the ventilations caused by these two agencies in simplified cases.

1.1 General Formula for Natural Ventilation

Let us imagine that between a and b of a flux tube illustrated in Fig. 1, heat H is applied to air of unit mass, and the air is moving upwards; P = pressure, u = mean velocity of air at each section, t, ρ = temperature and density of air.

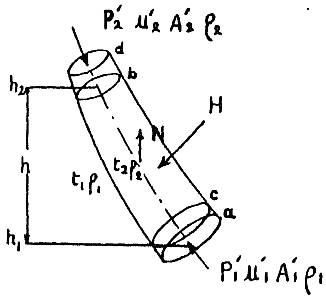


Fig. 1. Flux Tube.

The difference between the energy contained in the air of unit mass at a and that at b must become equal to the work or energy applied from outside.

Increase in kinetic energy $= (u'^2_2 - u'^2_1)/2g$,

Increase in heat energy $= E_2 - E_1$,

where $E = \int^t Cv\, dt$, Cv = specific heat at constant volume.

Work done by pressure $= P_1' A_1' u_1' d\theta - P_2' A_2' u_2' d\theta$

$= (P_1'/\rho_1 - P_2'/\rho_2)$,

where $A_1' u_1' \rho_1 d\theta = A_2' u_2' \rho_2 d\theta = 1$, θ = time.

Work done by buoyancy $= \int_a^b N dh = (\rho_1/\rho_2 - 1)h$, where it is assumed that the buoyancy, $N = (\rho_1/\rho_2 - 1)$, is constant in the flux tube.

Heat applied from outside = H

Equating the gain in energy to the total work done,

$$(u'^2_2 - u'^2_1)/2g + (E_2 - E_1) = (P'_1/\rho_1 - P'_2/\rho_2) + Nh + H \qquad (1)$$

If it is assumed that there is a friction loss F between a and b, and that it has been retained in the form of heat energy,

$$H + F = (E_2 - E_1) + W, \qquad (2)$$

where $W = \int_1^2 P dv$ = work of expansion.

The following is arrived at from (1) and (2)

$$(u'^2_2 - u'^2_1)/2g + F = (P_1'/\rho_1 - P_2'/\rho_2) + Nh + W, \qquad (3)$$

When P is taken as constant in the formula of an ideal gas, $P/\rho = bT$, and it is assumed that $T_2 - T_1 = \Delta T$. The work done by buoyancy, that is, the decrease in potential energy is

$$\int_a^b N\, dh = \int_a^b \Delta T/T_1 dh = h\Delta T/T_1, \qquad (4)$$

where ΔT is constant.

1.2 Ventilation by Temperature Difference, and the Amount of Ventilation.

Let us assume that there is a U shaped flux tube, as given in Fig. 2. The orifices are situated at O_1 and O_2. To unit mass of air between these is applied heat H from outside, and the air in the flux tube flows from the right of the tube to the left. The right limb corresponds to the external air, the left to a room and the orifices to openings such as windows.

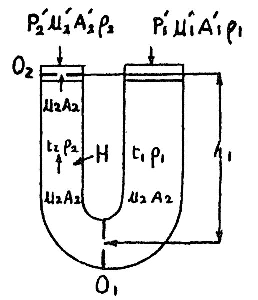


Fig. 2. Ventilation by Temperature difference.

When there is only temperature difference and no wind pressure, $P_1' = P_2' = P_0$

Work done by pressure $= (P_1'/\rho_1 - P_2'/\rho_2)$

$$= P_0(1/\rho_1 - 1/\rho_2) \qquad (5)$$

Work done by expansion $\quad W = \int_a^b P dv,$

If Δv represents the increase in volume which occurs when gas is transferred from ab to cd,

$$\Delta v = A_2' u_2' d\theta - A_1' u_1' d\theta = 1/\rho_2 - 1/\rho_1,$$

where $\quad A_2' u_2' \rho_2 d\theta = A_1' u_1' \rho_1 d\theta = 1,$

Since the pressure which is at work then is $P_1' = P_2' = P_0$

$$W = P_0(1/\rho_2 - 1/\rho_1) = -P_0(1/\rho_1 - 1/\rho_2) \qquad (6)$$

If (5) and (6) are taken into consideration with (3)

$$(u_2'^2 - u_1'^2)/2g + F = Nh. \qquad (7)$$

If in general we take K for the friction factor and u for the mean velocity at a section where friction occurs,

$$F = \Sigma K u^2/2g. \qquad (8)$$

If a is assumed to be the coefficient of discharge in the case of the orifice,

$$\alpha = K^{-1/2} \qquad (9)$$

when $\quad (u_2^2 - u_1^2)/2g \ll F$

$$\Sigma K u^2/2g = Nh. \qquad (10)$$

That is to say, the decrease in the work done by buoyancy or in potential energy is equal to the sum of friction losses.

If $\quad u_1 A_1 \rho_0 = u_2 A_2 \rho i = unAn\rho_1$, where $\rho_0 = \rho i$, $\rho i = \rho_2$,

$A_2/A_1 = m$, $Knun^2/2g = (A_2/An)^2 Kn$

is derived from $\quad P/\rho = bT$, and taking $u_2^2/2g = ru_2^2/2g$

then $$\Sigma K u^2/2g = \left\{K_2 + (T_0/T_1)^2 m^2 K_1 + r\right\} u_2^2/2g = Nh. \qquad (10')$$

The amount of ventilation Q_t is

$$Q_t = u_2 A_2 = \left\{K_2 + (T_0/T_1)^2 m^2 K_1 + r\right\}^{-1/2} (2gh\Delta T/T_0)^{1/2} A_2 \qquad (11)$$

If $\quad (T_0/T_1)^2 = 1$, $A_2/An = 0$

$$Q_t = (K_2 + m^2 K_1)^{-1/2} (2gh\Delta T/T_0)^{1/2} A_2 \qquad (11')$$

1.3 Neutral Zone in Ventilation by Temperature Difference

When the temperature inside a room is higher than that outside, the air flows out from an opening higher than a certain height and air flows in from an opening lower than this height. The space between these two is called the Neutral Zone. This is represented by n - n in Fig. 3.

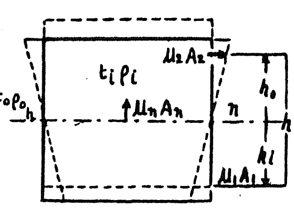


Fig. 3. Neutral Zone (The dotted lines indicate the distribution of pressure difference).

Some formulae for the amount of ventilation considered in these instances have been given by Randall and Conover (Ref. 1). What the writer proposes in the present discussion comes to the same thing as Randall's formula, but an interesting point in the writer's proposition is the fact that the mechanism of the Neutral Zone can be explained by taking buoyancy into consideration. The diagram in Fig. 3 corresponds to the left part of the U shaped flux tube shown in Fig. 2. The openings A_1, and A_2 correspond to the orifices O_1 and O_2. The air in the room is flowing upwards at a mean speed u_n. If (3) is applied to the space between A_1 and A_2 and expressed in the differential calculus,

$$dP/\rho i = N\ dh, \tag{12}$$

and

$$u'_1 = u'_2,\ F = 0,\ \rho_1 = \rho_2 = \rho_i,\ W = 0$$

This indicates that the pressure inside the room increases uniformly from bottom to top. If (12) is integrated between A_1 and A_2,

$$P_{A2} - P_{A1} = \rho_i\ Nh = (\rho_o - \rho_i)h, \tag{13}$$

That is to say the pressure difference at A_2 and A_1 in a room is equal to the decrease in potential energy. With $A_2/A_n = 0$,

$$\Sigma Ku'^2/2g = (K_1 u_1'^2 + K_2 u_2'^2)/2g = Nh. \tag{14}$$

If ΔP_1, ΔP_2 represent the pressure difference between the inside and outside the wall in the neighbourhood of the openings $A_1 + A_2$ $\Delta P_1/\rho_i = K_1 u_1'^2/2g$, $\Delta P_2/\rho_i$ *

$$= K_2 u_2'^2/2g \tag{15}$$

This should be $p_i^* = \rho_o$, but it is $\rho_i^* \doteq \rho_i$ in the neighbourhood of an outlet. From (14) and (15) we get

$$\Delta P_1 + \Delta P_2 = \rho_i\ Nh = (\rho_o - \rho_i)h_i \tag{16}$$

The relationships (12), (13) and (16) are graphically represented in Fig. 4.

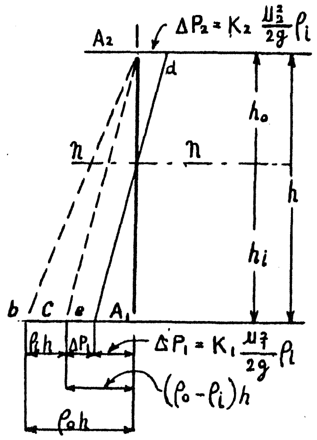


Fig. 4. Distribution of Pressure Difference and the Neutral Zone.

The pressure difference between the inside and the outside of the wall is A_2dne A_1 and the position for zero pressure difference is arrived at. This is the neutral zone. If an opening which is very small compared with A_1 and A_2 is made on the n - n line no air flows through the opening. By the use of smoke to make the air current visible the position is easily detected as described later. From Fig. 4 we arrive at the relationships between h and its distances h_o and h_i between the neutral zone and the outlet and inlet.

$$h_o = \Delta P_2/(\Delta P_1 + \Delta P_2)h = \left\{1 + K_1/K_2 . m^2\right\}^{-1} h. \tag{17}$$

when $K_1 = K_2 = K$

$$h_o = (1 + m^2)^{-1}h \qquad \text{or} \qquad h_i = m^2(1 + m^2)^{-1}h$$

Further, if $K = \alpha^{-2}$ is taken, (11') (18)

$$Q_t = \alpha\ (2gh_c\Delta T/T_o)^{1/2} A_2, \tag{19}$$

These are the formulae based upon the neutral zone; and Randall and his associate (Ref. 1) make $\alpha = 0.65$, $m = 1$ their standards.

1.4 Ventilation by Wind and the Amount of Ventilation

Let us consider a case in which there is no temperature difference between the inside and the outside of the room and only wind is present. If the pressure

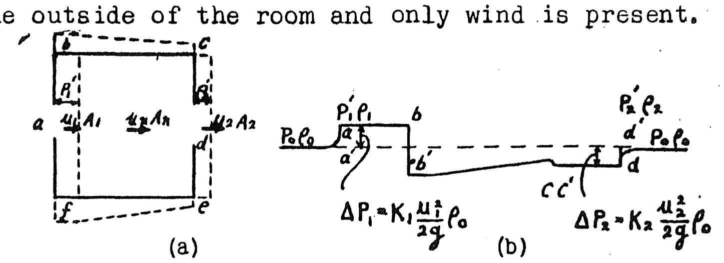


Fig. 5. Pressure Difference between the inside and the outside of the room in ventilation by wind.

distribution of wind (Ref. 12) round a building or room is as represented by the dotted lines in Fig. 5(a), let us assume that air flows from the opening A_1 to A_2. Work done by the pressure = $(P_1'/\rho_1 - P_2'/\rho_2) = 0$. (20)

∵ for an ideal gas $P/\rho = bT$, T = constant, the work of expansion

$$W = \int_a^d Pdv = bT\ln(P_1'/P_2') \doteqdot (P_1' - P_2')/\rho_2. \quad (21)$$

Work done by buoyancy = $Nh = (\rho_o/\rho_i - 1)h$, where h represents the perpendicular distance between the openings A_1 and A_2 in Fig. 5 (a). (22)

When there is no temperature difference between the inside and the outside of the room, $Nh \ll (P_1' - P_2')\rho_2$, or when $h = 0$, $Nh = 0$. Further, if $(u_2'^2 - u_1'^2)/2g \ll F$, (3) is

$$F = (P_1' - P_2')/\rho_2 \quad (23)$$

If the coefficients of pressure distribution (Refs. 13 & 14) at A_1 and A_2 are represented by C_1 and C_2 and the velocity of wind outside by V,

$$\Delta P = P_1' - P_2' = (C_1 - C_2)V^2/2g.\rho_o, \quad (24)$$

As before, $F = \left\{K_2 + (T_o/T_i)^2 m^2 K_1 + r\right\} u_2^2/2g$

If $\rho_2 = \rho_o$ is taken, we obtain the amount of ventilation Q_w from (23) and (24) as follows:

$$Q_w = u_2A_2 = \left\{K_2 + (T_o/T_i)^2 m^2 K_1 + r\right\}^{-1/2} (2g\Delta P/\rho_o)^{1/2}/A_2$$

$$= \left\{ \quad " \quad \right\}^{-1/2} (C_1 - C_2)^{1/2} VA_2 \quad (25)$$

If $(T_o/T_i)^2 = 1$, $A_2/A_n = 0$

$$Q_w = (K_2 + m^2K_1)^{-1/2}(C_1 - C_2)^{1/2} VA_2 \quad (25')$$

When the friction loss in a room is not taken into consideration, the distance between the line a'd' (broken line) and the line abb'cd in Fig. 5(b) represents the pressure difference between the inside and the outside of a room, and also shows that the outside pressure is large above the a'd' line and the inside pressure is large below the line. The a'd' line moves upwards when the opening ratio m is small, and downwards when m is large.

1.5 Comparison of the Amount of Ventilation produced by Temperature Difference to that by Wind.

Let us assume that there is an air flow at a section of a building or a room with a path as represented in Fig. 6.

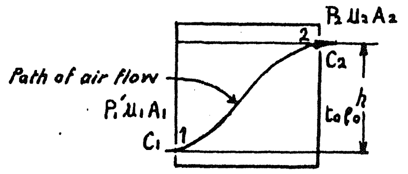


Fig. 6. Comparison between Ventilation produced by Temperature Difference and wind.

The equations (11) and (25) give

$$Q_t = \varphi(2gh\Delta T/T_o)^{1/2} A_2 \quad (26)$$

and $$Q_w = \varphi(C_1 - C_2)^{1/2} VA_2 \quad (27)$$

where $$\varphi = \left\{K_2 + (T_o/T_i)^2 mK_1^2 + r\right\}^{-1/2} \quad (27')$$

If (26) and (27) were represented graphically with T_o = 273 (C) they would be as shown in Fig. 7.

φ, A_2 are constant with reference to the same path of air flow. C_1 and C_2 vary greatly with the direction of wind, the shape of buildings, the position of openings, etc.

When we consider the cases $C_1 = 0.8$, $C_2 = 0.4$, $h = 2.5$ (m) we see that the Q_t of $\Delta T = 20$(C) is equal to Q_w of $V = 1.7$ (m/sec.); and that the Q_t of $\Delta T = 5$(C) is equal to Q_w of $V = 0.8$ (m/sec). There are a large number of localities where the mean wind velocity in winter is below 1.7 (m/sec.); and in ordinary dwellings

Ref. 12. Taniguchi: Architectural Review, No. 8, p. 53, (1938).
Ref. 13. Society for Architecture: Reinforced Concrete Structure: calculations explained p. 109 (1937).
Ref. 14. Muto: Journal of Architecture, pp. 144 - 231, (Feb., 1935).

the temperature difference between the inside and the outside of the room at night, particularly at dawn during summer sometimes reaches 5(C). Ventilation by temperature difference, therefore, must be considered in the same way as ventilation by wind.

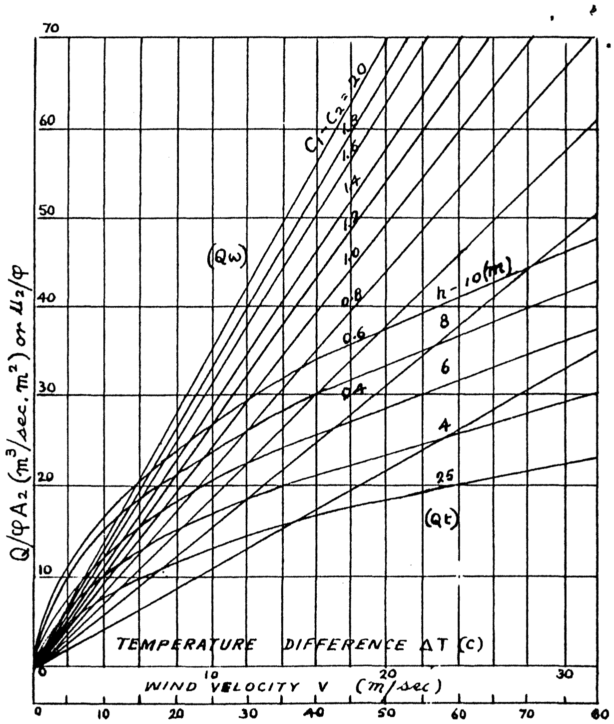


Fig. 7. Graphical Comparison between Ventilation Produced by Temperature Difference and Wind.

1.6 Amount of Ventilation when Temperature Difference and Wind are working at the same time. (Ref. 15).

In the three cases when the temperature difference works singly, when the wind works singly, and when they both work at the same time, we may consider that the path of air flow and the opening ratio vary in all cases. Further, there is also variation according to the extent of temperature difference and strength of wind. It is therefore exceedingly difficult to express in general formulae the amount of ventilation when both agencies work at the same time. However, by using the method described below, the writer believes that to some extent practical calculations are possible.

When the surface where the positive and negative pressures are produced by wind (chiefly facing the wind and with back to the wind) and the position of the opening are combined in various ways, there are nine combinations as illustrated in Fig. 8. The paths of air flow, when wind only and temperature difference only work through the openings, are formed as represented in columns 5 and 6 in Fig. 8.

Paths	Temp. Diff. Wind	Inlet (lower)	Outlet (upper)	Paths: Wind	Paths: Temp. Diff.
I	Facing Wind Back to wind	O —	O —	(a) (a′)	(b)
II	Facing Back	— O	— O	(a) (a′)	(-)
III	Facing Back	O —	— O	(a)	(b)
IV	Facing Back	— O	O —		
V	Facing Back	O —	O O		
VI	Facing Back	— O	O O		
VII	Facing Back	O O	O —		
VIII	Facing Back	O O	— O		
IX	Facing Back	O O	O O		

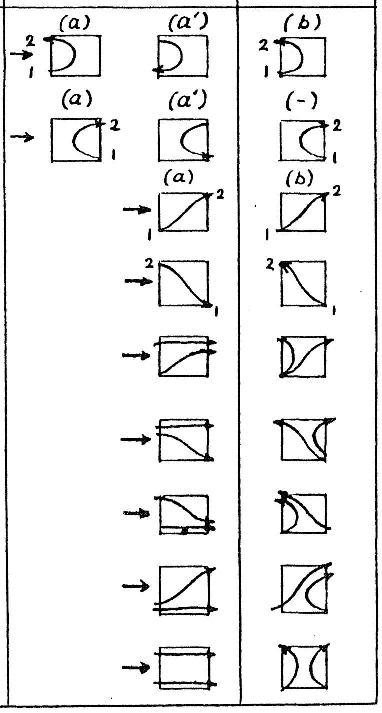


Fig. 8. Combinations of Paths of Ventilation.

Ref. 15. Shoda: Architectural Review, No. 38, pp. 100-102, (1949).

(1) When there is only one path of ventilation (Fig. 8).

When the direction of wind of I and III is reversed, II and IV are arrived at respectively. In these instances we can see that both the temperature difference and the wind work along the path shown in Fig. 6 at the same time; thus enabling us to apply (3).

The value of $(P_1'/\rho_1 - P_2'/\rho_2)\ \rho\ W$, with the ideal gas $P/\rho = bT$, that is, taking Fig. 9 into consideration, can be expressed:

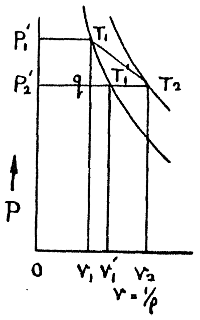


Fig. 9. Work done by Expansion and that by pressure.

$$(P_1'/\rho_1 - P_2'/\rho_2) = \square P'_1T_1v_1O - \square P_2'T_2v_2O$$

$$= -(\square P_2'T_2v_2O - \square P_2'T_1'v_1O)$$

$$= -\square T'/T_2v_2v_1'$$

$$W = \square T_1T_2v_2v_1$$

$$\therefore (P_1'/\rho_1 - P_2'/\rho_2) + W$$

$$= \square T_1T_2v_2v_1 - \square T_1'T_2v_2v_1'$$

$$= \square qT_1'v_1'v_1 + \Delta T_1T_1'q + \Delta T_1T_2T_1',$$

If the three R.H.S. terms are represented by A, B and C,

$$A = \square qT_1'v_1'v_1 = \square P_1'T_1qP_2' = \Delta P/\rho_1 = \Delta P/P_1'.bT_1,$$

$$B = \Delta T_1T_1'q = (P_1' - P_2')(v_1' - v_1)/2 = (\Delta P)^2/2P_1'P_2' - bT_1,$$

$$C = \Delta T_1T_2T_1' = (P_1' - P_2')(v_2 - v_1')/2 = \Delta P/2P_2'.b\Delta T,$$

$$P_1' \doteqdot P_2' = 1(\text{atm}) = 10340\ (\text{kg/m}^2),\quad P_1'-P_2' = \Delta P = 50\ (\text{kg/m}^2)$$

If we take the above, B is very much smaller than A, but if $T_1 = 273(C)$, $\Delta T = 30(C)$, then C is about 1/20 of A. If B and C are ignored, and $\rho_1 = \rho_0$

$$(P_1/\rho_1 - P_2/\rho_2) + W \doteqdot \Delta P/\rho_0, \qquad (28)$$

The equation (3) is

$$Q = \varphi\left\{2gh\ \Delta T/T_0 + \Delta P/\rho_0\right\}^{1/2} A_2, \qquad (29)$$

where

$$\varphi = \left\{K_2 + (T_0/T_i)^2m^2K_1 + r\right\}^{-1/2}$$

$$\Delta P/\rho_0 = (C_1 - C_2)V^2/2g$$

Referring to Fig. 8, in I (a) and (b); II (a) and (b); and III (a) and (b) the two agencies add to each other, whereas in I (a') and (b); II (a') and (b); and IV (a) and (b), they cancel each other out. Under these conditions, the

	$\frac{\Delta T}{T_0}h$	$\frac{\Delta P}{\rho_0}$	Direction of air flow
I (a) (b)	+	+	
II (a) (b)	+	+	$1\rightarrow2,\ h\Delta T/T_0 + \Delta P/\rho_0>0$
III (a) (b)	+	+	
I (a') (b)	+	−	
II (a') (b)	+	−	$1\rightarrow2,\ h\Delta T/T_0 - \Delta P/\rho_0>0$
IV (a') (b)	+	−	$2\rightarrow1,\quad <0$

Table 1. Ventilation by a combination of Temperature Difference and Wind.

symbols inside | | in (29) and the direction of air flow are as indicated in Table 1 (See also Fig. 8).

The wind velocity and temperature difference corresponding to $h\Delta T/T_0 - \Delta P/\rho_0=0$ can be obtained from the intersection points between Q_t and Q_W in Fig. 7.

(2) When there is more than one path of ventilation (Fig. 8)

V - IX may be said to be combinations of I - IV, but it appears that it is impossible to express the air flows produced in a general formula when the two agencies are combined. In those which contain the paths III the two agencies add to each other; when there is more than one path, they cancel each other out and the amount of ventilation never becomes zero; and finally in IX there is no change in the effect of ventilation even when the direction of the wind is reversed.

The procedure to be followed, therefore, when the temperature difference and the wind are considered at the same time, is as follows: the pressure distributions by wind pressure and temperature difference being taken into account at the same time, we should first obtain the two cases of maximum and minimum ventilations under the given conditions, and should consider the minimum case for the calculation of exchange of air in the room or expulsion of heat thereby, and the maximum case for the calculation of heat loss by ventilation.

CHAPTER II

MEASUREMENT OF THE AMOUNT OF VENTILATION

The measurement of ventilation of buildings or rooms are of two kinds.

(i) If the inlet and outlet enable us to measure the velocity of the air flow there, the amount of air flow can be obtained so long as the area of the section of the flow is also known.

(ii) If the inlet and outlet are dispersed, or it is not possible to measure the velocity of the air, the amount of flow itself is measured. In the first case, suitable anemometers are generally employed according to wind velocities. For example, they are the pilot tube, wind-mill anemometer, thermic ray anemometer, kata thermometer, etc. In the second case, the amount of air flow is obtained from the reduction in percentage of carbon dioxide, smoke, etc., mixed in the air, or from the calculation of the loss or gain of heat which has been provided to the room. Numerous methods have been employed for these purposes for a considerable time. (Ref. 16).

The measurement of ventilation for a very large building or room, apart from the first case mentioned above, is almost impossible. Practically speaking, calculation is the only method. In this chapter the writer examines experimentally the method of measuring the amount of air flow by means of carbon dioxide, describes a new kata thermometer, and deals with the basic theories relating to his experimental study.

2.1 Measurement of Air Flow by CO_2 (1)

If it is assumed that there is a ventilation of Q (m^3/sec) in a room as represented in Fig. 10, $C\alpha$, C representing CO_2 percentages (o/vl) inside and outside the room, v (m^3) the volume of the room, and θ (sec) the time,

$$(C_\alpha - C)\ Q\ d\theta = VdC \tag{30}$$

$$Q = 2.3\ V/\theta . \log \left\{(C_0 - C_\alpha)/(C_0 - C_\alpha)\right\} , \ (m^3/sec) \tag{31}$$

where at $\theta = 0$, and $\theta = \theta$ then $C = C_0$, and $C = C_\theta$

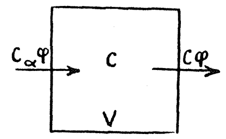


Fig. 10. Reduction in CO_2.

The equation (31) is known as Seidel's formula. The carbon dioxide in the atmosphere is approximately 0.04 (o/vl). This is negligible, so

$$Q = 2.3\ V/\theta . \log C_0/C_0 \ (m^3/sec.) \tag{32}$$

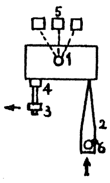
If the percentages of carbon dioxide are uniform in a room, the amount of ventilation can be obtained from two sets of observations of percentages and time; and if the area of section of an opening is known, u, the mean velocity of wind at that position is

$$u = Q/A \tag{33}$$

Ref. 16. H. Wolpert: Arch für Hygiene, Bd. 52, (1905) In this experiment the writer chiefly examined the question as to the condition in which (32) becomes practicable when Q, a certain amount of ventilation occurs in a room (box) in which the air is mixed with carbon dioxide.

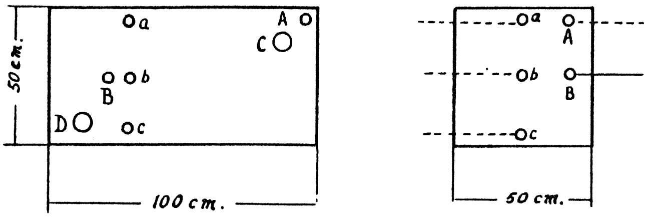
2.1.1 Method of Experiment

Here, we have a box, as represented in Fig. 11 and Fig. 12 of dimensions 50 X 50 X 100 (cm^3). In this box a certain amount of ventilation is carried out by means of a blower and regulating valve. The air mixed with carbon dioxide for the box is taken from the a, b and c positions as indicated in Fig. 12; CO_2 percentages are read off from three interferometers, and CO_2 percentage curves are obtained. The box is provided with a hand-driven fan with which the air is agitated so that the carbon dioxide is uniformly mixed with air. A kata thermometer or wind-mill anemometer is placed at the inlet in a position as is illustrated in Fig. 13 and the wind velocity at a section of the cylinder is read off.



1. CO_2 box
2. Inlet
3. Blower
4. Regulating valve
5. Interferometers
6. Kata thermometer

Fig. 11. Arrangement for Expt. (1).



A Inlet for CO_2
B Thermometer
C Inlet
D Outlet
a,b,c For collecting air

Fig. 12. Arrangement for Experiment (2).

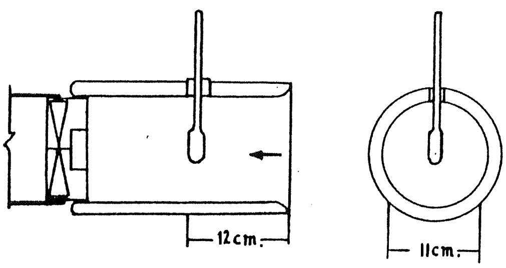


Fig. 13. Kata Thermometer and Windmill Anemometer

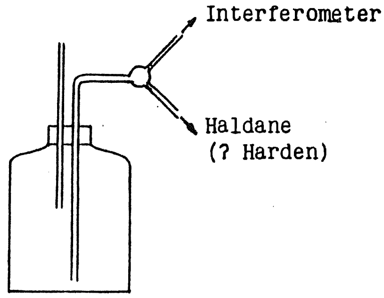


Fig. 14. Testing by Interferometer

2.1.2 Measurement of CO_2 percentages

The measurement of CO_2 percentages is done by means of the interferometer (Refs. 17 - 19). The same material (carbon dioxide) is submitted to testing by Haldane's analyser (Ref. 20) and the interferometer, as illustrated in Fig. 14. The comparison of readings between the two meters is represented graphically in Fig. 15.

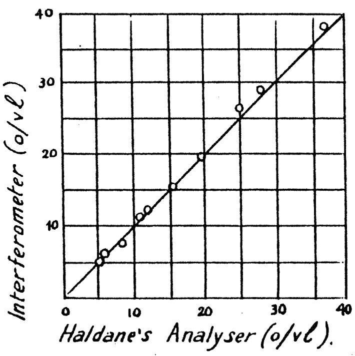


Fig. 15. Comparison between Interferometer and Haldane's Analyser.

Ref. 17. Majima: Experiments in Applied Physics, p. 173, (1940).
Ref. 18. Tsuji: Riken Iho (Bulletin of Riken), Vol. 8, No. 11, pp. 871 - 882, (1929).
Ref. 19. Yamao: Riken Iho, Vol. 14, No. 1, pp. 20 - 28, (1935).
Ref. 20. Handbook of Practical Chemistry, part 2, p. 312 (1941).

Fig. 16 gives a comparison between three interferometers which were examined in the same way.

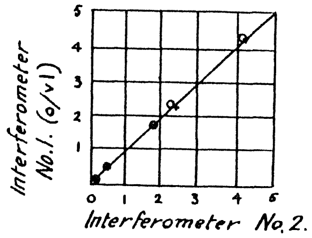


Fig. 16. Comparison between the three Interferometers.

If q represents the air mixed with carbon dioxide collected for the purpose of quantitative analysis of CO_2, and Q' the amount of ventilation by means of the blower, then at

$u = 0.05$ (m/sec),
$q = 0.27 \times 10^{-4}$ (m^3/sec),
$Q' = 0.05 \times \pi\ (1.1)^2/4 \times 10^{-4}$ (m^3/sec),
$q/Q' = 0.056$

Thus it was decided that the collected amount, q, was negligible.

2.1.3 Distribution of CO_2 percentages in the Box

The air inside the box was stirred at Q = 0 without the use of the blower so that the carbon dioxide percentages became uniform; and after that, the percentages were measured without agitation. Fig. 17 gives the result of the measurements. The percentages decrease slightly due to the collection, but so long as the amount of ventilation is very small, the carbon dioxide percentages are almost uniform. This appears to indicate that the uniformity in percentages is not disturbed in air mixed with carbon dioxide themselves (or itself). (Translator's Note: The word 'self' is used in the original, though the meaning is not clear to the translator).

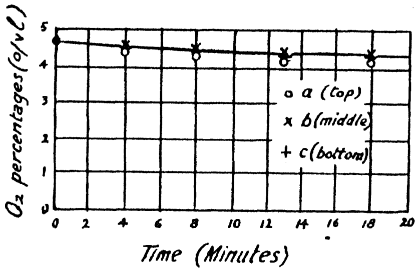


Fig. 17. Reduction in Percentages when Q = 0.

Let us see what happens when ventilation begins when, until now, uniformity has been kept in carbon dioxide percentages. As is represented in Fig. 18(a), great unevenness in percentages occurs at first, but later the percentages become generally uniform. In order to calculate the amount of ventilation from a certain percentage in the box by the equations (31) or (32) it is necessary to see that the carbon dioxide percentages in the room (or box) should be reduced uniformly. For this purpose, the writer gently agitated the gas with a fan. The result of this is shown in Fig. 18(b). When this operation was carried out, the writer made the agitation in such a way as to keep the kata thermometer at the inlet unaffected, and he regarded the agitation as making no difference to the amount of ventilation.

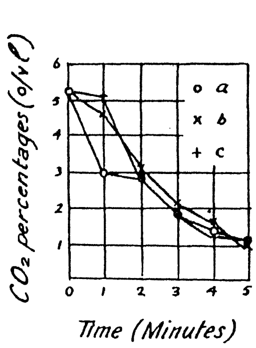


Fig. 18(a) When not Agitated.

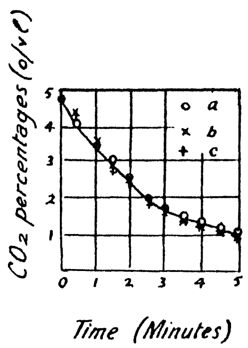


Fig. 18(b) When Agitated.

2.1.4 Wind Velocities by CO_2 Method and by Kata Thermometer. (Ref. 21)

The kata thermometer used by the writer was one made in Japan. He calculated the wind velocity by the Kata-factor (K.F.) of the Kata thermometer and used the measured values of temperature and time in the formula given by L. Hill, thus obtaining the wind velocity.

$$\left.\begin{array}{l} u>1 \text{ (m/sec)},\ H = (0.13 + 0.47\ u^{1/2})\Delta t \\ u<1 \text{ (m/sec)},\ H = (0.20 + 0.40\ u^{1/2})\Delta t \end{array}\right\} \quad (34)$$

where $H = (K.F.)/\theta$: (millical/cm^2sec), θ:sec,
$\Delta t = 36.5 - t_\alpha$; t_α = air temperature (C).

Ref. 21. Shoda: Studies in production, Vol. 2, No. 1, p. 16, (1950)

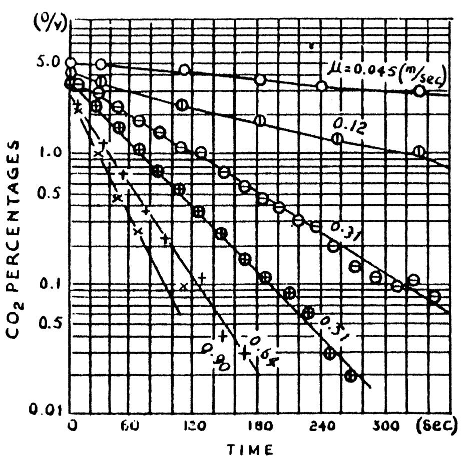


Fig. 19. Relationships between CO_2 percentages, Time and Velocity of Flow.

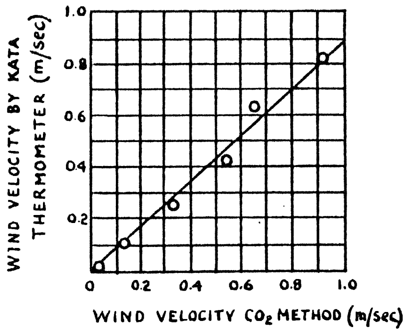


Fig. 20. Wind Velocities by CO_2 method and by Kata Thermometer.

If the relation of the CO_2 values to the time is drawn on logarithmic graph paper, we may plot all observations in straight lines as represented in Fig. 19, thus indicating that (32) is quite possible.

The relationship between the wind velocity by the CO_2 method and that by the Kata thermometer can be expressed almost in a straight line, as represented in Fig. 20.

2.1.5 Wind Velocity by Kata Thermometer and by Windmill Thermometer.

If the wind velocity by Kata thermometer is compared with that by the windmill thermometer for the same amount of flow, that is, wind velocity, as is clear in Fig. 21, the wind velocity by windmill thermometer gradually decreases under 1 (m/sec), and in the neighbourhood of 0.3 (m/sec) the windmill stops.

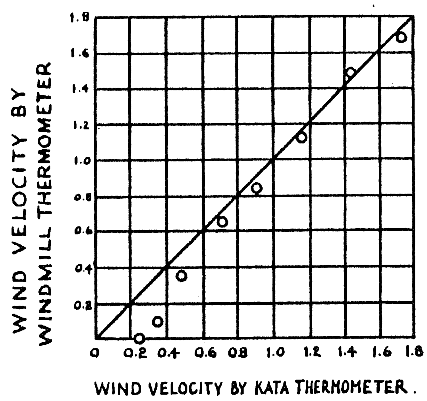


Fig. 21. Kata Thermometer and Windmill Thermometer.

2.2 Measurement of Air Flow by CO_2 (2)

As explained in 2.1, if the carbon dioxide percentages are uniform in the room (box), it is possible to find out the amount or velocity of air flow by a simple formula such as (31); but when there is ventilation the uniformity in carbon dioxide percentages is disturbed, as indicated in Fig. 18; and for this reason, the calculated amount of air flow (the amount of ventilation) varies with the position of the room from which the percentage was taken. Even when the uniformity in percentages is secured by agitation, this time the amount of flow is probably affected. This means that the unknown condition has merely been replaced by another. The writer, to overcome this difficulty, managed to measure the reduction in CO_2 percentages at the outlet without resorting to agitation.

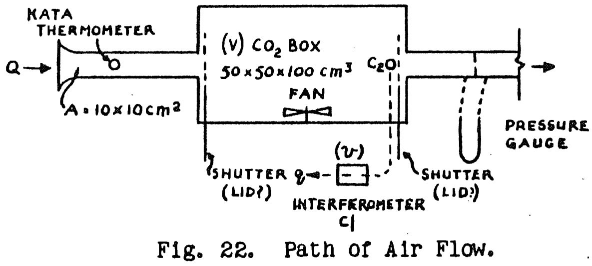


Fig. 22. Path of Air Flow.

Let us assume that in a path of air flow as illustrated in Fig. 22, the first uniform percentage in the carbon dioxide box is C_0' (o/vl), a certain amount of air flow, Q (m^3/sec) occurs for θ (sec), and the uniform percentage after the flow is C'_θ. Then the percentages at the outlet during this time are measured with the interferometer. The reading of C_1 reveals a lag with respect to the real percentages C_2. This is represented graphically in Fig. 23.

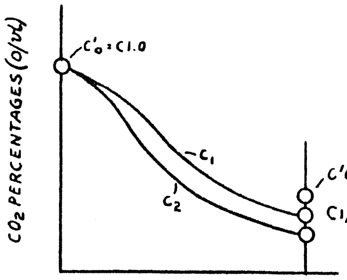


Fig. 23. Relation of C_1 to C_2.

If we represent the air in the CO_2 box (which has been collected for the interferometer) by q (m^3/sec), and the volume of the box by V (m^3),

$$(Q + q)\int_0^\theta C_2 d\theta = (C_0' - C_\theta')V, \qquad (35)$$

and between C_1 and C_2 there is an approximate relationship as given below:

$$q\,(C_2 - C_1)\,d\theta = v\,dC_1, \qquad (36)$$

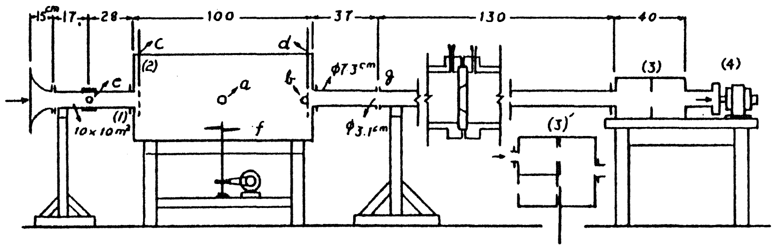
where v = volume (m^3) of path of air flow for interferometer. From (35) and (36)

$$u = Q/A = [(C_0' - C_\theta')V/\left\{F - v/q.(C_{10} - C_1\theta)\right\} - q]/A, \qquad (37)$$

where A = area of (m^2) of section of air flow, $F = \int_0^\theta C_1 d\theta$, F is the area between the curve C_1 and the time axis. This can be obtained from a measured value whatever form the curve assumes. (See Fig. 23).

2.2.1 Experiments

The path of air flow consists of an inlet tube, CO_2 box, outlet tube, orifice, regulating valve for the amount of air flow and blower (1/10 H.P.), as represented in Fig. 24.



(1) Inlet tube; (2) CO_2 box; (3) Regulating valve for the amount of air flow; (4) Blower; a and b: Openings for collecting CO_2; c and d: Shutters; e: Kata thermometer; f: fan; g: Orifice.

Fig. 24. Arrangement for Experiment.

The carbon dioxide percentages were measured by the interferometer, the pressure difference ΔP at the orifice by a Göttingen type pressure gauge (graduated 1/20 mm Hg), and 'Chatock' Inclined tube type pressure gauge (1/100 mm Hg.) (Ref. 22): With reference to the Chatock pressure gauge, the writer had one made very carefully so that the volumes of the bulbs could satisfy the conditions for temperature compensation. The kata thermometer used was one made in Great Britain.

If the voltage and valve of the blower are regulated and the pressure difference at the orifice is made ΔP,

$$u_0 = \alpha(2g\Delta P/\rho)^{1/2} \qquad (38)$$

where u_0 = mean velocity at the orifice, and α = coefficient of discharge.

If u and A represent respectively the velocity of air flow and the area of the section at the inlet, and a is the area of the orifice,

$$u = (a/A)u_0, \qquad (38')$$

Ref. 22. W. S. Duncan: Technical Rep. 1069, A.R.C. (1927).

In the measurement of air flow at the orifice we first find ΔP, and work out u_0 by equation (38); and so α must be a known value. In the present experiment the wind velocities by the CO_2 method and the Kata thermometer were compared through the intermediary of ΔP, and the value α was for the time being ignored.

We now close the shutters c and d (Fig. 24) at the entrance and exit of the CO_2 box. Carbon dioxide is introduced into the box to approximately 2 (o/vl); using the fan in the box we obtain uniformity in carbon dioxide percentages at a and b, and assume that they are uniform all over the box. When c and d are opened, air begins to flow. Taking this moment as 0, we begin the measurement of time, and read the carbon dioxide percentages of the air in the box which we have collected from b. θ (sec) later, the shutters are again closed, and by the use of the fan we satisfy ourselves that the carbon dioxide percentages are uniform at a and b. The ventilation is discontinued, as in Fig. 23, and after agitation we note that the percentage $C'\theta$, which is higher than $C_{1}\theta$ has been reached. This indicates that the air which entered the box has left again without mixing well with the carbon dioxide.

2.2.2 Wind Velocities by the CO_2 Method and by Kata Thermometer (Continued).

The relationship between the wind velocities by the CO_2 method and Kata thermometer and the pressure difference at the orifice is shown in Fig. 25; and it will be noted that the two nearly agree.

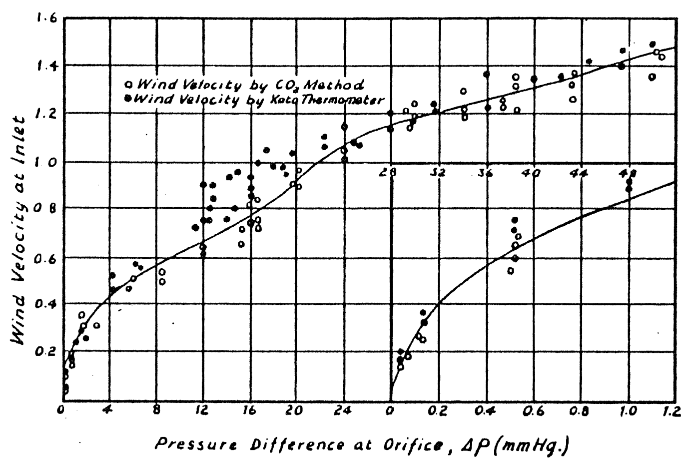


Fig. 25. Wind Velocity and Pressure Difference at the Orifice.

The Kata thermometer is already recognised for its capability to deal with small wind velocities, but for calibration it is desirable to have a known small wind velocity as a standard. If the CO_2 method is employed, it is now confirmed that this method can measure the amount of air flow, that is, wind velocity, direct; and it is particularly suitable for handling a gentle wind.

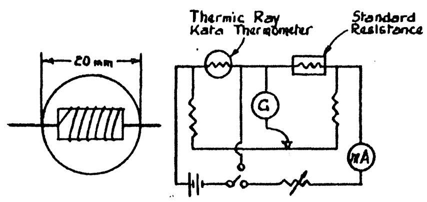
2.3 Thermic Ray Kata Thermometer (Ref. 23)

Inconveniences have been experienced by some experimenters in the use of the Kata thermometer; for instance, in the measurements of ventilation or liquid in buildings, it is not possible to carry out 'remote operation'; further, hot water is required, etc. There is a method for measuring wind velocities by heating the thermometer electrically, and this has been proposed by C. P. Yaglou (Ref. 24). In the present research the writer designed and constructed a new Kata thermometer in which platinum wire is sealed in the bulb which is filled with oil. The platinum wire acts both as resistance thermometer and heater. In the sense that this new instrument is a combination of a thermic ray anemometer with the Kata thermometer, the writer christens it tentatively Thermic Ray Kata Thermometer.

Ref. 23. Shoda and Katsuno: Architectural News, No. 5, (January, 1950).
Patent applied for in 1950 - Application No. 10951.
Ref. 24. C. P. Yaglou: Journ. Industrial Hygiene and Toxicology, Vol. 20, No. 8, pp. 495-510, (Oct., 1938); Journal of Sanitary Engineering, Vol. 13, No. 8, pp. 740-741, (1939).

The principle underlying the instrument is the same as in the old Kata thermometer, but the writer does not use the mean temperature (36.5 C) as in L. Hill's equation (34). If the bulb in the Thermic ray Kata thermometer is uniformly cooled (Fig. 26(a)),

$$t - t\alpha = (t_o - t\alpha)\,e^{-c/EA.\theta} \qquad (39)$$



(a) Receiver. (b) Circuit for Measurement.

Fig. 26. Thermic Ray Kata Thermometer.

where t_o, $t\theta$, $t\alpha$ = initial temperature of the bulb; θ (sec) subsequent temperature and the temperature of the surrounding air; c = heat capacity of the bulb; E = conductivity of heat; and A = surface area of the bulb.

Further, $E = a + b\,u^{1/2}$ (Ref. 25) (40)
where a and b are constants, u = wind velocity.

If we represent by θ the time during which the initial temperature t_o drops to $t\theta$, and if we take

$$y = \log\left\{1 + (t_o - t_\theta)/(t_\theta - t\alpha)\right\}/\theta,\quad k = A/2.3c,$$
$$y = k(a + bu^{1/2}),\quad u = \left\{(y/k - a)/b\right\}^2, \qquad (41)$$

If $ka = 1$, $kb = m$

$$y = 1 + mu^{1/2},\quad u = \left\{(y - 1)/m\right\}^2 \qquad (41')$$

The Kata-factor in this case is

$$(K.F.) = (t_o - t_\theta)/2.3k. \qquad (42)$$

2.3.1 Experiment

The Kata thermometer is hung in the position as indicated in Fig. 24, and testing commences. The receiver of the Thermic Ray Kata thermometer and the circuit for temperature measurement are both arranged as illustrated in Fig. 26 (a) and (b) respectively.

The receiver consists of a glass bulb of diameter approximately 20 (mm) containing a glass bobbin with platinum wire, 0.04 (mm) in diameter, 25 ohms at normal temperature, wound on it; it also contains transformer oil at approximately 50 C. This is hung in a position where measurement is required, by two conductors. There are also standard resistances equivalent to 38, 28 and 18 (C) arranged according to the bulb and atmospheric pressure, to be used in a bridge. By the galvanometer each drop of 3 (C) from the temperatures above mentioned is observed and the cooling time, θ, is measured.

2.3.2 Wind Velocity by the Thermic Ray Kata Thermometer.

The relationship between y obtained from the value measured by the Thermic Ray Kata thermometer and the wind velocity by the CO_2 method is represented in Fig. 27. It is nearly a straight line. From this it may be said that the equations (39) and (40) are correct. 1 and m in (41') can be obtained from the calibration curves for their respective bulbs.

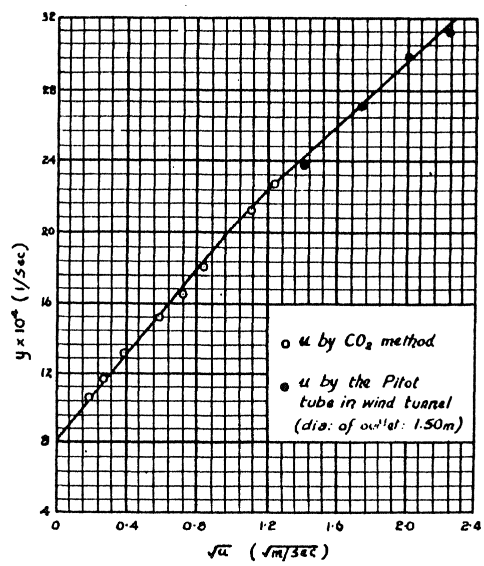


Fig. 27. Calibration curve from the Thermic Ray Kata Thermometer.

Ref. 25. E. Ower: Measurement of air flow, pp. 191-194, (1927).

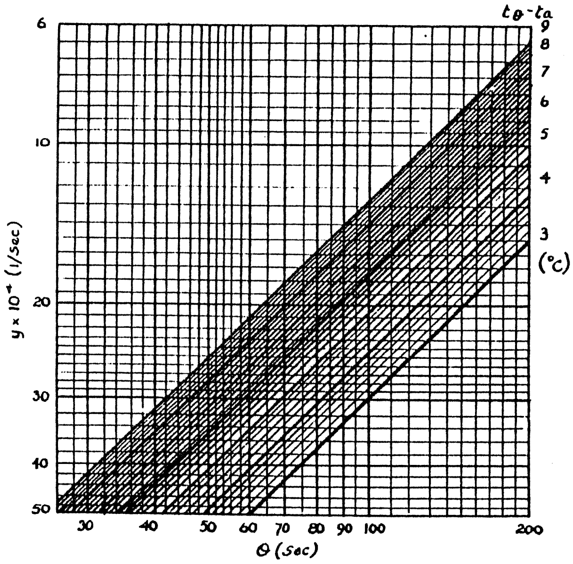


Fig. 28. Relations between
y, tθ, tα and θ.

The relations between y, t_θ, t_α and θ are represented in Fig. 28. The writer believes, from the experiment described above, that the Thermic Ray Kata Thermometer can be used as accurately as the old Kata thermometer for the measurement of wind velocities.

CHAPTER III

VENTILATION WHEN THE INSIDE TEMPERATURE IS HIGHER THAN THE OUTSIDE TEMPERATURE

There have been a number of experimental researches on ventilation by temperature difference. For example, it is reported that valuable results have been obtained from experiments with various models (Refs. 26 - 30) and ventilators (Ref. 31). In the study of the general properties of the ventilation by temperature difference, a desirable procedure is to analyse the various elements governing ventilation which have been found in experiments, and consider whether theoretical hypotheses, such as outlined in Chapter I of this paper are practicable. In the present chapter the writer proposes to seek, by the CO_2 method and the calculation of heat, the amount of ventilation when the temperature inside a room is higher than that outside. He will accomplish this with the aid of models of factories and rooms.

3.1 Experiments with Models of Factories (Ref. 32)

For these experiments the writer chose the most usual form of factories which are kept at high temperatures. In this form air enters through windows and goes out through the monitor or chimney in the roof. The models are on a reduced scale of 1/10 - 1/20. As the experiment was carried out during the early period of the war, there were some examples in which a blacked-out monitor was used, but the writer believes that this makes no difference to the study of the general properties of ventilation.

Ref. 26. Sato: Architectural Review, Nos. 32-35, pp. 27-31, (1947).
Ref. 27. Sato: Architectural Review, Nos. 26, 27, 29 & 31, (1942-3).
Ref. 28: Hirayama: Architectural Review, No. 28, pp. 51-57, (1943).
Ref. 29. Hirayama: Architectural Review, No. 28, pp. 58-62, (1943).
Ref. 30. Hirayama: Architectural Review, No. 29, pp. 105-111, (1943).
Ref. 31. Hirayama: Journal of Sanitary Engineering, Vol. 12, No. 4, p. 255, (1938).
Ref. 32. Shoda: Lecture given at the general meeting of the Society for Architecture in November, 1946.

3.1.1 Experiment

The models of factories are of two varieties, I and II. The area of I is 1.80 x 1.80 (m^2) (Fig. 29 (b)), and II is on a reduced scale of 1/2 of I. The front and back are glass plated; both sides and the roof are veneered (3.5 mm thick); the floor is made of cryptomeria board (14 mm thick), and the model is on a stand 75 cm. high.

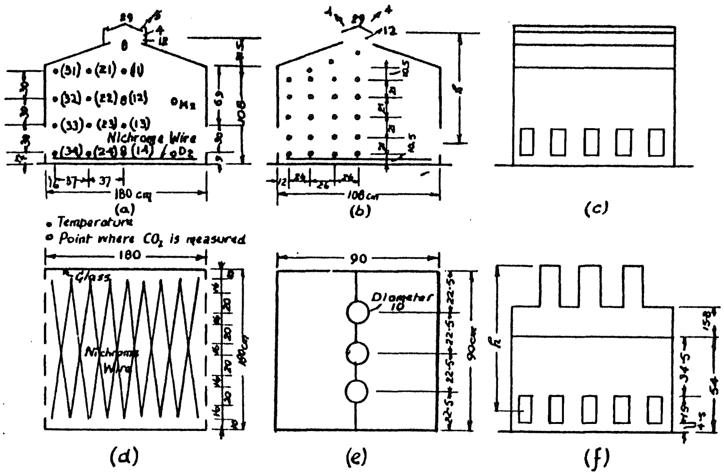


Fig. 29. Models of Factories.

Outlets are of three kinds. They are:

Blacked out Monitor: Models I and II (Fig. 29 (a)).

Chimney: Model II (Fig. 29 (e) and (f)).

Monitor: Model I (Fig. 29 (c) and (d)).

The sources of heat are distributed evenly along the floor. As represented in Fig. 29 (b), Nichrome wire is stretched 3 (cm) above the floor in Model I and 1.5 (cm) in Model II; and the supply of heat is measured with a voltmeter and ammeter.

The points of measurement are fixed at 13 positions for experiments with the blackout monitor and chimney, and 23 positions for the monitor (Fig. 29, (a) and (c)). The measurement is made with a resistance thermometer or Alcohol thermometer hung from a travelling beam.

The positions for collecting carbon dioxide are U, M_1, M_2, D_1 and D_2 as indicated in Fig. 29 (a), and the points U, M and D are led respectively to the three interferometers, thus effecting the measurement of carbon dioxide percentages at the top, middle and bottom positions. Liquid carbon dioxide contained in a 'bomb' was used in the experiment, and an electric fan was needed to mix air and carbon dioxide in the model at the beginning and end of the experiment.

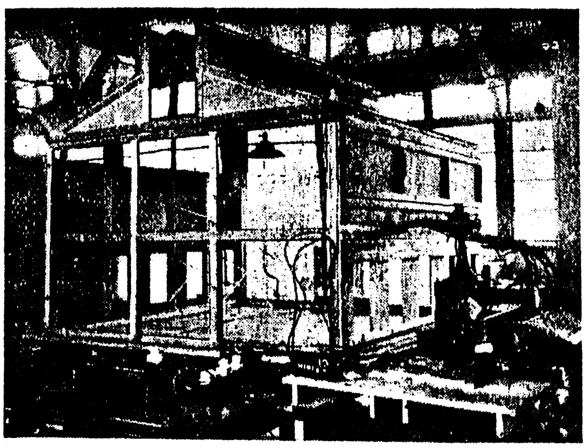


Fig. 30. Model of a factory under Experiment

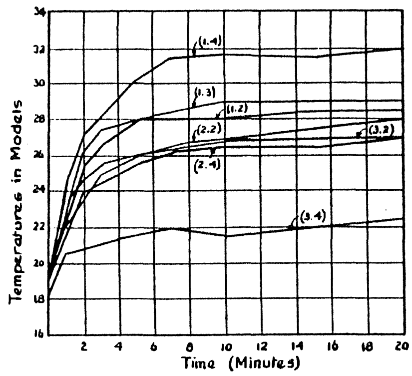


Fig. 31. Temperature Rises in Models.

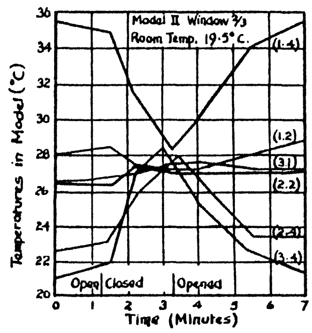


Fig. 32. Temperature Changes in a Model.

3.1.2 Method of Measurement

While ventilation is going on after the openings have been opened, a certain amount of heat is applied and in approximately 20 minutes' time, normal conditions are reached and the temperature at each point settles down as represented by the graph, Fig. 31. Then all the openings are closed and carbon dioxide is introduced. Agitation is now thoroughly performed, (the temperature at all the points agrees within the range of approximately 2 (°C) as is clear in Fig. 32). The carbon dioxide percentages at U, M and D are read off by interferometers. Then the openings are opened, and the carbon dioxide percentages at the outlet U are measured (the distribution of temperatures returns to the original condition). After 3 - 5 minutes, the openings are again closed, agitation takes place, and the percentages at U, M and D are read.

The writer did not use the carbon dioxide method for the experiments with the monitor (Fig. 29 (c)), but he obtained the amount of ventilation by calculation of heat; so it was necessary only to restore the temperature inside the model to normal.

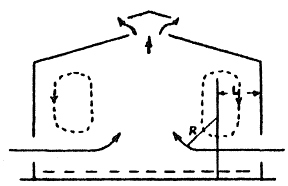
All openings are arranged symmetrically (right and left), but the areas of inlets (windows) are varied. This idea applies to chimneys, too; further, the height of chimneys also is varied.

3.1.3 Mean Temperatures

The question as to what point should represent the temperature of the room must be solved by consideration of the object for which the room is heated. For example, if it is desired to heat people, the temperature at a point at least 1 (m) from a wall and 1.5 (m) above the floor (the position of human breathing) should represent the temperature of the room. If it is for a factory at high temperature, the position of operation must be made the standard on which our considerations must be based. If the amount of ventilation in a room is to be considered, it is necessary to consider the mean temperature of the room.

When the working of ventilation is observed by means of the white smoke of NH_4Cl, we know how the main paths run, as indicated in the diagram, Fig. 33.

It may be said (1) that the opening ratio remaining the same, the larger the temperature difference between the inside and outside of a room, the larger the part (L) where the inflow of the air occurs horizontally, and the smaller the angle (R) made by the rising path. Also (2) that the temperature difference remaining the same, the larger the opening ratio (when the inlet is small), the smaller the (L) and the larger the (R).



ig. 33. Paths of Ventilation.

Some change in temperature in the direction of the cross beam is noted very near the glass, but it is negligible. For our purposes, the measured value at a section in the centre is taken.

(1) The distribution of temperature, in spite of the uniform distribution of the heat sources, becomes exceedingly uneven with the main paths of ventilation as represented in Fig. 33, and a space with the highest temperature is formed at the bottom of the centre of the room. However, in other parts of the room, the difference in temperature is not so appreciable. This lack of uniformity in temperature increases in proportion to the increase in the supply of heat and in the amount of ventilation.

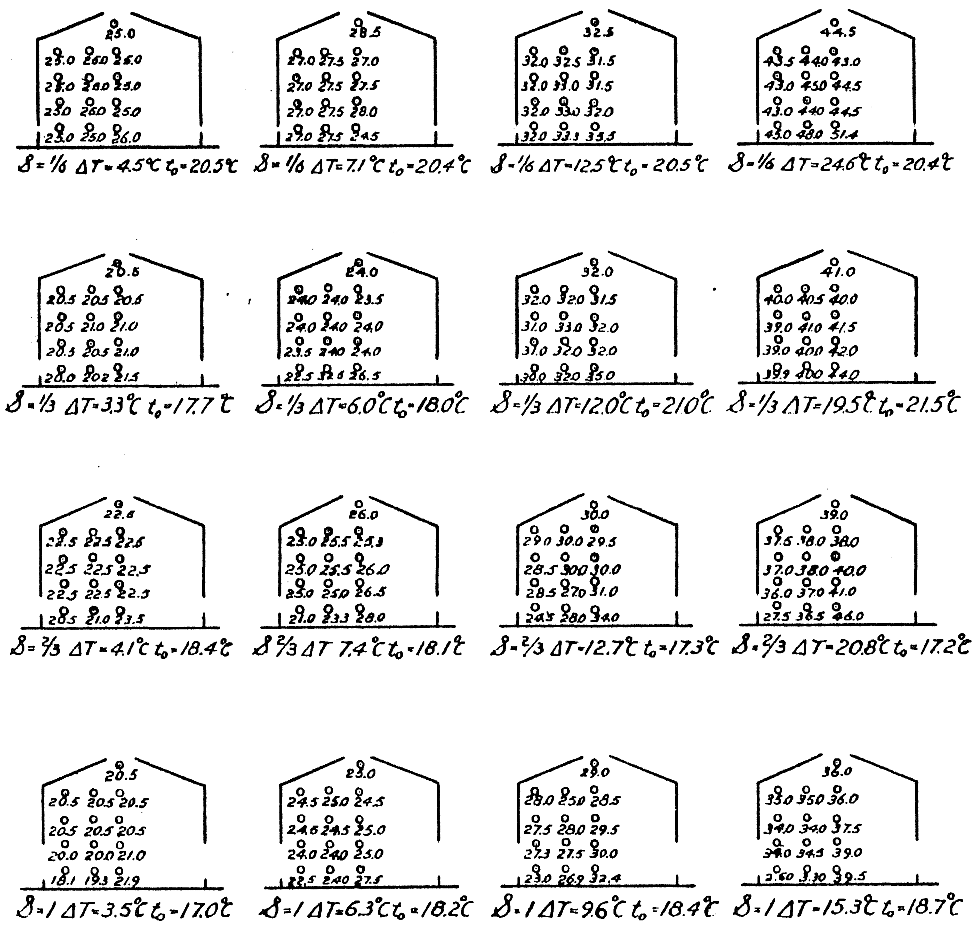


Fig. 34. Distribution of Temperatures (1).

Black-out monitor, Model I: Outlet $A_2 = 0.18\ m^2$, Inlet $A_1 = s.A_W$, Area of window $A_W = 0.48\ m^2$.

(2) For example, in the experiment with the blacked out monitor (Model I), the distribution of temperature takes place in the manner as represented in Fig. 34, and the mean temperatures at all the points on the horizontal position are nearly the same, regardless of height, as is shown in Table 2; that is to say, they come near the mean value of all. Further, in this case, it will be noticed that the temperatures at (2.2) are almost in agreement with the mean value.

ΔT	(1.0)	Average of (1.1) (2.1) & (3.1)	Average of (1.2) (2.2) & (3.2)	Average of (1.3) (2.3) & (3.3)	Average of (1.4) (2.4) & (3.4)	Average of 13 points	(2.2)
		s = 1/6			m = 2.24		
4.5	25.0	25.0	25.0	25.0	25.3	25.1	25.0
7.1	27.5	27.2	27.3	27.5	28.0	27.5	27.5
12.1	32.5	38.0	32.2	32.3	33.6	32.5	33.0
24.6	44.5	43.5	44.2	43.8	48.1	44.7	45.0
		s = 2/6			m = 1.12		
3.3	20.5	20.5	20.8	20.7	20.6	20.6	21.0
6.0	24.0	23.8	24.0	23.8	23.8	23.9	24.0
12.0	32.0	31.8	32.0	31.7	22.3	32.0	33.0
14.5	41.0	40.2	40.5	40.6	40.6	40.5	41.0
		s = 4/6			m = 0.56		
4.1	22.5	22.5	22.5	22.5	21.7	22.3	22.5
7.4	26.0	25.3	25.5	25.5	24.1	25.2	25.5
12.7	30.0	29.5	29.5	29.5	23.8	29.4	30.0
20.8	39.0	37.8	38.5	38.0	36.6	37.8	38.0
		s = 6/6			m = 0.37		
3.5	20.5	20.5	20.5	20.6	19.9	20.3	20.5
6.3	25.0	24.6	24.6	24.3	24.7	24.6	24.5
9.6	29.0	28.2	28.3	28.3	27.4	28.1	28.0
15.3	36.0	35.3	35.2	35.8	32.5	34.8	34.0

s indicates the ratio between the area of inlet utilized and that of the total available inlet.

Table 2. Mean Temperatures

(Blacked out monitor, Model I)

This feature of the mean temperatures on the horizontal position being identical can be found in all the cases. Further, when the points at which the temperatures are measured are closer together, the results reveal the same feature (Fig. 35).

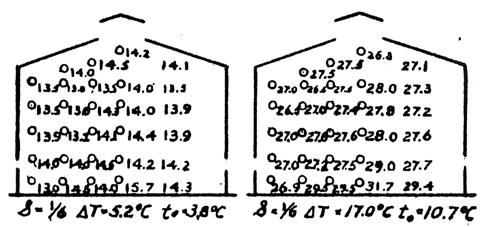


Fig. 35. Distribution of Temperatures (2).

Thus, when the general motion of the air in the room is considered, we see that the buoyancy operating in a certain horizontal stratum is not affected by height, and this state, therefore, may be said to be the same, dynamically speaking, as that when the temperatures in the room are uniform. It appears that this tendency occurs even when the sources of heat are concentrated. If we require to find out the amount of ventilation in such a case, therefore, it is only necessary to consider the 'spatial' mean temperature of the room. In practical matters, too, the writer is very much inclined to believe that the mean value of the temperatures at several points on a certain level can serve useful purposes.

3.1.4 Calculation of the Amount of Ventilation

The calculation of the amount of ventilation from the curves of the reduction in carbon dioxide percentages is done by the method described in 2.2 of Chapter 2. In the present experiment, however, it is necessary to correct the mean temperature in the model. When the air in the room is mixed with carbon dioxide, the density of the air increases, as represented in Fig. 36; and for this reason it may be said that the ventilation by temperature difference is equivalent to that obtained when the temperature is lower than that indicated by the thermometer.

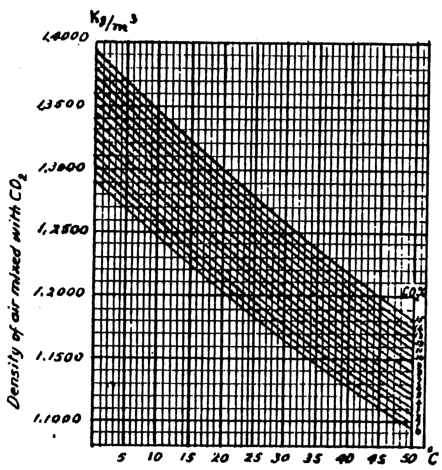


Fig. 36. Relationships between CO_2 Percentages, Density and Temperature.

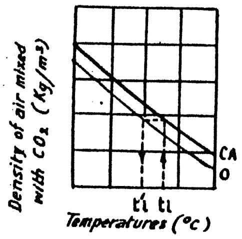


Fig. 37.
Corrected
Temperature.

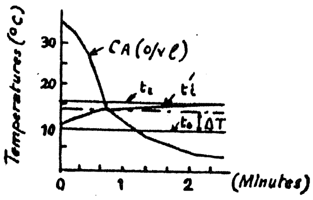


Fig. 38.
Corrected
Temperature
Difference.

Thus, in comparison with CA, the mean value of carbon dioxide percentages at the top, middle and bottom, the temperature t_i in the model is now altered to t_i' as shown in Fig. 37, and the ΔT, the temperature difference, becomes as represented in Fig. 38.

If H' represents the amount of heat supplied to the model; H_t, loss of heat by conduction, and H_v, loss by ventilation,

$$H' = H_t + H_v \qquad 43$$

$$H' = 0.86i^2 R, \quad (\text{kcal/hr})$$

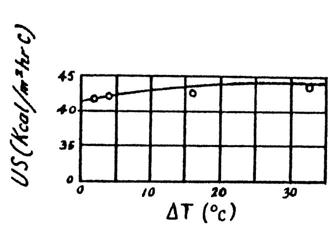
$$H_t = U.S.\ \Delta T, \quad (\quad " \quad)$$

$$H_v = 3600 C_p\, Q\Delta T, \quad (\quad " \quad)$$

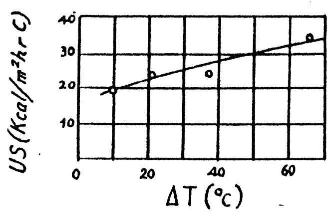
where i = electric current (amperes); R = resistance (ohms); u = mean coefficient of conduction of heat (kcal/m²hrC); S = area of heat conducting surfaces (m²); $C\rho$, p = specific heat (kcal/kgC) and density (kg/n³) of air respectively,; and Q = amount of ventilation (m³/sec).

$$Q = (0.86i^2 R/\Delta T - US)/3600\, C_\rho p. \qquad 44$$

U, S can be worked out experimentally from the amount of heat supplied and the mean temperature difference at the time when all the openings and cracks are hermetically sealed. In this way, the value US for model I (factory) may be represented as in Fig. 39(a).



(a) Model of Factory I.



(b) Model of Room.
(Ref. Chapter 3; 3.2).

Fig. 39. Value of US.

Referring to the equation (2) in Chapter 1,

$$1\ (\text{kgm}) = 2.34 \times 10^{-3} (\text{kcal})$$

$$C_p = 0.24\ (\text{kcal/kgC}), \text{ therefore,}$$

$$2.34 \times 10^{-3} (H + F) = 0.24\ \Delta T,$$

that is to say,

$$H + F = 103\ .\ \Delta T; \qquad (2')$$

From the equations (4), (8) and (10, we get

$$F = (\Delta T/T_o) h,$$

Even at $\Delta T = 30$ (C), $T_o = 273$ (C), h = 10 (m),

$F \doteqdot 1$; thus F is negligible compared with H, so

$$H_v = \rho . 3600\ QH, \quad (\text{kgm/hr}).$$

The H in the equation (2) in Chapter 1 can also mean the ventilation loss per unit mass.

3.1.5 The Amount of Ventilation

(a) The measured value of the amount of ventilation.

(1) Blacked out monitor: Models I and II.
Chimney: Model II.

The measured values are given in Tables 3 and 4 and in Fig. 40.

Blacked out monitor, Model I			Blacked out monitor, Model II		
ΔT	Q	t_0	ΔT	Q	t_0
h = 1.38, s = 1/6, m = 2.24, $\bar{\varphi}$ = 0.28			h = 0.67, s = 1/6, m = 2.24, $\bar{\varphi}$ = 0.27		
2.1	0.0246	21.6	6.3	0.0057	13.5
5.2	0.0347	21.1	12.3	0.0095	14.5
8.5	0.0391	21.4	18.5	0.0117	14.9
10.2	0.0495	21.6	26.5	0.0135	14.6
14.0	0.0568	21.8	32.4	0.0151	14.1
21.5	0.0671	21.8			
h = 1.36, s = 2/6, m = 1.12, $\bar{\varphi}$ = 0.37			h = 0.66, s = 2/6, m = 1.12, $\bar{\varphi}$ = 0.34		
1.7	0.0223	21.0	6.8	0.0076	13.0
5.5	0.0433	20.4	11.5	0.0109	13.0
7.5	0.0533	21.0	17.4	0.0132	12.9
7.9	0.0558	21.2	26.4	0.0170	13.0
12.0	0.0730	21.4	35.0	0.0202	13.0
17.8	0.0763	21.3			
h = 1.31, s = 4/6 m = 0.56, $\bar{\varphi}$ = 0.42			h = 0.61, s = 1, m = 0.37, $\bar{\varphi}$ = 0.43		
1.9	0.0291	21.0	4.1	0.0081	10.0
5.4	0.0537	20.9	7.4	0.0107	10.0
10.1	0.0705	20.8	14.1	0.0147	10.0
18.5	0.0960	20.8	23.7	0.0192	10.0
			30.4	0.0206	10.1
h = 1.24, s = 1, m = 0.37, $\bar{\varphi}$ = 0.45					
2.0	0.0273	20.9			
4.4	0.0465	18.3			
6.3	0.0587	21.4			
7.5	0.0692	18.4			
12.5	0.0855	21.5			
23.1	0.1040	21.3			

Table 3. Amount of Ventilation
in Model of Factory (1)

Chimney, Model II, h' = 40(cm)			Chimney, Model II, h' = 23(cm)		
ΔT	Q	t_0	ΔT	Q	t_0
h = 1.04, s = 1/6, m = 1.18, $\bar{\varphi}$ = 0.43			h = 0.67, s = 1/6, m = 1.18, $\bar{\varphi}$ = 0.45		
5.2	0.0052	13.0	5.0	0.0067	7.3
11.2	0.0092	12.9	10.5	0.0094	7.3
10.2	0.0103	12.8	11.0	0.0103	7.4
24.6	0.0147	12.7	29.3	0.0140	7.5
			33.5	0.0158	7.8
h = 1.03, s = 2/6, m = 0.59, $\bar{\varphi}$ = 0.52			h = 0.86, s = 2/6, m = 0.59, $\bar{\varphi}$ = 0.55		
4.9	0.0066	13.1	5.1	0.0072	7.0
5.2	0.0071	13.3	9.1	0.0090	7.0
8.9	0.0105	9.5	15.8	0.0132	7.1
17.7	0.0143	13.5	26.3	0.0162	7.3
26.6	0.0189	13.5			
h = 1.00, s = 4/6, m = 0.30, $\bar{\varphi}$ = 0.59			h = 0.83, s = 4/3, m = 0.30, $\bar{\varphi}$ = 0.64		
4.4	0.0052	11.1	5.3	0.0085	7.8
10.9	0.0128	12.1	12.6	0.0132	7.9
18.4	0.0154	11.3	18.1	0.0160	8.0
25.5	0.0176	11.5	31.6	0.0192	8.6
29.9	0.0192	11.8			
h = 0.98, s = 1, m = 0.20, $\bar{\varphi}$ = 0.64			h = 0.81, s = 1, m = 0.20, $\bar{\varphi}$ = 0.69		
4.8	0.0088	12.0	4.6	0.0084	6.6
10.4	0.0116	12.1	10.3	0.0122	7.1
16.7	0.0161	12.2	14.5	0.0158	7.4
21.5	0.0190	12.1	26.0	0.0188	7.7

h' indicates the height of the chimney - from the ridge to the mouth of the chimney.

Table 4. Amount of Ventilation
in Model of Factory (2)

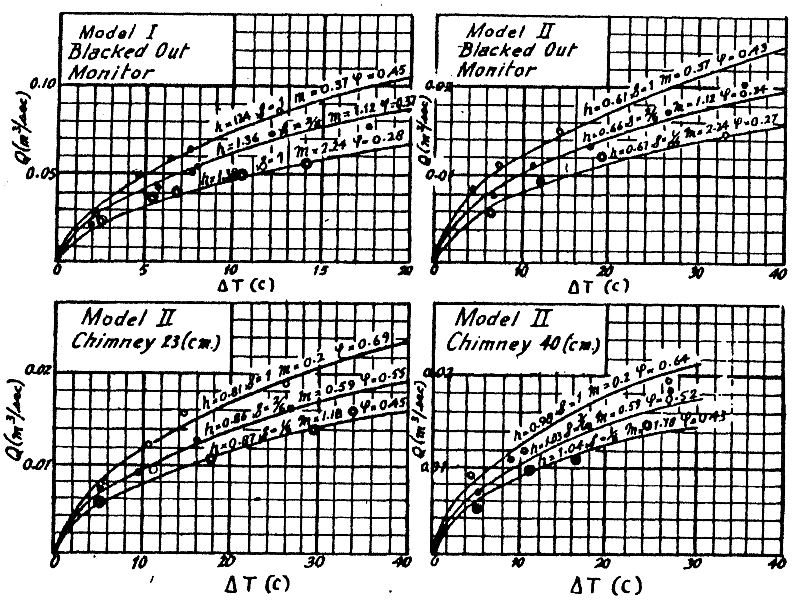


Fig. 40. Amount of Ventilation and Temperature Difference in Model of Factory (1).

(2) Monitor: Model I

The measured values are set forth in Table 5 and represented graphically in Fig. 41.

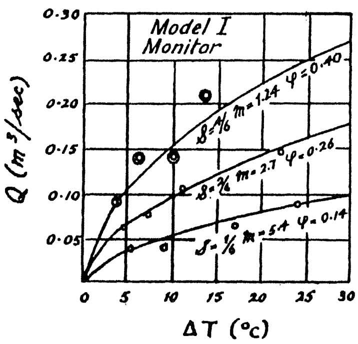


Fig. 41. Amount of Ventilation & Temperature Difference in Model of Factory (2).

Monitor, Model I		
ΔT	Q	t_o
	h = 1.24, s = 1/6, m = 5.4, $\bar{\varphi}$ = 0.14	
5.2	0.040	8.8
9.1	0.041	9.8
17.0	0.065	6.7
24.0	0.091	13.0
	h = 1.24, s = 2/6, m = 2.7, $\bar{\varphi}$ = 0.26	
4.2	0.061	6.1
7.0	0.077	6.2
10.8	0.105	7.0
22.0	0.146	7.9
	h = 1.24, s = 4/6, m = 1.35, φ = 0.40	
3.4	0.088	6.9
6.0	0.140	7.3
9.0	0.142	8.3
13.6	0.210	10.4

Table 5. Amount of Ventilation in Model of Factory (3)

(b) The Observed Values and Calculated Values of the Amount of Ventilation.

Referring to equation (26) in Chapter 1, all quantities except φ can be found by measurement; and therefore it is possible to arrive at the mean value $\bar{\varphi}$ from all the measured values. The values of Q which have been worked out from $\bar{\varphi}$ are the curves shown in Figs. 40 and 41.

(c) Reduced Scale and the Amount of Ventilation.

When the blacked out monitors in Models I and II are compared, we find that the values are almost constant in regard to large and small models, as shown in Table 6. However, this result does not necessarily determine whether the value of $\bar{\varphi}$ is constant in a wider range of reduced scales.

m	$\bar{\varphi}$	
	Model I	Model II
2.24	0.28	0.27
1.12	0.37	0.34
0.37	0.45	0.43

Table 6. Reduced Scale of $\bar{\varphi}$

(d) The effect of Chimney type Exhaust Openings.

The areas of outlets of the blacked out monitor: Model I, and the chimney (10 cm in diameter, 3 chimneys): Model II are 0.045 (m^2) and 0.024 (m^2) respectively. When the chimney 23 (cm) high is compared with the blacked out monitor, the area of the outlet in the one being half that of the other, the amount of ventilation in both is almost the same. Further, there is no difference in ventilation whether the chimney is 23 (cm) or 40 (cm) high. Theoretically speaking, the amount of ventilation under the chimney 40 (cm) high should be larger by 8 % due to the greater height; so the writer presumes that this drop in efficiency is due to the cooling of the iron in the chimney.

3.1.6 Friction Factor (Coefficient of Discharge)

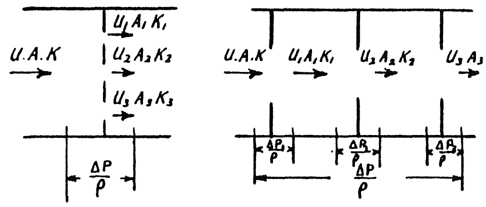
(a) Combination of Friction Factors.

(1) Parallel combination.

When there are several windows or cracks in parallel in the path of the air flow, as illustrated in Fig. 42 (1)

$$uA = u_1A_1 + u_2A_2 + u_3A_3 + \cdots\cdots, \quad (45)$$

If $\Delta P/\rho$ represents the friction loss due to the windows,



(1) Parallel (2) Series

Fig. 42. Combination of Friction Factors.

$$\Delta P/\rho = Ku^2/2g = K_1u_1^2/2g = K_2u_2^2/2g = \cdots\cdots (46)$$

$$K^{-1/2} = (A_1K_1^{-1/2} + A_2K_2^{-1/2} + A_3K_3^{-1/2} + \cdots\cdots)/A, \quad (47)$$

If $K_1 = K_2 = \cdots\cdots = K_i$, $A = \sum A_i$

$$K = K_i, \quad (48)$$

That is, when windows with the same friction factor are arranged in parallel, the arrangement may be identified with a window whose area is the total area of the windows.

(2) Series combination.

The diagram (2) in Fig. 42 gives an instance of series combination. Here, ρ being constant,

$$uA = u_1A_1 = u_2A_2 = u_3A_3 = \cdots\cdots, \quad (49)$$

$$\Delta P/\rho = Ku^2/2g,\ \Delta P_1/\rho = K_1u_1^2/2g,\ \Delta P_2/\rho = K_2u_2^2/2g, \cdots\cdots, \quad (50)$$

$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \cdots\cdots, \quad (51)$$

If $A_n/A_1 = m_1$, $A_n/A_2 = m_2$, $\cdots\cdots$, is taken

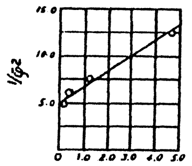
$$Ku^2/2g = (K_n + K_{n-1}\,m^2_{n-1} + \cdots\cdots)u_n^2/2g \quad (52)$$

If $u = u_2$, $n = 2$

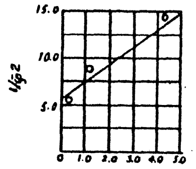
$$K = K_2 + K_1\,m_1^2, \quad (53)$$

The relation between the coefficient of discharge, α, and K has already been expressed in (9), $\alpha = K^{-1/2}$

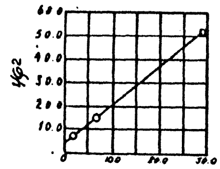
(b) The value of the friction factor (coefficient of discharge.)



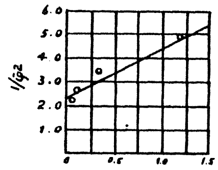
(1) Model I
Blacked out Monitor.



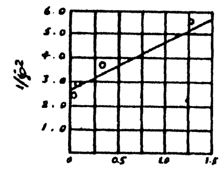
(2) Model II
Blacked out Monitor.



(3) Model I
Monitor.



(4) Model II
Chimney (23cm)



(5) Model II
Chimney (40cm)

Fig. 43. Friction Factor obtained from the Amount of Ventilation.

If K_1 and K_2 are obtained, the results are shown graphically in Fig. 43, and given numerically in Table 7. The coefficient of discharge of a window is 0.7 - 0.8.

Model		K_1	α_2	K_1	α_1
I	Blacked out Monitor	5.0	0.45	1.6	0.79
II	"	5.8	0.42	1.8	0.75
I	Monitor	3.5	0.36	1.6	0.79
II	Chimney (23 cm)	2.3	0.67	2.0	0.71
II	Chimney (40 cm)	2.6	0.62	2.0	0.71

Table 7. Friction Factor (Coefficient) of discharge) obtained from the Amount of Ventilation

(c) Neutral Zone when Friction Factor of Outlet and Inlet Varies.

Referring to the monitor, Model I, we make small openings, 6 (mm) in diameter, at intervals of 5 (cm) on the upper and lower lines on the central walls and the roof, and ascertain the position of the neutral zone by means of the smoke of an incense stick.

Let us use $h = 1.24$(m), $K = 1.6$, $K_2 = 3.5$ in equation (17) in Chapter 1. When the calculated value h_0 from the above is compared with the observed value $\bar{h}_0$, the results are as shown in Fig. 44 and Table 8. From the graph, we can see that both values are in general agreement with each other.

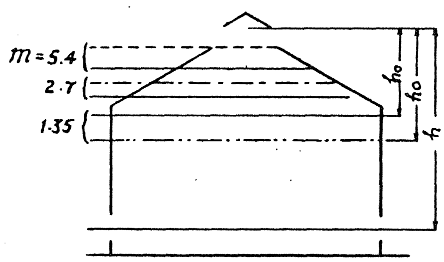


Fig. 44. Measured Values and Calculated Values Compared in the Neutral Zone.

Broken & Chain lines:
Calculated Value;
Continuous Line:
Measured Value.

m	h_0	$\bar{h}_0$
5.4	8.7	22.5
2.7	28.5	38.0
1.35	67.5	49.0

Table 8. Comparison of Calculated and Measured Values in the Neutral Zone.

This is an experiment carried out for the same purposes as the one described in 3.1. We require to examine what becomes of all the elements in the ventilation by temperature difference in the model of a room. As in the previous experiment, the heat sources are distributed uniformly over the floor, and the openings are arranged symmetrically (right and left). To simplify the conditions still further, all the outlets and inlets are of the same form.

3.2.1 Experiment

The area of the model is 1.80 x 1.80 (m^2) and the height of the ceiling, 1.05 (m) - the roof in model (a) in Fig. 29 has been replaced by a ceiling. The points of temperature measurement are the same as were given in Fig. 29 (c), except the upper three points which were removed. The openings were of two kinds: High windows and circular openings.

(A) High Windows.

When there are five windows in the upper and lower lines on both sides. (Fig. 45). The distance from the centre of the upper window to that of the lower window, h = 0.67 (m) is constant and the opening ratios include m = 0.25, 0.5, 1, 2 and 4.

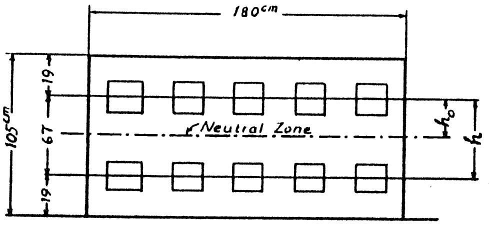


Fig. 45. High Window.

(B) Distribution of Circular Openings

When circular openings are 32 (MM) in diameter, and are distributed on both sides, as illustrated in Fig. 46.

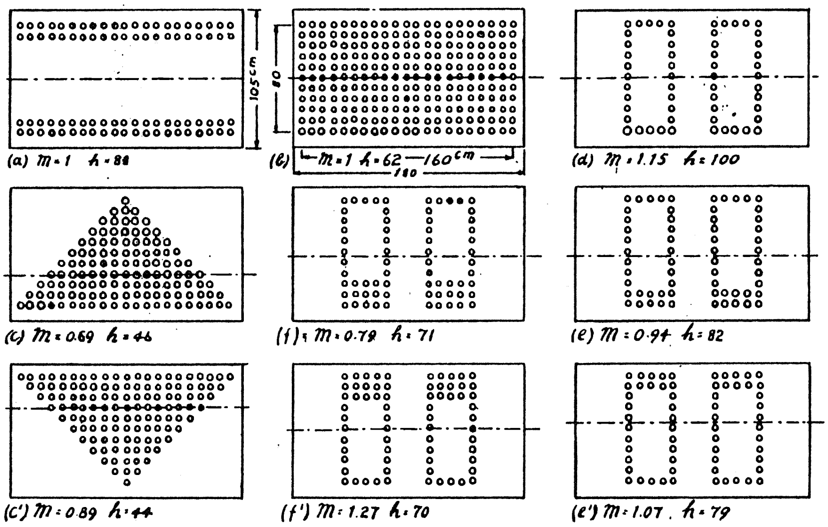


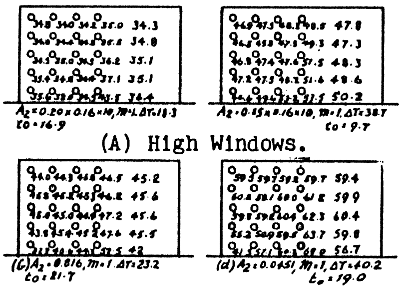
Fig. 46. Model of Room. Distribution of Circular Openings.

This is a case in which inlets and outlets are not separated. As the border between the inlet and outlet is obtainable by measuring the neutral zone, the opening ratio, m, can be determined, but it is not possible to fix the distance, h. Ventilation in a room which occurs through cracks, under normal living conditions, is more or less similar to the above mentioned state.

Ref. 33. Shoda (15).

3.2.2 Mean Temperatures

In this experiment it has been discovered that mean temperatures on a level are the same, and in a vertical direction there is little variation. This can be seen in Fig. 47.



(A) High Windows.

(B) Distribution of Circular Openings.

Fig. 47. Distribution of Temperatures in Model of Room.

3.2.3 Amount of Ventilation

(a) Measured value of the amount of ventilation.

When the amount of ventilation by high windows and by the distribution of circular openings is obtained by the calculation of heat, the results are as given in Tables 9 (A) and (B) and Fig. 48 (A) and (B).

ΔT	Q	t_o	ΔT	Q	t_o
m = 0.25, A_2 = 0.05 x 0.16 x 10, $\bar{\varphi}$ = 0.86			m = 0.5, A_2 = 0.05 x 0.16 x 10, $\bar{\varphi}$ = 0.67		
4.5	0.035	16.5	5.0	0.021	11.5
8.6	0.047	16.5	8.3	0.033	11.8
14.8	0.052	17.4	14.7	0.046	12.0
27.9	0.074	17.5	27.1	0.070	12.3
m = 0.5, A_2 = 0.10 x 0.16 x 10, $\bar{\varphi}$ = 0.80			m = 1, A_2 = 0.20 x 0.16 x 10, $\bar{\varphi}$ = 0.73		
3.1	0.073	12.7	2.2	0.096	11.2
6.5	0.070	12.8	5.7	0.125	14.9
10.7	0.087	13.3	9.7	0.138	16.3
18.7	0.117	14.3	18.3	0.178	16.9
m = 1, A_2 = 0.10 x 0.16 x 10, $\bar{\varphi}$ = 0.69			m = 2, A_2 = 0.10 x 0.16 x 10, $\bar{\varphi}$ = 0.32		
4.7	0.058	5.5	4.7	0.023	14.3
7.6	0.067	6.6	9.5	0.041	15.0
14.2	0.075	7.0	16.3	0.051	15.3
26.0	0.099	7.7	26.6	0.070	16.4
m = 1, A_2 = 0.05 x 0.16 x 10, $\bar{\varphi}$ = 0.65			m = 4, A_2 = 0.20 x 0.16 x 10, $\bar{\varphi}$ = 0.28		
5.9	0.028	6.7	5.4	0.032	8.6
10.2	0.040	7.4	8.2	0.056	9.6
19.5	0.044	8.5	14.9	0.071	10.2
38.7	0.070	9.7	26.5	0.093	10.6
m = 2, A_2 = 0.20 x 0.16 x 10, $\bar{\varphi}$ = 0.41					
3.7	0.043	18.7			
6.0	0.080	19.0			
10.6	0.091	21.4			
18.3	0.118	21.6			

Table 9(A)

Amount of Ventilation by High Windows

ΔT	Q	t_o	ΔT	Q	t_o
(a) m = 1, A_t = 0.0676 x 2, $\bar{k}$ = 0.010			(d) m = 1, A_t = 0.0451 x 2, $\bar{k}$ = 0.007		
6.1	0.023	19.3	6.5	0.022	19.2
11.3	0.032	19.6	12.2	0.023	19.3
14.5	0.043	17.4	20.5	0.027	18.5
29.3	0.054	16.8	40.2	0.048	19.5
(b) m = 1, A_t = 0.186 x 2, $\bar{k}$ = 0.023			(e) m = 0.94, A_t = 0.0499 x 2, $\bar{k}$ = 0.007		
4.0	0.053	18.3	7.8	0.010	18.7
7.7	0.058	19.2	12.1	0.024	18.9
13.1	0.088	20.1	21.3	0.029	19.0
23.2	0.110	22.1	37.5	0.044	19.6
(c) m = 0.68, A_t = 0.0975 x 2, $\bar{k}$ = 0.010			(e') m = 1.09, A_t = 0.0499 x 2, $\bar{k}$ = 0.007		
6.5	0.023	18.0	6.9	0.017	18.1
11.0	0.033	19.0	12.0	0.031	18.5
16.7	0.036	19.5	21.7	0.029	18.4
27.3	0.056	20.5	34.9	0.049	18.7
(c') m = 0.89, A_t = 0.0975 x 2, $\bar{k}$ = 0.012			(f) m = 0.79, A_t = 0.0548 x 2, $\bar{k}$ = 0.007		
5.6	0.033	22.0	6.8	0.023	16.5
10.0	0.040	22.6	11.4	0.024	16.9
22.0	0.055	21.0	17.6	0.029	17.0
37.7	0.069	22.0	33.7	0.037	17.5
(f') m = 1.27, A_t = 0.0548 x 2, $\bar{k}$ = 0.007					
6.4	0.016	18.8			
10.3	0.024	19.0			
21.2	0.036	20.0			
31.6	0.044	18.9			

Table 9(B)

Amount of Ventilation by Distribution of Circular Openings

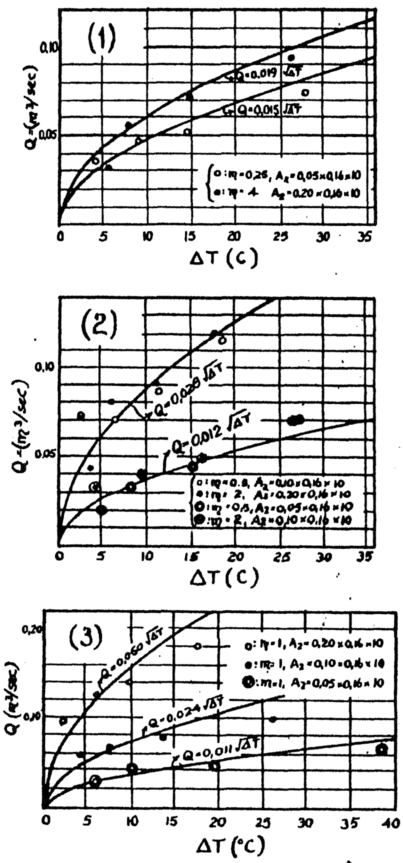


Fig. 48(A) Amount of Ventilation and Temperature difference by High Windows.

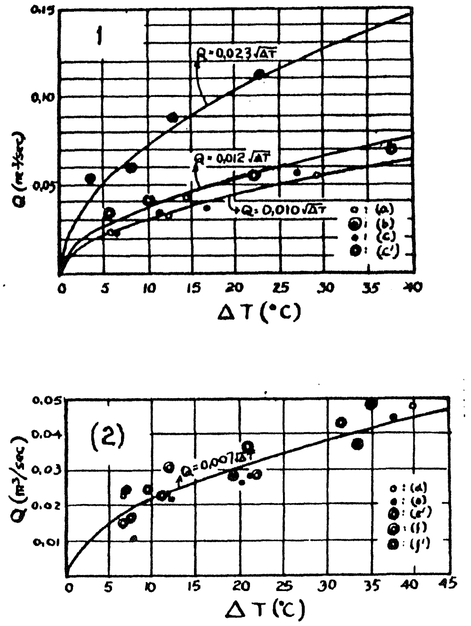


Fig. 48(B) Amount of Ventilation and Temperature difference by the distribution of Circular Openings.

(b) Measured value and formula of the amount of ventilation.

(A) High windows.

(1) $$Q = k\Delta T^{1/2} \tag{55}$$

and if $\bar{k}$ represents the mean value obtained from the measured value, we arrive, from (26) at

$$\bar{k} = \bar{\varphi}(2gh/T_0)^{1/2} A_2$$

Thus the curves in Fig. 48(A) are

$$Q = \bar{k}\Delta T^{1/2}$$

(2) If the areas of the inlet, outlet and total openings are A_i, A_2 and A_t respectively, we get, from $A_t = A_1 + A_2$, $A_2/A_1 = m$,

$$A_2 = m/(1 + m).A_t \tag{56}$$

If $K_1 = K_2 = K$, the equation (11') is

$$Q = \alpha m(1 + m)^{-1}(1 + m^2)^{-1/2} (2gh\Delta T/T_0)^{1/2} A_t \tag{57}$$

The above indicates the fact that if h and A_t are constant, the amounts of ventilation are the same when the opening ratio is m, and also when it is 1/m. The measured values represented in (1) and (2) in Fig. 48(A) generally satisfy this relationship.

(3) What of the relation between the area of the outlet and the amount of ventilation? It may be said that as shown in Table 10 when the opening ratio m is the same, Q is on the whole proportionate to the area of the outlet.

When the opening increases, we note a tendency for the amount of ventilation to become slightly larger than the area ratio. The writer wishes to suggest that this is due to the high temperature air column which has been exhausted, causing h to work more actively.

m	0.5		1.0			2.0	
A_2	0.16	0.08	0.32	0.16	0.08	0.32	0.16
$Q/\sqrt{\Delta T} = \bar{k}$	0.028	0.012	0.050	0.024	0.011	0.028	0.012

Table 10. The Amount of Ventilation (High Windows) and the Area of the Outlet

(B) Distribution of Circular Openings (Fig. 46).

(1) Here too, as in Fig. 48(B), Q can be expressed $Q = \bar{k}\Delta T^{1/2}$.

(2) When the triangular distribution of circular openings is arranged upside down as illustrated in (c) and (c') in Fig. 46, the amounts of ventilation area almost the same (Fig. 48(B)).

(3) When equally distributed, (b), (c) and (c') are compared with one another, it will be seen that at the ratio of the total opened area 2:1, the ratio of $\bar{k}$, that is, the ratio of the amount of ventilation, is nearly 2:1. See (1) in Fig. 48(B)).

(4) Window-type distribution (d), (e), (e'), (f) and (f') may be said to be the same amount of ventilation within the range of errors, as will be understood from the curve (2) in Fig. 48(B).

3.2.4 Neutral Zone and Counter Flow. (Ref. 34)

(A) High Windows.

When the calculated value of h_0 from the equation (18) is compared with the measured value $\bar{h}_0$ they are in good agreement as shown in Table 11.

Ref. 34. Shoda: Lecture at a meeting of the Society for Architecture in November, 1947.

When the outlet is large, the opening ratio m remaining the same, the neutral zone tends to be higher than the calculated value. This is probably due to the fact that the exhausted air, even after coming out of the window, forms a high temperature air column and is working in less restricted conditions than h, the distance between the upper and lower windows, thus raising the position of the neutral zone.

m	$A_2\,(m^2)$	$\bar{h}_0$ (m)	h_0 (m)
0.25	0.08	0.58	0.63
0.5	0.16	0.41	0.54
0.5	0.08	0.53	
1.0	0.32	0.28	0.34
1.0	0.16	0.30	
1.0	0.08	0.33	
2.0	0.32	0.10	0.13
2.0	0.16	0.12	
4.0	0.32	0.05	0.04

When m = 0.25, m = 4.0, the neutral zone goes across the window; and for this reason, when observed by means of the smoke of incense sticks, counter flows are noted, as illustrated in Fig. 49.

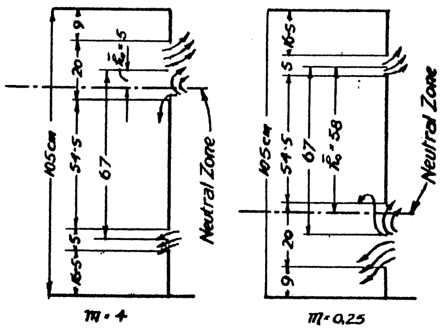


Fig. 49. Counter Flows. (See also Table 11).

(B) Distribution of Circular Openings

The measured position of the neutral zone in the distribution of circular openings is as indicated in Fig. 46 by chain lines. In equation (57), if h has no relation with the opening ratio m, the writer presumes that m is determined so that Q becomes maximum for the equilibrium of heat. $dQ/dm = 0$; that is, m = 1 is obtained from $d\left\{m(1+m)^{-1}(1+m^{1})^{-1/2}\right\} dm = 0$.

The writer ventures to assume that this hypothesis becomes possible probably for the mean value of m = 0.8 in the triangular distribution (c) and (c') in Fig. 46.

3.2.5 Friction Factor and h in the Distribution of Circular Openings

(a) Friction Factor (Coefficient of Discharge).

In the case of high windows, from the relationship between $1/\bar{\varphi}^2$ and m^2 (excepting m = 0.25, 4 in which counterflows are formed) we obtain $K_1 = K_2 = K = 1.35$ or $\alpha = 0.86$. (See Fig. 50).

(b) h in the distribution of circular openings. (Fig. 46).

If $K_1 = K_2\ K$, we get from (11')

$$h = KT_0(1+m^2)\bar{k}^2/2gA_2^2 \qquad (58)$$

If h is obtained with k = 1.35, g = 9.8, T_0 = 290, the results are set forth in Table 12.

If k = 1.35 or $\alpha = 0.86$, we may write $h \doteq H$ for the distribution of windows (Fig. 46), that is, we may have h for the distance between the upper and lower ends of the window.

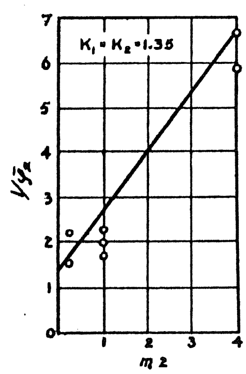


Fig. 50. Friction Factor of Windows.

Type	m	$\bar{k}$	$A_2\,(m^2)$	h (m)	h/H
(a)	1	0.010	0.068	0.88	1.1
(b)	1	0.023	0.186	0.62	0.8
(c)	0.68	0.010	0.079	0.46	0.6
(c')	0.89	0.012	0.092	0.44	0.6
(d)	1	0.070	0.045	1.00	1.3
(e)	0.94	"	0.048	0.82	1.0
(e')	1.08	"	0.052	0.79	1.0
(f)	1.79	"	0.048	0.71	0.9
(f')	1.29	"	0.061	0.70	0.9

H = 0.8 (m): Distance between upper and lower ends of opening

Table 12. h in the Distribution of Circular Openings

CHAPTER 4

VENTILATION OF A ROOM WHEN THE INSIDE TEMPERATURE IS LOWER THAN THAT OUTSIDE

In the experiments in which carbon dioxide has hitherto been used to measure the ventilation of a room, the carbon dioxide has generally speaking acted merely as an indicator. In this Chapter, the writer proposes to deal with this gas, not only as an indicator, but also mixed with air, causing the density to become greater than that of the atmosphere. That is to say, he likens this state to that in which the temperature of the air inside a room is lower than that outside, thus causing ventilation; and he intends to examine experimentally the properties of natural ventilation with models of a room. (Refs. 35 and 36).

4.1 Distribution of Carbon Dioxide Percentages in a Room (Experiment 1)

In this experiment, observations are made of the way in which the air mixed with carbon dioxide in a room (box) flows out of the room because of its difference in density from the air outside.

4.1.1 Experiment

A box was made of veneer board, of dimensions 50 x 50 x 50 (cm^3). In the centre of one of the sides was made an opening 10 x 10 (cm^2). Glass tubes fixed inside the box distributed the collecting points, as illustrated in Fig. 51. The carbon dioxide percentages were measured with interferometers in two cases; one when the opening was on the upper side of the box, and the other when the opening was on one of the sides. The arrangement for the experiment is illustrated in Fig. 52.

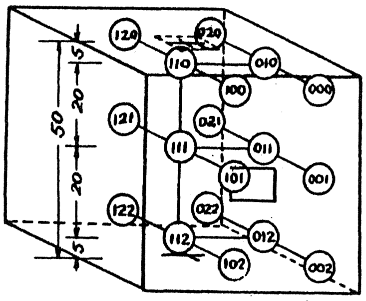
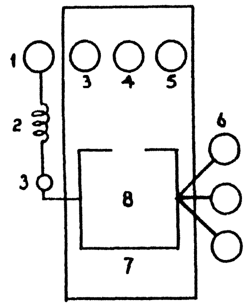


Fig. 51. Model.



1. CO_2 vessel
2. Glass Tube
3. Thermometer
4. Kata Thermometer
5. Wet bulb Thermometer
6. Carbon Dioxide Tester
7. Screen
8. Box for Experiment

Fig. 52. Arrangement for Experiment.

Since this experiment was conducted underground, there was practically no change in temperatures and wind velocities in the room. The wind velocity in the room measured by the Kata thermometer was 0.01 - 0.02 (m/sec).

The measurement of carbon dioxide percentages consisted of 12 sets of observations, as given below. (See also Fig. 51).

(A) When the opening was in the centre of one of the sides.

(a): (100, 110, 120), (101, 111, 121), (102, 112, 122), (000, 010, 020), (001, 011, 021), (002, 012, 022), (110, 010), (111, 011) and (112, 012).

(b): (110, 111, 112).

(c): (101, 0, U).

(B) When the opening was in the centre of the upper side.

(110, 111, 112).

The side with the opening: It was so arranged that 101 should be with the side opening, and 110 with the upper opening.

Ref. 35. Shoda: Architectural Review; No. 28, pp. 63-69 (1943).
Ref. 36. Shoda: Architectural Review; No. 31, pp. 36-39 (1944).

O.U: These points were situated at the upper and lower ends of the opening and outside at a distance of 3 (cm) from the sides (See Fig. 54).

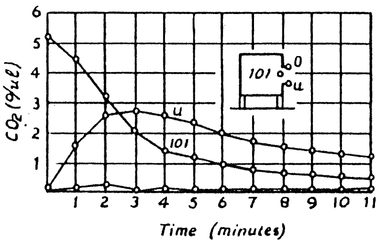


Fig. 54. CO_2 percentage-time curves. (Near the opening).

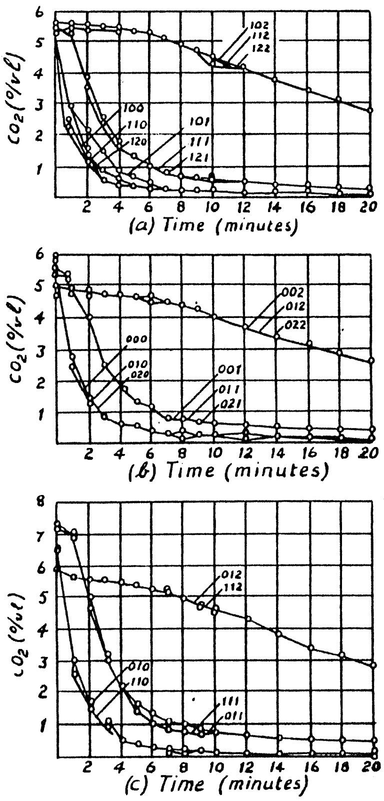


Fig. 53. CO_2 percentage-time Curves.

4.1.2 Results of the Experiment

The relationships between carbon dioxide percentages and time are given in Fig. 53 (a), (b), (c), Fig. 54 and Fig. 55.

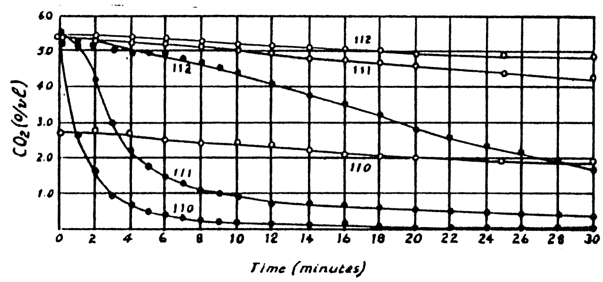
From these distributions of carbon dioxide percentages, we come to the following conclusions:

(1) Percentages on the same level are all identical. The percentages at the opening however, are small compared with those inside. (Fig. 53 (a), (b) and (c).

(2) The air mixed with carbon dioxide in the box goes out at the lower part of the opening and the outside air flows in at the upper part of the opening. (Fig. 54).

(3) When the opening is on the upper side of the box there is no air flow. As shown by the white circles in Fig. 55, which indicate the case in which the opening is on the upper side, there is very little reduction in carbon dioxide percentages compared with the curves plotted from the black circles, indicating the case of the side opening.

(4) It may be suggested that the reduction in carbon dioxide percentages in the box is due chiefly to the air flow created by the difference in air density between the inside and outside of the room.



o: percentages in the centre of the upper opening, top, middle and bottom.

o: percentages in the centre of the side opening, top, middle and bottom.

Fig. 55. (Experiment 1). The Position of the Opening and the Reduction in CO_2 Percentages.

4.2 Position and Size of Opening, and the Amount of Ventilation. (Experiment 2).

What we have learnt in the previous section about the exit from the room of air mixed with CO_2 is now about to be applied to the natural ventilation which occurs when the temperature inside the room is lower than that outside, and it is proposed to consider the relation of the size and position of openings to the amount of ventilation.

4.2.1 Experiment

The model was made of veneer board, dimensions 90 x 90 x 90 (cm^3). It was a 1/4 scale model of an 'eight matted room'.* For the collection of carbon dioxide, three positions, top, middle and bottom were arranged in the centre. Fig. 56 illustrates the arrangement for the experiment, and Fig. 57 the arrangement of the openings.

1. Vessel for CO_2
2. Glass Tube
3. Thermometer
4. Kata Thermometer
5. Wet bulb Thermometer
6. CO_2 Tester
7. Resistance
8. Box for Experiment
9. For collecting CO_2
10. Fan

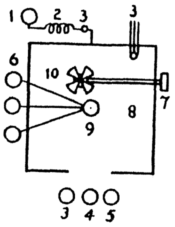


Fig. 56. Arrangement for Experiment (2).

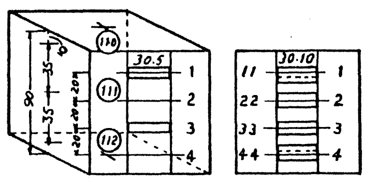


Fig. 57. Model. (Experiment 2).

The lines 1, 2, 3 and 4 were arranged at intervals of 20 (cm) to standardize the horizontal central lines of the openings. The standard size of the openings was 30 x 5 (cm^2) (See Fig. 57). Further, the walls facing each other were represented by A and A'; B and B'. (Fig. 58).

The position, size and number of openings were in the following combinations:

(I - A) When there is no opening.

(I - B) When there are two openings on the same wall. The opening ratio m = 1. (12), (13), (14), (24), (34), (23).

(I - C) When there is one opening. (11), (22), (2 1/2, 2 1/2) (33), (44).

(II - A) When two openings are on opposite or adjacent walls. The opening ratio m = 1. (Fig. 58, Nos. 1 - 8).

(II - B) When there are two windows at the top and bottom of the same wall. (Fig. 58, Nos. 9 and 10).

(II - C) When there are two openings on the same wall, the opening ratio m = 1, and the area varies. (Fig. 58, Nos. 11 - 14).

(II - D) When there are two openings on the same wall, and the opening ratio m varies. (Fig. 58, Nos. 15 - 22).

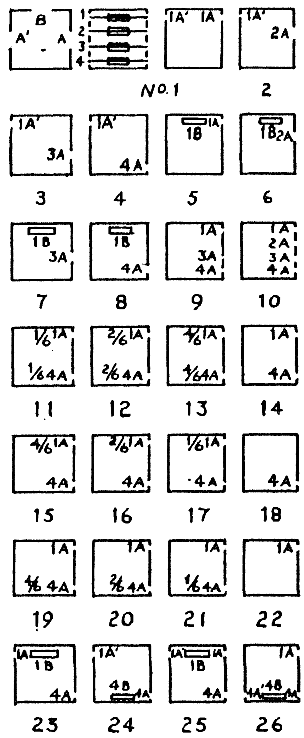


Fig. 58. Various Combinations of Openings.

(II - E) When the position and area (number) of openings at the top and bottom are reversed. (Fig. 58, Nos. 23 - 26).

4.2.2 CO_2 Percentage Reduction Curves and the Amount of Ventilation

The distribution of carbon dioxide percentages in a model changes considerably as the gas goes out, as has been described. If the air in a room is stirred with a fan in order to secure uniformity of carbon dioxide percentages, there is in

* Translator's Note: A domestic term for the floor space of a room. The area of one mat is approximately 3' x 6'.

consequence a certain amount of ventilation. Further it may be said that the collection of material (gas) is itself a certain amount of ventilation.

Let Q_g represent an amount of ventilation caused by density difference, and Q_e an amount of ventilation from another cause. Then

$$Q = Q_g + Q_e \tag{59}$$

where Q is the amount of ventilation which can be measured.

If carbon dioxide percentages are uniform in the model, there are the following relationships between the percentages $C(\theta)$ and the amount of ventilation $Q(\theta)$ at time θ:

$$C + dC = C(V - Qd\theta)/V,$$

$$Q = - dC(d\theta/C.V, \tag{60}$$

where the carbon dioxide in the atmosphere is negligible, and V is the volume of the model.

$$C = F(\theta) \tag{61}$$

If, from the measured value of carbon dioxide percentages, we obtain the above experimental formula, the amount of ventilation per unit volume n is

$$n = Q/V = - F'(\theta)/F(\theta) \tag{62}$$

further, $$n = n_g + n_e \tag{63}$$

When $C \to 0$, from $n_g \to 0$ it follows

$$n_{c \to o} = n_e \tag{64}$$

Therefore, n and n_e can be derived from the measured value, and we can obtain $Q_g = n_g.V$. The amount of ventilation in the present experiment is calculated by this method.

The carbon dioxide percentage-time curves for the measured values can be expressed

$$C = F(t) = a/(\theta + b) - d \tag{65}$$

For example, if the above is expressed with reference to the combinations of openings (11), (12), (13) and (14), the results are as given in Table 13 and Fig. 59.

Positions of Openings	a	b	d
(11)	22	1.5	6.0
(12)	33	2.2	0.5
(13)	64	4.4	0.2
(14)	170	10.7	1.5

Table 13

An example of $C = F(\theta)$

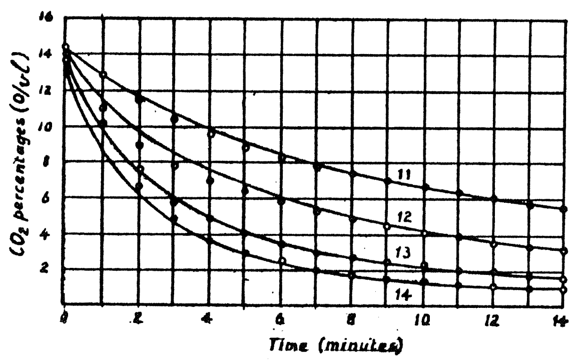


Fig. 59. Measured Value and $C = F(\theta)$.

The relation between n and c is almost a straight line; for example, the one relating to the combination (14) is represented by the continuous line in Fig. 60.

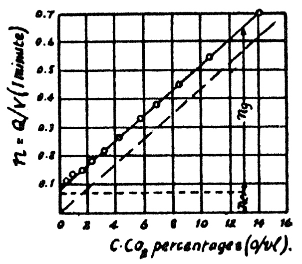


Fig. 60. Relation between n and C.

As the broken line in Fig. 60 shows,

$$Q_g = n_g V = B_g VC, \tag{66}$$

Bg is determined by the shape, size and position of the openings and various forms of friction.

If ρ_2 is the density of air in the model; ρ_1 that of the air outside the model, and the atmospheric pressure is 760 (mm Hg),

$$\Delta\rho = \rho_2 - \rho_1 = 0.00684/(1 + \alpha t).C, \ (kg/m^3) \tag{67}$$

From (66) and (67) it may be stated that the amount of ventilation is proportional to the difference in density of air between the inside and outside.

4.2.3 Results of Experiment. (1)

(I - A ~ C)

(1) The amount of ventilation is almost proportional to carbon dioxide percentages; that is, the difference in the density of the air between the inside and outside of a room.

(2) When there are two openings, the amount of ventilation is proportional to the interval of the openings, and has no connection with their positions. When there is only one opening, too, it may be said that its position has no bearing on the amount of ventilation (Table 14 and Fig. 61).

Positions of Openings	$B_g = Q_g/C.V$ (m^3/min.o/vl.m^3)
(14)	0.044
(13) (24)	0.031, 0.028
(12) (23) (34)	0.016, 0.013, 0.013
(11) (22) (33)	0.0012, 0.0023, 0.0084
(44)	0.0059

Table 14. Amount of Ventilation and Intervals and Positions of Openings

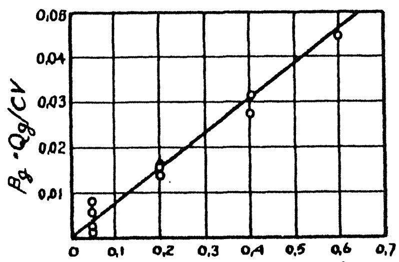


Fig. 61. Amount of Ventilation and Intervals of Openings.

(3) The amount of ventilation by one opening is almost equal to that by two openings arranged close to each other, whose areas are each 1/2, so that they may be regarded as one opening (Fig. 61).

(II - A ~ E)

(1) The measured values of Nos. 1 - 26 and the values derived from the empirical formula are as given in (a) - (g) in Fig. 62, and in Table 15.

No.	a	b	d	Bg	No.	a	b	d	Bg
No. 1	323	13.6	9.3	.002	No. 15	53	3.3	2.0	.017
No. 2	183	8.6	6.6	.003	16	87	5.2	2.5	.010
3	117	6.0	5.3	.007	17	159	8.8	4.0	.005
4	78	4.4	3.8	.012	18	318	16.6	4.9	.002
5	98	5.3	4.4	.007	19	48	2.9	2.2	.019
6	253	12.2	6.5	.003	20	94	5.3	3.6	.009
7	88	5.1	3.5	.009	21	155	7.9	5.2	.005
8	47	2.8	2.2	.018	22	263	13.5	6.8	.003
9	26	1.7	1.2	.037	23	32	2.1	1.2	.034
10	20	1.3	1.3	.046	24	30	1.9	1.6	.032
11	330	17.5	4.4	.003	25	16	1.1	0.9	.058
12	150	8.5	3.3	.006	26	17	1.2	1.1	.055
13	61	3.7	2.3	.021					
14	26	1.7	1.2	.035					

Fig. 15. Values of B_g from the Empirical Formula

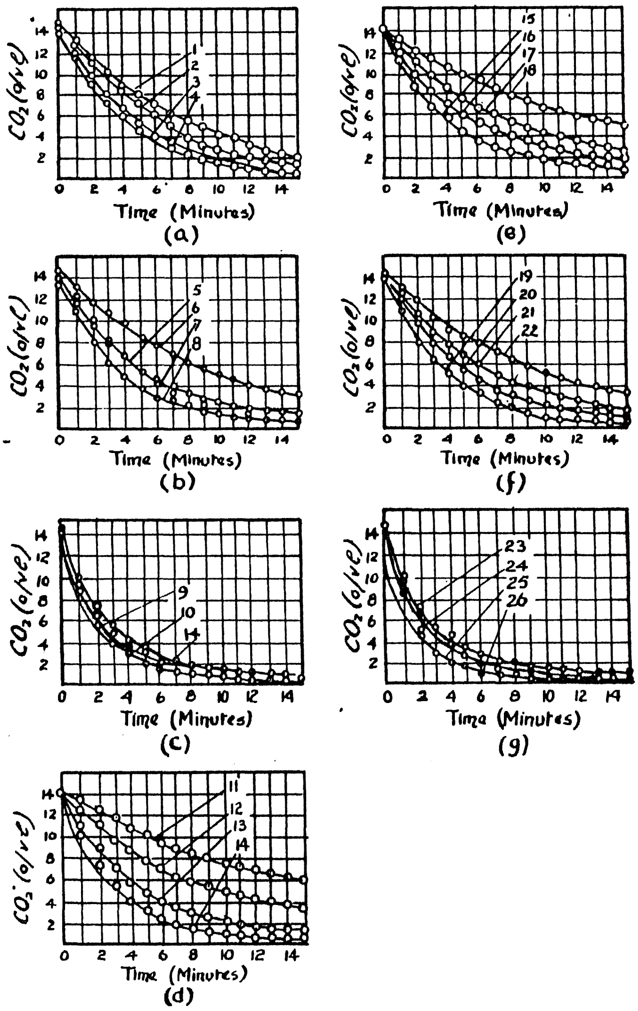


Fig. 62.
Measured Value and
C = F(θ)

(2) When there are two openings (m = 1) on the same wall (Fig. 58, Nos. 1 - 8), B_g is a maximum, approximately double that when they are on walls opposite to each other or walls adjacent to each other (Fig. 63).

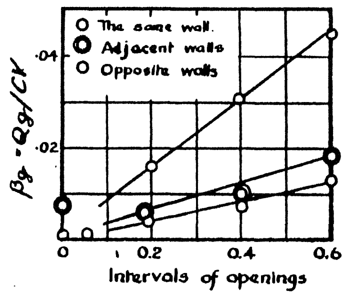


Fig. 63. Amount of Ventilation and Positions of Openings.

(3) When there are more than two openings at the top and bottom of the same wall, (Fig. 58, Nos. 9 and 10), the results are shown by examples:- No. 14: B_g = 0.0350; No. 9: 0.0374 and No. 10: 0.0464. Thus the openings of No. 14 prove to be 'dominant', and the result indicates that the amount of ventilation does not increase in exact proportion to the increase in the areas of the openings.

(4) When there are two openings, B_g is proportional to the area of openings (Fig. 64), if intervals are constant at m = 1. (Fig. 58, Nos. 11 - 14). In this case, however, the area of the opening is 30 x 5 (cm^2) = 1.

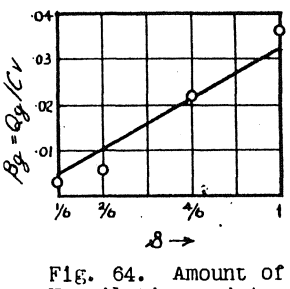


Fig. 64. Amount of Ventilation and Area of Openings.

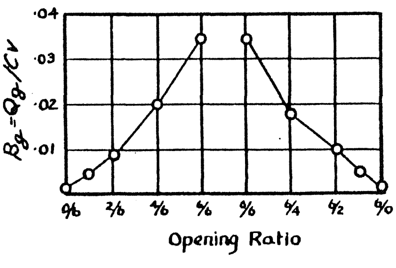


Fig. 65. Amount of Ventilation and Opening Ratio.

(5) When two openings are on the same wall, and the opening ratio m varies, (Fig. 58, Nos. 15 - 22), B_g is proportional to the small opening, and B_g is almost the same at m and 1/m.

(6) When the position, area and number of the inlets and outlets at the top or bottom are reversed, (Fig. 58, Nos. 23 - 26), B_g is almost the same. For example, No. 23: B_g = 0.0355, No. 24: 0.0322, No. 25: 0.0578 and No. 26: 0.0550; thus No. 23 is almost equal to No. 24 and No. 25 to No. 26.

4.2.4 Results of Experiment (2)

In the previous section the results of the experiment were described entirely on the basis of the measurements. Here it is proposed to examine the result of the combination (14): $A_1 = A_2 = 0.30 \times 0.05$ (m^2), $h = 0.6$ (m) by equation (11') in 1.2 in Chapter 1.

We obtain the density difference equivalent to the carbon dioxide percentages C by (67); we then arrive at the temperature inside the model, t_i, which produces the density difference for the temperature at time t_o. The conversion can be readily carried out with the aid of the graph, Fig. 36.

The straight line in Fig. 66 is the result of the experiment with combination (14), and the curve has been produced by the equation (11') with $K_1 = K_2 = K = 1.6$ (Chapter 3, 3.1.6, Table 7), m = 1, h = 0.6 (m), $A_2 = 0.30 \times 0.05$ (m^2). The two lines join where ΔT is large.

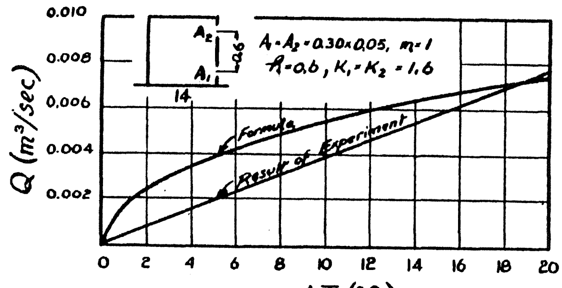


Fig. 66. Formula and result of Experiment.

In this experiment agitation is carried out with a fan for the purpose of keeping the carbon dioxide percentages uniform. Taking this matter into consideration, correction is made in the amount of ventilation, but the friction factor and the internal resistance are still unknown. Further, there is some room for consideration of the empirical formula. However, we have obtained some result to cope with the case where the inside of a room is at high temperature.

CHAPTER 5

Coefficient of Discharge of Openings and Cracks

The amount of ventilation is controlled by the friction which exists in the path of the air, as expressed in equation (29) in Chapter 1. When the ventilation of buildings or rooms is considered, therefore, the coefficient of discharge, α, or the friction factor, K, of the inlet and outlet is an important subject for study.

The coefficient of discharge of the orifice and nozzle in the tube (Refs. 37 and 38), if the Reynolds' number of the opening is small, is large in the case of the orifice and small in the case of the nozzle. So the value is not constant.

Windows, ventilators, etc., are equivalent to orifices on walls. (Refs. 39 and 40). (Fig. 67).

The case of a nozzle in a tube is represented in Fig. 68. (Ref. 41). In this experiment, several things have been clarified, including the fact that the changes in the coefficient of discharge of the openings below the Reynolds' Number 4×10^3 and the properties of the coefficient of discharge of cracks are equivalent to the reciprocals (Ref. 42) of the friction factor of nozzles or round tubes.

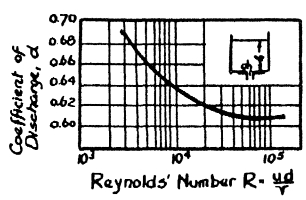


Fig. 67. Coefficient of Discharge of Orifice on the Wall.

(Schneider)

Ref. 37. DIN. 1952, Regelen für die Durchflussmessung mit genormten Düsen u. Blenden, (1935).
Ref. 38. Uchida: Chemical Engineering, pp. 72 - 75, (1944).
Ref. 39. Handbuch Experimental Physik, IV, 1 Teil, S.585, (1931).
Ref. 40. Handbook of Mechanical Engineering (Japanese), p. 795, (1937).
Ref. 41. (39) S. 584.
Ref. 42. (38) p. 21, p. 30.

What attracts our attention most in the present subject is that in ventilation by wind or temperature difference the coefficient of discharge is not constant, as referred to before. It is particularly interesting that in our model experiments with ventilation by temperature difference, the Reynolds' number of the opening is 10^3 or below. The changes in the coefficient of discharge are not considered in experiments with either a lattice for ventilation (Ref. 43) or a lattice for light screening (Refs. 44 and 45).

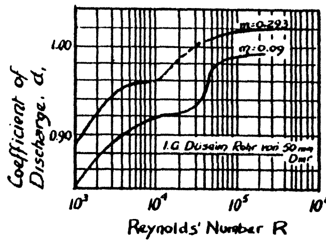


Fig. 68. Coefficient of Discharge of a Nozzle.

5.1 Coefficient of Discharge for Several forms of Openings and Cracks

For openings of various shapes, sizes and finishes, it is necessary to measure the coefficient of discharge in each case. When we have to deal with cracks it is not possible to measure the amount of air flow or the coefficient of discharge by ordinary methods (Ref. 46), because the amount of air flow in cracks is small, and also a leakage of air is inevitable in the equipment itself during the measurement. It is therefore proposed to describe a method of measuring the coefficient of discharge most suitable for a small amount of air flow (also naturally for a small Reynolds' number), and the results of such measurements.

5.1.1 Experiment. (Ref. 47)

The main part of the arrangement for the experiment consists of a pressure room and a carbon dioxide box, as illustrated in Fig. 69. The opening or crack which we wish to measure is arranged in the position indicated by A in the carbon dioxide box. In the present equipment there is no risk of air getting into the carbon dioxide box except through the opening or crack provided, because there are no joints on the border between the pressure room and the carbon dioxide box.

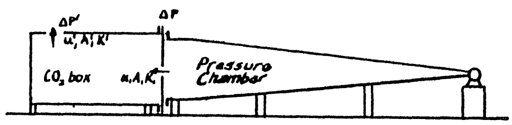


Fig. 69. Equipment for Measuring Coefficient of Discharge.

The amount of air flow, Q, is

$$Q = uA = \alpha(2g\ \Delta P/\rho)^{1/2} A, \quad \alpha = K^{-1/2} \qquad (68)$$

where Q = the amount of air flow (m^3/sec), u = mean velocity (m/sec) of air flow at the opening or crack, A = area (m^2) of section of the opening or crack α = coefficient of discharge, g = 9.8 (m/sec^2), ΔP = pressure difference (kg/m^2) between either side of the opening or crack, ρ = density of air (kg/m^3). α or K can be obtained from equation (68).

To find out the amount of air flow at A in the diagram Fig. 69, it is necessary (1) to place an orifice whose coefficient of discharge is known at A or further upstream, so that the pressure difference between either side can be measured by the manometer; and (2) to measure the distribution of the velocity at the section with a Pitot tube, thermic ray anemometer, Kata thermometer, etc. This is only an example of obtaining the amount of air flow; there are other methods. The arrangement described above means that we measure, in addition, the air which is further upstream than A and is at high pressure, escaping from some joints other than A; that is, leaking from cracks inevitably produced by the nature of the structure. Even when such leakage is prevented, it is not possible to measure satisfactorily pressure differences or wind velocities if the amount of air flow is very small. Under a wind velocity of 1 (m/sec) or under a pressure difference of 0.05 (mm Hg) the calibration of the meters is exceptionally difficult. These difficulties can be removed by using the carbon dioxide method.

Ref. 43. W. Krüger: Journal of Sanitary Engineering, Vol. 13, No. 8, p. 747 (1939).
Ref. 44. Sato: Architectural Review, No. 23, (1941).
Ref. 45. Sato: Architectural Review, No. 25, (1942).
Ref. 46. Toshiroda: Pamphlet of Society for Architecture, Vol. 5, No. 12, p. 47, (1933).
Ref. 47. Shoda: Architectural News, No. 2, (July, 1949).

Referring to the diagram, Fig. 69,

$$\Delta P/\rho = Ku^2/2g \qquad \Delta P'/\rho = K'u'^2/2g \tag{69}$$

$$uA = u'A' \tag{70}$$

$$\Delta P'/\rho = K'(A/A')^2 u^2/2g \tag{71}$$

If $A' >> A$, then $\Delta P'$ is negligible compared with ΔP. Further, if ΔP is made very small, there is no need to prepare a rigid structure against the leakage of the air through some cracks and openings in the carbon dioxide box other than A'. As our plan is to find out the amount of air flow from the decrease in carbon dioxide percentages in the CO_2 box by the method outlined in 2.2 in Chapter 2, only the amount of air which has passed through A can be obtained. For this reason it may be said that the air upstream from A in the pressure room, which leaks through the joint does not matter.

The details of an opening and a crack submitted to tests are illustrated in Fig. 70.

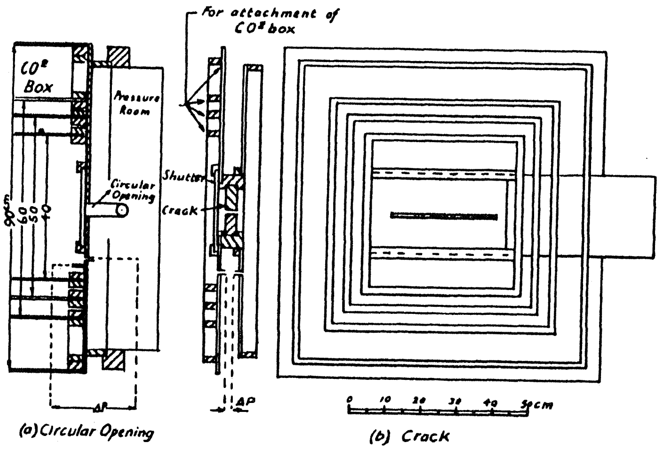


Fig. 70.

Structure of Circular Openings and Cracks

5.1.2 Method of Measurement

The measurement of air flow dealt with in 2.2 in Chapter 2 consists of a reduction in pressure in the carbon dioxide box, but in the present method the pressure is increased. That is the only difference, and the operations in the experiment and the measurement method are the same.

Let us make the first percentage, C_0', 1.5 - 2.0 (o/vl) and the last percentage, C_0', approximately $C_0'/2$. We use a carbon dioxide box just large enough to make the interval between the first and last conditions last 3 - 5 minutes. The carbon dioxide boxes are of four different sizes: 0.9 x 0.9 x 1.8, 0.6 x 0.6 x 1.8, 0.5 x 0.5 x 1.2, and 0.4 x 0.4 x 0.6 (m^3). It was ascertained that where the size of the carbon dioxide box was changed the amount of air flow was proportional to each size.

The pressure difference, ΔP, is arranged in 10 steps, 0.05, 0.10, 0.20, 0.30, 0.50, 1.0, 5.0, 10.0, 20.0, 30.0 (mm Hg), for each form. For each step measurement was made 4 - 10 times, thus obtaining the mean value of the amount of air flow.

The interferometer is used for the measurement of carbon dioxide, the Chatock inclined tube pressure gauge for pressures below 0.5 (mm Hg), and the Göttingen type pressure gauge for those above that pressure.

The forms of opening and crack submitted to test are represented in Fig. 71.

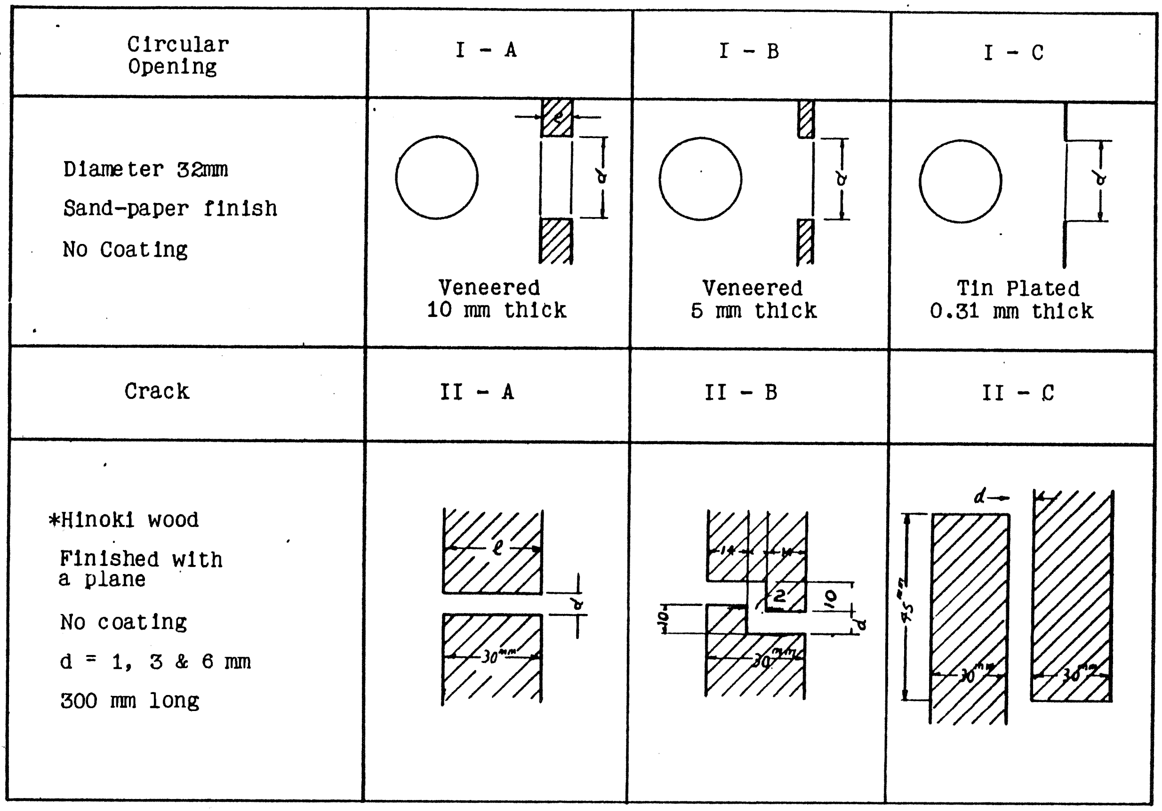


Fig. 71.

Forms of Opening and Crack

5.1.3 Coefficient of Discharge of Circular Opening

(1) The results of the measurement are given in Fig. 72, (a), (b) and (c). The relation of the mean velocity of air flow at a section of the opening or the amount of flow per unit area, $\bar{u} = Q/_A$, to ΔP, describes a parabola, and all three, I - A, I - B and I - C assume almost the same form. However, it must be added that none of them is exactly a parabola.

(2) The coefficient of discharge α obtained by the equation (68) is shown by the curves in Fig. 73. The relation between α and Reynolds' number $R = \bar{u}d/_\nu$ assumes a more or less similar shape in the three cases. Above $R = 2 \times 10^4$ they agree with the case of the orifice for a constant $\alpha = 0.62 - 0.65$. Below $R = 2 \times 10^4$ they assume their individual variations.

(3) The Shape factors (l/d) (Fig. 71) are 0.31, 0.16 and 0.01 respectively in I - A, I - B and I - C.

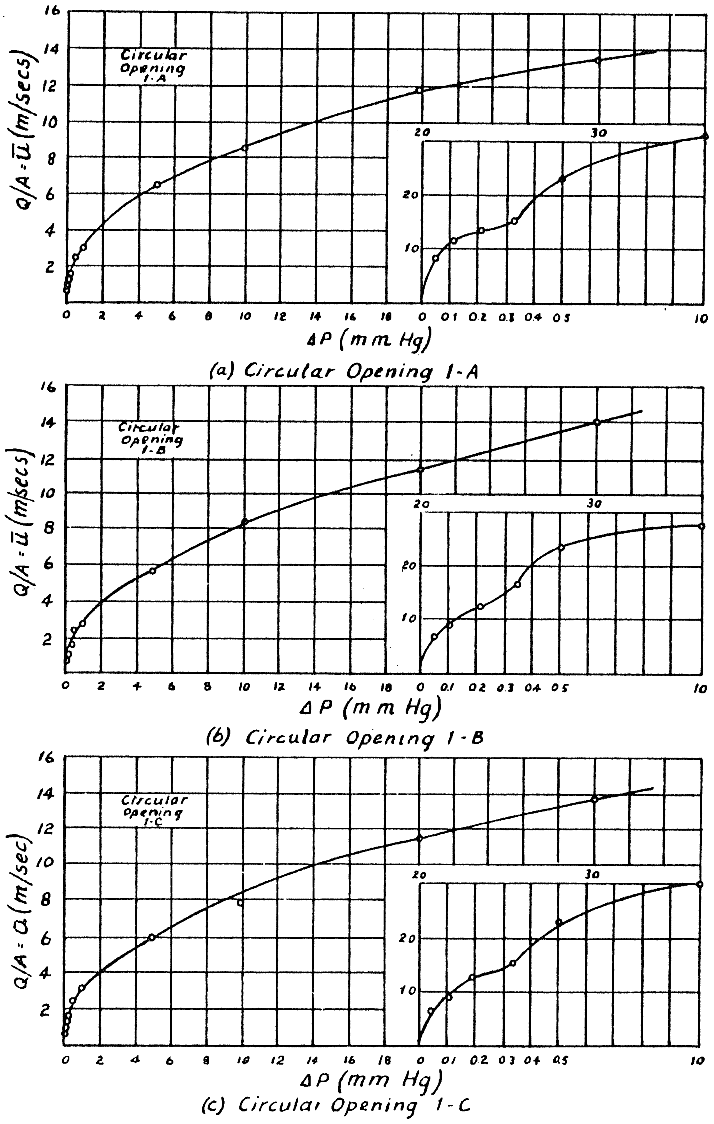


Fig. 72. Relation between $\bar{u}$ and ΔP.

* Translators Note: A Japanese Cypress

For the rectangular orifice we take $d = 2bh/(b + h)$, where b is the breadth, and h the height of the window (Ref. 40). The coefficient of discharge of a window is $\alpha = 0.7 - 0.86$ obtained from Table 7 in 3.1.6 in Chapter 3, or from the amount of ventilation in Fig. 50 in 3.2.5. As these are mean values below $R \doteqdot 5 \times 10^3$, it will be seen that they are appropriate values of the coefficients of discharge if they are compared with the curve of I - B in Fig. 73.

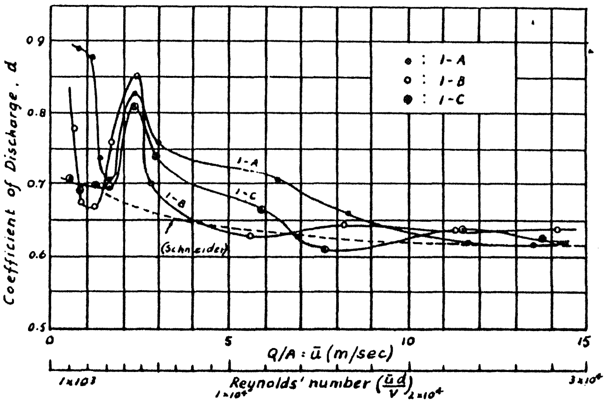


Fig. 73. Coefficient of Discharge of Circular Openings.

(4) In this section the coefficient of discharge is shown by its relation to Reynolds' number for convenience of general comparison. If we take $v = 1/7$ (cm^2/sec) for the air, Reynolds' numbers are $R = 7 \times 10^4$, 7×10^3 and 7×10^2 respectively, for d = 100, 10 and 1 (cm), at u = 100 (cm/sec). We obtain u_2/φ by temperature difference or wind in Fig. 7 in 1.5 of Chapter 1, arrive at u_2^* at a tentative estimate $\varphi = 0.5$. We then obtain α^* from Reynolds' number R^*; and φ^* is obtained. Repeating this method φ can be obtained suitably in each case. In a practical matter, such as the ventilation for a window, d = 100 (cm) as given in Table 16, it is best to consider the constant of $\alpha = 0.65$ at $\frac{l}{d} < 0.3$. When we have to deal with a ventilator or a lattice for ventilation with d = 10, 1 (cm), it would be necessary to assume that those coefficients of discharge have a range of 0.65 - 0.9. In these cases we have to consider first the nature and object of the ventilation, as dealt with in 1.6 of Chapter 1, and accordingly the calculation of the ventilation should be carried out, choosing either the large or small value of α given in Table 16, so that the amount of ventilation remains within reasonable limits.

$R = \bar{u}\, d/v$	$\sim 6 \times 10^3$	$6 \times 10^3 \sim 2 \times 10^4$	$2 \times 10^4 \sim$
α	0.65 ~ 0.90	0.60 ~ 0.75	0.60 ~ 0.65

Table 16

Coefficient of Discharge (l/d < 0.3) of Windows & Openings

When ventilation by cracks is dealt with, the object of the calculation being taken into consideration, α is chosen from among the figures given in Table 21 by the same procedure as before. For the ventilation of a room with openings and cracks of different descriptions, it is necessary for us to consider those basic points which have been discussed here, and thus to simplify complicated conditions.

5.1.4 Coefficient of Discharge of Cracks

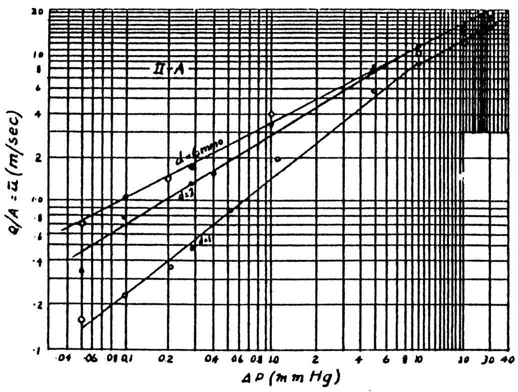
(1) The results of the measurement are given in Fig. 74, (a), (b) and (c). On the whole the relationship can be expressed by $\log \bar{u} \propto \log \Delta P$.

(2) II - A: (Fig. 74, (a)).

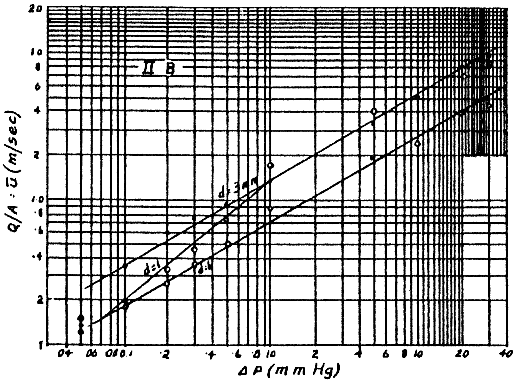
$\bar{u}$ of d = 6, 3 and 1 (mm) is almost the same, above ΔP = 10 (mm Hg); that is to say, the amount of air flow, Q, is proportional to the area of the cracks. The smaller d, the smaller $\bar{u}$. ((a) in Fig. 75).

When the amount of air flow Q is considered, it is found that for d = 3 (mm), it is 4 - 9 times as much as for d = 1 (mm); and for d = 6 (mm) it is 8 - 26 times as much. As for d = 6 (mm), it is 2 - 3 times as much as for d = 5 (mm), and is almost proportional to the area (Table 17).

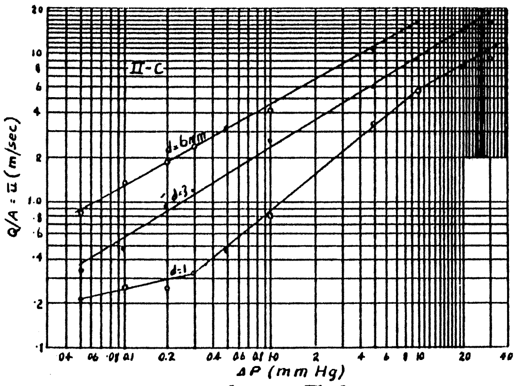
Ref. 40. Handbook of Mechanical Engineering, p. 795, (1937).



(a) Cracks II-A



(b) Cracks II-B

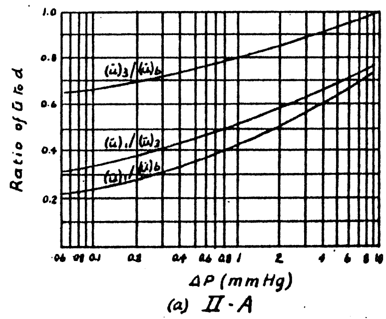


(c) Cracks II-C

Fig. 74. Relation of ū to ΔP

ΔP (mm Hg)	Q_6/Q_1	Q_3/Q_1	Q_6/Q_3
0.1	26	9	3
1.0	15	6	2.5
8.0	8	4	2

Table 17. Breadth of Crack and the Amount of Air Flow. (II - A)



(a) II-A

Fig. 75 (a). Breadth of cracks, d, and ū.

II - B: ((b) in Fig. 74).

The difficulty here is that the section of the path through a crack is not always the same. Let us therefore assume that the area is A = d x 300 (mm²).

Above ΔP = 1.0 (mm Hg), ū of d = 1, 3 (mm) is almost the same. For values of ΔP < 1.0 (mm Hg), d = 1 (mm), becomes smaller. ū for d = 3, 6 (mm) are parallel, and contrary to the case II-A, ū for d = 3 (mm) is larger. ((b) in Fig. 75).

As regards the amount of air flow, Q, d = 3, 6 (mm) is almost the same. From this it will be seen that the friction which occurs at the centre of the rabbet is a controlling factor. The ratio for d = 3 and 6 (mm) to d = 1 (mm) is 3.0 - 5.4, and it is noted that the effect of breadth, d, is very small compared with II - A. (See Table 18).

ΔP (mm Hg)	Q_6/Q_3	Q_3/Q_1
0.1	0.96	5.4
1.0	0.96	4.0

Table 18. Breadth of Crack and the Amount of Air Flow (II - B)

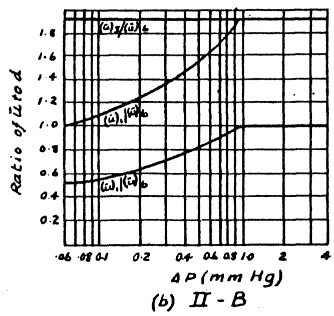


Fig. 75 (b). Breadth of cracks, d, and ū.

II - C: (Fig. 74, (c)).

The curves ū of d = 1, 3 and 6 (mm) become straight lines more or less parallel to one another and ū decreases as d decreases, as represented by (c) in Fig. 75.

As regards Q, the amount of air flow, d = 3 and 6 (mm) are 6.5 - 9 times and 14 - 43 times as much as d = 1 (mm), respectively, and d = 6 (mm) is 3.5 - 4.5 times as much as d = 3(mm). (See table 19).

ΔP (mm Hg)	Q_6/Q_1	Q_3/Q_1	Q_6/Q_3
0.1	31	6.5	4.5
0.3	43	9.3	4.3
8.0	14	7	3.5

Table 19. Breadth of Cracks and the Amount of Air Flow. (II - C)

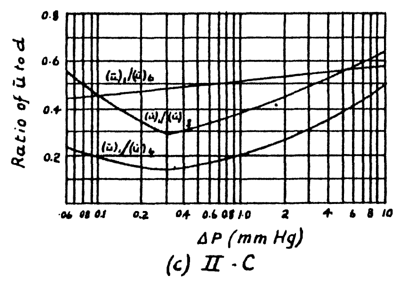


Fig. 75 (c). Breadth of Cracks, d, and ū.

Suppose d = 1, 3 and 6 (mm) correspond to the top, middle and bottom of the fixtures in a house, then we see that the amount of air flow varies from one to another in the ratio of the order of multiples of 10.

(3) The coefficient of discharge for d = 6, 3 and 1 (mm) is shown in Fig. 76 (a), (b) and (c) respectively.

When the relation between α and ū is examined, we observe that where ū is small, α is also small (contrary to the case of circular openings); and the form of the curve resembles the case of nozzles (Fig. 68).

$$\alpha = a . R^n \quad (72)$$

where $R = ud/v$ $a = \phi\left(\frac{1}{d}\right)$ and, taking into consideration the equation (68),

$$\left(\frac{1}{a}\right)(ud/v)^{-n}\left\{u(2g\ \Delta P/\rho)^{-1/2}\right\} = 1 \quad (73)$$

Logarithmically expressed,

$$\log u = \log a' + n(1-n)^{-1}\log d + \left\{2(1-n)\right\}^{-1}\log \Delta P \quad (74)$$

where $a' = \left\{a v^{-n}(2g/\rho)^{1/2}\right\}^{1/(1-n)}$

From the straight lines in Fig. 74,

$$k = \log(u_2/u_1)/\log(\Delta P_2/\Delta P_1) \quad (75)$$

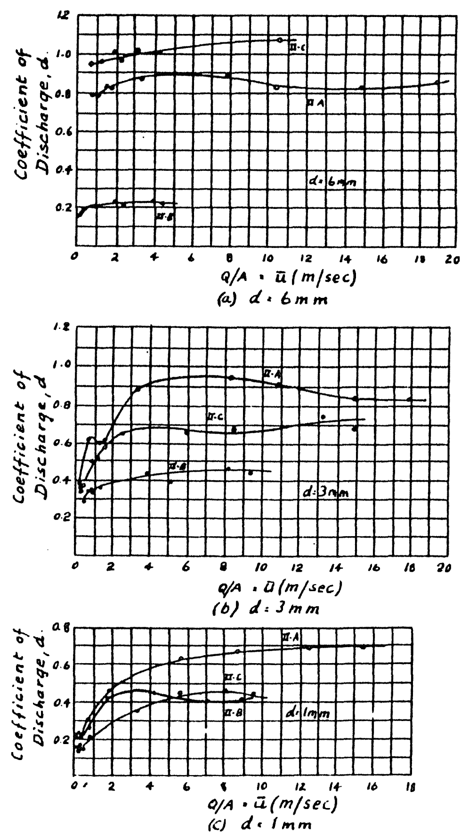


Fig. 76. Coefficient of Discharge of Cracks.

When the above is obtained,

$$n = (2k-1)/2k \qquad (76)$$

The values of n are set forth in Table 20.

Form	II-A	II-B	II-C
d = 6 (mm)	0.04	0.13	0.07
3	0.15	0.13	0.15
1	0.36	0.39	0.39*

* $0.4 < \Delta P < 10$ (mm Hg)

Table 20. $\alpha = a.R^n$

As d increases, n decreases. With the exception of II - B of d = 6 (mm), the values of n in the three forms II - A, II - B and II - C are near to one another for corresponding values of d.

When d = 1 (mm), n ≑ 0.4, and from (74) $u = C\Delta P^{0.83}$ C = constant (77) thus approaching $Q\alpha\Delta P$.

As the models are full-sized, it is possible for us, by the use of Table 21, to discover the coefficients of discharge of cracks in fixtures which correspond to the parts in the model already studied.

d (mm)	ū (m/sec)	II - A	II - B	II - C
6	~ 1	0.8	0.15 ~ 0.2	0.95
	1 ~ 5	0.8 ~ 0.9	0.2	0.95 ~ 1.0
	5 ~	" ~ "	"	1.0 ~ 1.1
3	~ 1	0.4 ~ 0.6	0.35 ~ 0.35	0.35 ~ 0.55
	1 ~ 5	0.6 ~ 0.95	0.35 ~ 0.45	0.55 ~ 0.65
	5 ~	0.8 ~ 0.95	0.45	0.65 ~ 0.7
1	~ 1	0.2 ~ 0.3	0.15 ~ 0.2	0.15 ~ 0.2
	1 ~ 5	0.3 ~ 0.6	0.2 ~ 0.45	0.2 ~ 0.4
	5 ~	0.6 ~ 0.7	0.4 ~ 0.45	0.4 ~ 0.45

Table 21

Coefficient of Discharge of Cracks

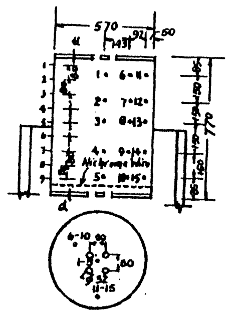
5.2 Coefficient of Discharge in the Ventilation by Temperature Difference. (Ref. 48)

The writer has measured various factors, each separately, of ventilation by temperature difference; and has ascertained, by means of a cylindrical model, the fact that the values he had obtained in the experiment can basically satisfy the formulae in connection with ventilation. Items of measurement include the amount of ventilation, distribution of temperature and distribution of pressure difference. For the coefficient of discharge, we are referred to the results of measurements described in 5.1.3 of Chapter 5.

5.2.1 Experiments with a cylindrical model

The diagrams in Fig. 77 indicate a cylinder and various points for measurement.

The wall of the cylinder is of tin plate and is lagged with asbestos packing. The top and bottom covers are of veneered board, 10 (mm) thick. When the ventilation experiment is carried out, the middle of the top and bottom covers is fitted with veneered board 5 (mm) thick, 13 x 13 cm^2 with four circular holes, 32 mm in diameter, arranged at a distance of 80 (mm) from centre to centre. These circular holes are the same as those used in the model of the room and introduced in 3.2.1 (B) in Chapter 3.



1-15: Points for measuring temperature
u, 1-9, d: Points for measuring pressure.

Fig. 77. Cylinder.

At a height of about 30 mm from the bottom, Nichrome wire is stretched, and it is so arranged that the inside is uniformly heated. It is further arranged that the

Ref. 48. Shoda: Architectural News, No. 5 (Jan., 1950) currents and voltages under normal conditions can be read, and the distribution of internal temperatures and the distribution of pressure difference on the outer wall can be measured at the same time. For the temperature the alcohol thermometer is used, and for the pressure, Chatock's inclined tube pressure gauge.

5.2.2 Various Factors in Ventilation by Temperature Difference (Measured Values and Formulae)

(1) Distribution of Temperature.

An example of the distribution of temperatures is set forth in Table 22.

	1 - 5	6 - 10	11 - 15	Mean Level
When there is no Ventilation				
ΔT = 21.5 t_i = 45.3 t_o = 23.8	47.1 45.5 45.2 46.5 46.2	46.5 46.5 47.2 47.2 49.5	43.5 43.5 42.9 42.9 40.0	45.7 45.2 45.1 45.5 45.2
When there is Ventilation				
	1 - 5	6 - 10	11 - 15	Mean Level
ΔT = 14.9 t_i = 43.6 t_o = 28.7	44.8 44.0 43.8 44.2 39.0	44.0 44.0 44.0 44.2 47.9	41.0 42.9 43.0 44.0 40.5	43.5 43.6 43.6 44.1 43.4

Table 22

Distribution of Temperatures (Cylinder)

Referring to this table, it will be noted that the mean temperatures on levels are more or less the same. The more ventilation and the larger the temperature difference, the less the uniformity in Temperatures. (3.1.3 and 3.2.2 in Chapter 3).

(2) Distribution of Pressure Difference

The distribution of pressure difference when there is ventilation is represented in Fig. 78.

When the mean temperature in a room is t_i = 65 (C), and the outside temperature t_o = 25.2 (C), $\Delta P = (\rho_o - \rho_i)h$ = (1.184 - 1.043) x 0.77 = 0.11 (mm Hg), and the measured value 0.12 (mm Hg), thus showing agreement. The distribution of pressure is rectilinear, and the neutral zone is situated at h/2. As the opening ratio is m = 1, the equation (18) in 1.3 in Chapter 1 is satisfied.

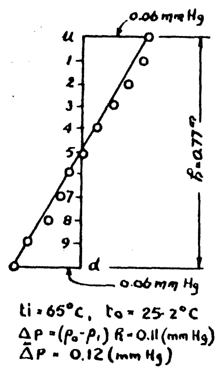


Fig. 78. Distribution of Pressure Difference.

(3) The Amount of Ventilation.

The amount of ventilation is obtained by heat calculation. From the equation (43) (3.1.4 in Chapter 3),

$$3600\ C_p \rho Q = H'/\Delta T - H_t/\Delta T \qquad (78)$$

The measured value is represented in Fig. 79.

The relation between the amount of ventilation and $\Delta T^{1/2}$ is rectilinear, as is clear in Fig. 80.

From Fig. 80,

$$Q = 0.00045\ \Delta T^{1/2}\ (m^3/sec) \qquad (79)$$

$C_p \rho$ = 0.3 and the area of outlet $A_2 = \pi(0.016)^2 \times 4$.

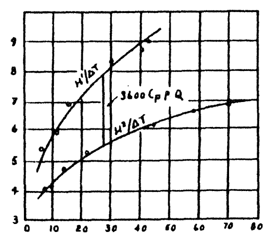


Fig. 79. Amount of Ventilation and the Amount of Heat Supplied.

When t_i = 65 (C), t_o = 25.2 (C), ΔT = 39.8 (C), $\bar{u}$ = 0.87 (m/sec).

If we take $K_1 = K_2 = K$ or $\bar{\alpha} = K^{-1/2}$, $m = 1$ in equation (11') in 1.2 of Chapter 1,

$$Q = \bar{\alpha}\ (gh\Delta T/T_0)^{1/2} A_2 \qquad (80)$$

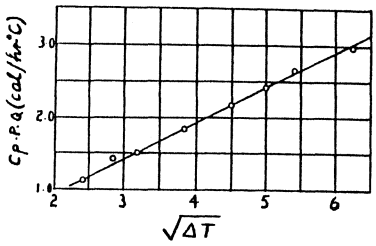


Fig. 80. Amount of Ventilation and Temperature Difference.

where $\bar{\alpha}$ in this case is the mean coefficient of discharge of ΔT<40 (C).

When α is obtained from equations (79) and (80) with h = 0.77 (m), T_0 = 300 (ab. C), g = 9.8 (m/sec^2),

$$\bar{\alpha} = 0.9 \text{ or } \bar{K} = 1.25 \qquad (81)$$

According to the measured value (see I - B curve in Fig. 73 in 5.1.3 of Chapter 5) of the coefficient of discharge of a circular opening, ΔT = 39.8 (C); that is to say, when $\bar{u}$ = 0.87 (m/sec), α = 0.7. Below this velocity, the coefficient of discharge suddenly increases. For this reason 0.86 - 0.9 are quite conceivable values for $\bar{\alpha}$.

Thus we come to the conclusion that, if we use coefficients of discharge determined taking Reynolds' number into consideration, the equations (80) and (26) become generally practicable as formulae for ventilation by temperature difference. Special attention is called in such a model experiment; when α = 0.63 and α' = 0.9, K = 2.5 and K$'$ = 1.25. Therefore, in our experiment, the amount of ventilation by temperature difference at $\Delta T/_2$ can be calculated if Q is obtained by equation (80) with α = 0.63.

CHAPTER 6

VENTILATION BY WIND (TSUFU)*

Ventilation by wind for buildings or rooms is controlled by various factors, such as the pressure of wind, direction of wind, position of window, size of window, resistance to the path of wind, etc. In this chapter the writer proposes to use the term 'tsufu' for ventilation by wind.

Wind pressure has already been considered in 1.4 of Chapter 1, and the writer is not quite sure whether the wind pressure acting on buildings can be expressed by coefficients of pressure distribution, even when the windows of such buildings are open. Further, in consideration of the effect of ventilation, the distribution of wind velocities in a room is an important factor. A number of experiments have been carried out with models on ventilation by wind; for instance, for classrooms (Ref. 49), factories (Refs. 50, 51 and 52), dwellings (Ref. 53) and for grouped buildings (Ref. 54). Further, there are instances in which the distribution of wind velocities in a room was taken into consideration and research has yielded some quantitative results. (Ref. 55).

* Translator's Note: The word ventilation is either 'Kanki' or 'Tsufu' in the Japanese language. Technically speaking there is some difference between the two, but laymen never distinguish between them. Prof. Shoda, the writer of this booklet, appears to define 'tsufu' as ventilation by wind. In fact 'fu' in 'tsufu' means wind. From Chapters 1 - 5 the writer used mostly 'kanki', but in this chapter, the new term is used throughout.

Ref. 49. Ito: Architectural Review, No. 3, pp. 66 - 75, (1936).
Ito: Architectural Review, No. 3, pp. 58 - 65, (1936).
Ito: Architectural Review, No. 5, pp. 271 - 280, (1937).
Ito: Architectural Review, No. 6, pp. 44 - 53, (1937).
Ref. 50. Sato: Architectural Review, No. 13, pp. 360 - 369, (1939).
Ref. 51. Ito: Architectural Review, No. 17, pp. 94 - 102, (1940).
Ref. 52. Kimura: Journal of Sanitary Engineering, Vol. 15, No. 4, p. 221, (1941).
Ref. 53. Watanabe and Shoda: Architectural Review, No. 31, pp. 145 - 153, (1944).
Watanabe and Shoda: Architectural Review, Nos. 32 - 35, pp. 43 - 46, (1947).
Ref. 54. S. Shoda: Architectural Review, No. 5, pp. 261 - 270 (1937).
S. Shoda: Architectural Review, No. 26, p. 38, (1942).
Ref. 55. Hitomasu: Architectural Review, No. 1, pp. 254 - 261, (1936).
Hitomasu: Architectural Review, No. 31, pp. 40 - 44, (1944).
Hitomasu: Journal of Sanitary Engineering, Vol. 17, No. 9, (1943).

In the present experiment, apartments, school buildings, etc. are considered, and the main object is to examine sizes of windows, their combinations and the effect of these factors on ventilation. In the measurement of wind velocities the thermic ray Kata thermometer was employed (2.3, Chapter 2). This experiment was carried out at the laboratory of the Institute of Industrial Science, Faculty of Science and Engineering, University of Tokyo.

6.1 Method of Experiment

A model of a three storied building was introduced into a wind tunnel in which there was a certain velocity. Changing the conditions, such as the direction of wind, position of rooms, windows and openings in partitions, the wind velocities in the rooms were measured.

6.1.1 Arrangement for Experiment (Model of a Three-Storied building)

The model is of floor space 42 x 49 (cm^2), and is 54 (cm) high. It is divided into a centre room and unit rooms on each side. One unit room consists of two (front and back) rooms. The sizes of the windows on the outer walls of the front and back rooms and the openings on the partitions are of four grades, as detailed in the diagrams. The model is a 1/15 reduced scale model of an apartment (Fig. 81).

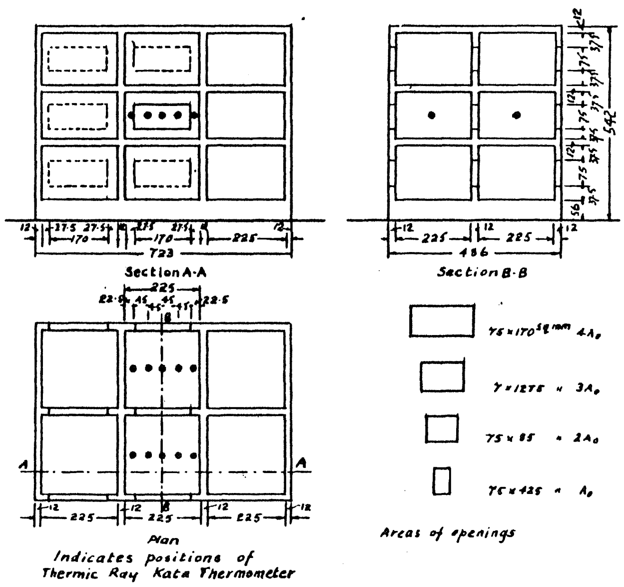


Fig. 81. Model of a Building.

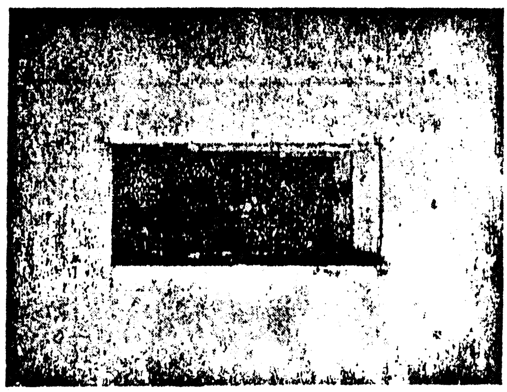


Fig. 82 (b).
Bulbs of Thermic Ray Kata Thermometer.

In each room there are five points for measurement of wind velocities on a central line in the room, as illustrated in Fig. 81. Kata Thermometers are suspended between sliding scales, as illustrated in Fig. 82 (a) and (b), and are installed at the positions mentioned. The model is placed on a plate and introduced into a wind tunnel, as illustrated diagrammatically in Fig. 83 (a). For convenience of measurement, small wind velocities are mainly chosen, and the outlet of the tunnel is covered with wire net (mesh 0.5 mm, and wire 0.18 mm in diameter).

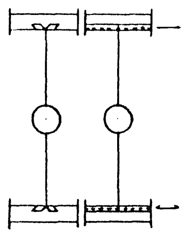


Fig. 82 (a).
Bulbs of Thermic Ray Kata Thermometer

The wind velocity at the outlet is kept at V = 1.57 (m/sec), and in each unit room, a wind is raised and the wind velocities in the room are measured.

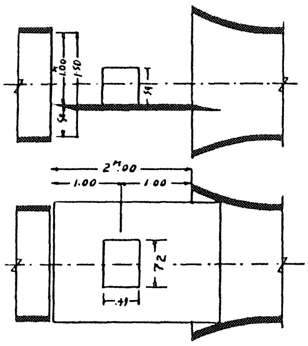


Fig. 83 (a). Wind Tunnel.

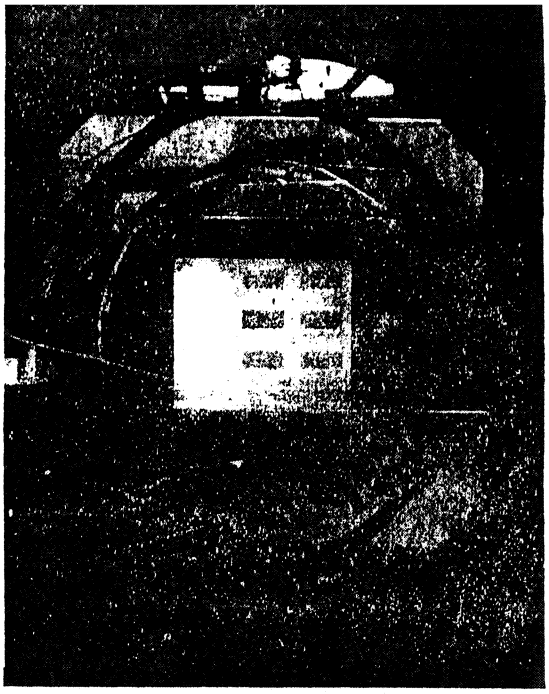


Fig. 83 (b) Wind Tunnel.

6.1.2 Formulae for the Amount of Ventilation

The amount of ventilation in each unit room of the model is now considered, taking into consideration equation (25) in 1.4 of Chapter 1, and the friction factor dealt with in (a) in 3.1.6 of Chapter 3. The amount of ventilation, Q, is

$$Q = uA = \alpha(1 + m_1^2 + m_3^2)^{-1/2} (C_1 - C_3)^{-1/2} VA_3 \qquad (82)$$

where u = mean wind velocity in the room, A = area of section of the room, $K_1 = K_2, = K_3 = K$, $\alpha = K^{-1/2}$, $m_1 = A_3/A_1$ $m_2 = A_3/A_2$, A_1, A_2, A_3 = areas of windward windows, openings in partitions and leeward windows, C_1, C_3 = coefficients of pressure distribution at windward and leeward windows, V = external wind velocity. Hitherto, the amount of ventilation by wind has been calculated in the following manner:-

$$Q = cV_0A_1, \qquad V_0 = V\cos\delta \qquad (83)$$

where V = external wind velocity, c = constant and A_1 = area of a windward window. For example, according to Randall (Ref. 1), the values of c are as set forth in Table 23.

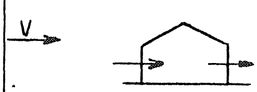
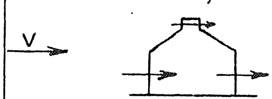
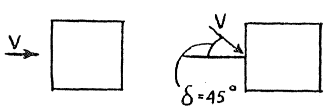
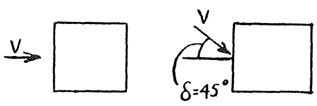
	(a)		(b)	
Path of Wind in Ventilation (by wind)				
Direction of wind				
Randall	0.50	0.30	0.60	0.35
Equation (85)	0.46	0.32	0.58	0.40

Table 23

Values of C

With $A_3 = m_1 A_1$ the equation (82) is

$$Q = \alpha m_1 (1 + m_1'^2 + m_2'^2)^{-1/2} (C_1 - C_3)^{-1/2} V A_1 \tag{84}$$

When (83) and (84) are compared,

$$c = \alpha m_1 (1 + m_1'^2 + m_2'^2)^{-1/2} (C_1 - C_3)^{-1/2} \tag{85}$$

For the path of wind as indicated in Table 23, c derived from the equation (85) is (a): $C_1 - C_3 = 1$ $m_1 = 1$ $m_2 = 0$ $\alpha = 0.65$ $\delta = 0$ and 45°, (b): $m = 2$, and the rest is assumed to be the same as (a). If so, the values from (85) agree quite well with Randall's figures, as is clear in Table 23.

If $A_1 = n_1 A_0$, $A_2 = n_2 A_0$, $A_3 = n_3 A_0$ are taken for the areas of the openings, (82) produces

$$(u/V)(1 + m_1'^2 + m_2'^2)^{1/2} = kn_3$$

$$(u/V)(1 + m_1'^2 + m_2'^2)^{1/2} (m_2)^{-1} = kn_2$$

$$(u/V)(1 + m_1'^2 + m_2'^2)^{1/2} (m_1)^{-1} = kn_1 \tag{86}$$

where $k = \alpha (C_1 - C_3)^{-1/2} (A_0/A)$

6.1.3 Groupings of Observations

In the experiment the direction of wind, positions of unit rooms and openings are combined in various ways; thus there are 34 combinations falling into 6 groups. The numbers and symbols are given in Fig. 84.

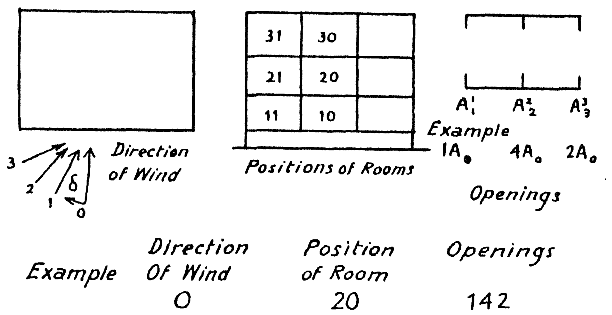


Fig. 84. Numbers & Symbols.

I: When the direction of wind changes,

(020242), (120242), (220242), (320242).

II: For unit rooms in different positions,

(010242), (020242), (030242),

(011242), (021242), (031242).

III: When windward windows, openings in partitions and leeward windows are of the same size,

(020444), (020333), (020222), (020111).

IV: When only the leeward windows change, the others remaining unaltered, and windward windows only change, the others remaining unaltered,

(020244), (020243), (020242), (020241).

(020442), (020342), (020242), (020142).

V: When the windward windows and leeward windows change in the same ratio, and openings in partitions are $4A_0$, A_0,

(020444), (020343), (020242), (020141).

(020414), (020313), (020212), (020111).

VI: When the openings in partitions change, windward and leeward windows remaining unaltered,

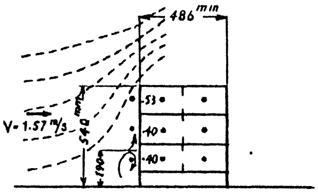
(020242), (020232), (020222), (020212).

6.2 Results of Experiment

The writer proposes to call the ratio of u, wind velocities at the points in the room, to V, the external wind velocities, u/V, tentatively the 'ventilation factor'. As the six groups of combinations are all associated with one another through a common link, each result can be compared with any other by means of the ventilation factor.

6.2.1 Wind Velocity before a Window

When the outlet of the wind tunnel is at a wind velocity of 1.57 (m/sec), all the windows of the model are closed. What happens then? Points of measurement for the wind velocities at a position 3 (cm) in front of the central window and the condition of flow in the vertical plane round the building are illustrated in Fig. 85. The angle of wind direction in this case is $\delta = 0$.



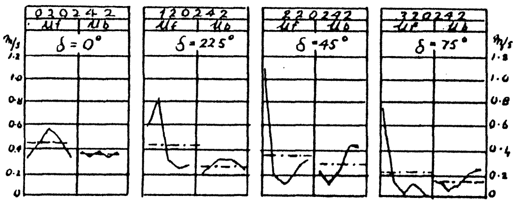
• Indicates the positions of the Thermic Ray Kata Thermometers

Fig. 85. Wind Velocities Before a Window.

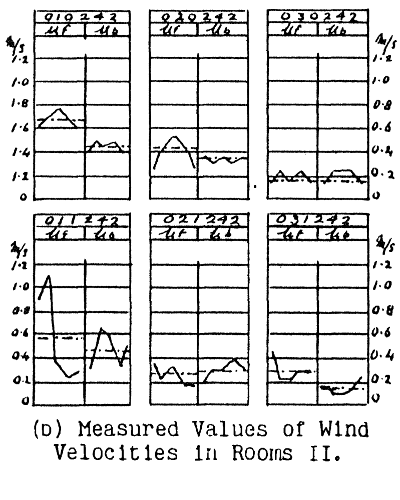
Referring to the stream lines in Fig. 85, the continuous lines are the results of the observation made by means of string, and the broken lines are imaginary. The ratio of the height of the 'turning point' to that of the building is 0.35. This is small compared with Prof. Taniguchi's figure, which is approximately 0.6 (Ref. 12), but there seems to be no appreciable difference in the form of the stream line. So the wind velocities before a window are 0.4 - 0.53 (m/sec), that is 1/4 - 1/3 of V (Fig. 85).

6.2.2 Measured Values of Wind Velocities in a Room

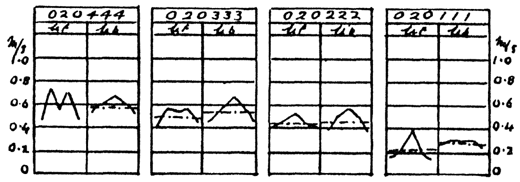
The measured values at the five points on the central line, when the external wind velocity is V = 1.57 (m/sec) and u_f and u_b representing the wind velocities of the windward and leeward rooms respectively, are graphically represented in Fig. 86, (a) to (f).



(a) Measured Values of Wind Velocities in rooms I.

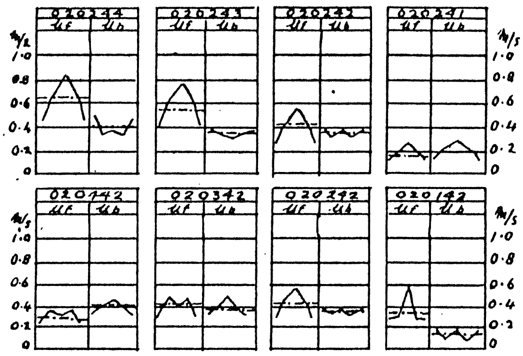


(b) Measured Values of Wind Velocities in Rooms II.

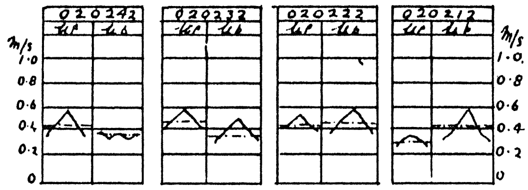


(c) Measured Values of Wind Velocities in Rooms III.

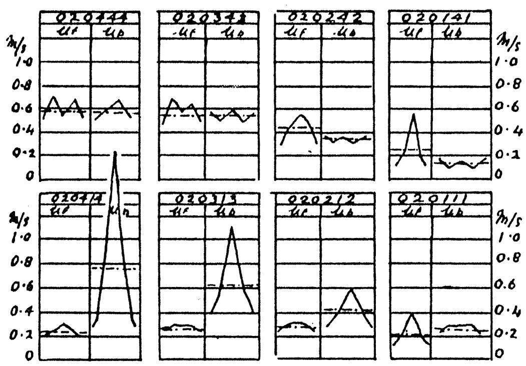
Fig. 86. Distribution of Wind Velocities in Rooms.



(d) Measured Values of Wind Velocities in Rooms IV.



(f) Measured Values of Wind Velocities in Rooms VI.



(e) Measured Values of Wind Velocities in Rooms V.

Fig. 86. Distribution of Wind Velocities in Rooms.

6.2.3 Direction of Wind and Ventilation, Group I

The opening form 242, consists of four sections of a window, 9 feet high, the central two of which are opened. As $m_2 = 0.5$, it may be said that in this form there are no sections in the partition.

(1) The distribution of wind velocities is asymmetrical when there is an angle of wind direction, δ. (Fig. 86 (a)).

(2) The values of the ventilation factor u/V are given in Table 24.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}$/V) of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group I	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.26
	120242	0.55	0.15	0.28	0.21	0.12	0.18	0.23
	220242	0.70	0.07	0.24	0.29	0.08	0.19	0.22
	320242	0.49	0.00	0.14	0.15	0.04	0.10	0.12

Table 24

Values of Ventilation Factor u/V (I)

(3) Windward rooms have larger mean ventilation factors than leeward rooms.

(4) When the angle of wind direction, δ, increases, the ventilation factor for the whole decreases. In the case when the angle of wind direction is $\delta = 45$, a maximum value 0.7 of the ventilation factor appears in the windward rooms. (Table 24, Direction of wind 2).

(5) When the maximum velocities of the front and back rooms are joined it will be seen that the path of ventilation definitely changes with the direction of wind, as is evident from Fig. 87.

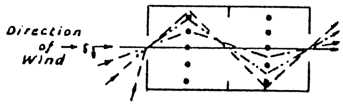


Fig. 87. Direction of Wind and the Path of Ventilation.

The position of unit room is 20.

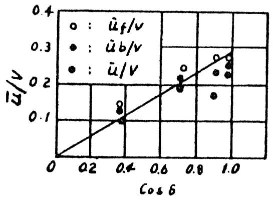


Fig. 88. Direction of Wind and Ventilation Factor I.

(6) The mean ventilation factor of the front and back rooms, $\bar{u}/V$ is approximately proportional to cos δ. (Fig. 88).

6.2.4 Position of Unit Rooms and Ventilation, Group II

(1) Even when the angle of wind direction is δ = 0, the distribution of wind velocities in the first, second and third stories at the ends of the building is asymmetrical. (Fig. 86, (b)).

(2) The values of the ventilation factor u/V are given in Table 25.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}/V$) of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group II	010242	0.49	0.39	0.43	0.31	0.25	0.28	0.36
	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.26
	030242	0.14	0.09	0.12	0.13	0.08	0.12	0.12
	011242	0.69	0.15	0.36	0.41	0.17	0.29	0.33
	021242	0.24	0.12	0.17	0.26	0.11	0.18	0.17
	031242	0.28	0.13	0.18	0.14	0.07	0.10	0.14

Table 25. Values of Ventilation Factor u/V (II)

(3) The windward rooms have larger mean ventilation factors than the leeward rooms.

(4) The ventilation factor is slightly smaller for unit rooms which are at the ends of buildings than for those at the centre. The maximum, 0.69, appears when the position is 11. (Table 25, position of room 11).

(5) The higher the storey, the smaller the ventilation factor. (Fig. 89).

(6) When the path of ventilation in a room is considered in terms of three dimensions, taking into account the features indicated in Figs. 85 and 87, the results mentioned in (4) and (5) will be easily understood.

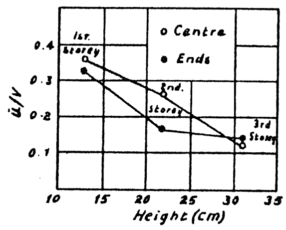


Fig. 89. Number of Stories and Ventilation Factor II.

6.2.5 Areas of Windows and Ventilation, Group III

The conditions are: the angle of wind direction, δ = 0; the position of the room, 20; $A_1 = A_2 = A_3 = 4A_0$, $3A_0$, $2A_0$, A_0, $m_1 = m_2 = 1$. (Fig. 86, (c)).

(1) The values of the ventilation factor u/V are given in Table 26 and in Fig. 90.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}/V$ of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group III	020444	0.47	0.30	0.38	0.42	0.33	0.37	0.38
	020333	0.36	0.25	0.32	0.42	0.38	0.35	0.34
	020222	0.33	0.25	0.27	0.36	0.22	0.28	0.28
	020111	0.25	0.10	0.14	0.18	0.16	0.17	0.16

Table 26

Values of Ventilation Factor u/V (III)

(2) The mean ventilation factors of windward and leeward rooms are almost the same.

(3) The relation of the mean ventilation factor of the front and back rooms to the areas of windows is rectilinear under $n_1 = A_1/A_0 = 3$, as shown in Fig. 90, but above that, the rate of increase diminishes. In actual buildings, many correspond to conditions below $A_1 = 2A_0$.

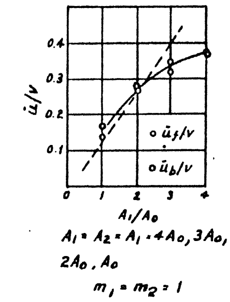


Fig. 90. Area of Windows and Ventilation Factor III.

6.2.6 Areas of Windward and Leeward Windows and Ventilation. Group IV

The angle of wind direction, $\delta = 0$, and the position of the room is 20. Two sub-groups, (a) and (b), are compared. They are (a) $A_1 = 2A_0$, $A_2 = 4A_0$, $A_3 = 4A_0$, $3A_0$, $2A_0$ and A_0. ($m_1 = 2$, 1.5, 1, 0.5, $m_2 = 1$, 0.75, 0.5, 0.25); (b) $A_1 = 4A_0$, $3A_0$, $2A_0$ and A_0; $A_2 = 4A_0$, $A_3 = 2A_0$, ($m_1 = 0.5$, 0.67, 1, 2); $m_2 = 0.5$). (Fig. 86, (d)).

(1) The values of the ventilation factor u/V are set forth in Table 27 and represented graphically in Fig. 91.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}$/V) of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group IV (a)	020244	0.55	0.28	0.41	0.28	0.22	0.25	0.33
	020243	0.47	0.26	0.36	0.24	0.23	0.23	0.30
	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.25
	020241	0.17	0.09	0.11	0.17	0.10	0.13	0.12
Group IV (b)	020442	0.22	0.14	0.19	0.30	0.23	0.25	0.22
	020342	0.33	0.20	0.27	0.29	0.22	0.24	0.26
	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.25
	020142	0.38	0.15	0.20	0.13	0.08	0.10	0.15

Table 27

Values of Ventilation Factors u/V (IV)

(2) In both the cases of (a) and (b), with $m_1 > 0.5 - 0.6$, the windward room tends to have a large ventilation factor, but with $m_1 < 0.5 - 0.6$, it is the leeward room which has this tendency. (Fig. 91).

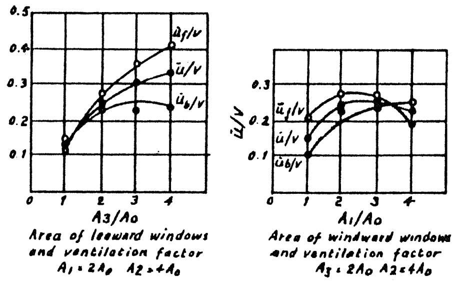


Fig. 91. Effects of Windward and Leeward Windows, IV.

(3) At the mean ventilation factor of the front and back rooms the leeward window (when $A_3 = 4A_0$) is about 1.5 times as large as the windward window (when $A_1 = 4A_0$); and at the ventilation factor of the windward room it is approximately twice as much. (Fig. 91).

(4) As A_3 of the leeward window increases, the ventilation factor, too, increases, but at $A_3 = 3 - 4A_0$ ($m = 1.5 - 2.0$), the rate of increase diminishes.

(5) When the size of the windward window changes, the maximum ventilation factor is in the neighbourhood of $A_1 = 2.5A_0$ ($m_1 = 0.8$). If A_1 is increased beyond that, the ventilation factor rather decreases. (Fig. 91, IV (b)).

(6) From (4) and (5) it may be judged that the most suitable area-ratio between the leeward and windward windows is $m_1 = 1 - 2$.

(7) If u/V in the equations (86) is replaced by $\bar{u}$/V, we can observe a more or less straight line, as represented in Fig. 92, thus obtaining the value $\bar{k} = 0.19$ or 0.17.

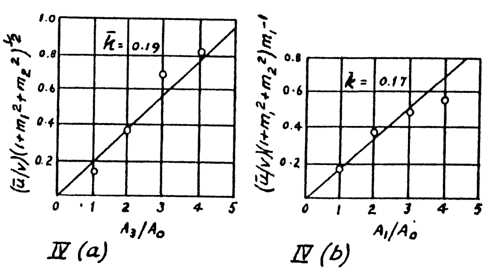


Fig. 92. Values of $\bar{k}$ IV (a), IV (b).

6.2.7 Area of Windows and Openings in Partitions and Ventilation, Group V

The angle of wind direction, $\delta = 0$, and the position of the room is 20. Two sub groups, (a) and (b) are compared. They are V(a): $A_1 = A_3 = 4A_0, 3A_0, 2A_0, A_0$, $A_2 = 4A_0$, ($m_1 = 1$, $m_2 = 1, 0.75, 0.5, 0.25$); V(b): $A_1 = A_3 = 4A_0, 3A_0, 2A_0, A_0$, $A_2 = A_0$ ($m_1 = 1$, $m_2 = 4, 3, 2, 1$). (Fig. 86 (e)).

(1) The values of the ventilation factor u/V are given in Table 28 and Fig. 93.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}/V$) of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group V (a)	020444	0.47	0.30	0.38	0.42	0.33	0.37	0.38
	020343	0.42	0.27	0.35	0.38	0.33	0.35	0.35
	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.25
	020141	0.36	0.08	0.24	0.11	0.07	0.09	0.13
Group V (b)	020414	0.17	0.12	0.14	0.10	0.20	0.49	0.32
	020313	0.19	0.18	0.19	0.70	0.24	0.40	0.29
	020212	0.21	0.17	0.19	0.37	0.20	0.26	0.22
	020111	0.26	0.10	0.13	0.19	0.16	0.17	0.15

Table 28

Values of Ventilation Factor u/V (V)

(2) When openings in partitions are large ($A_2 = 4A_0$), the mean ventilation factors of the windward and leeward rooms are almost the same, and the ventilation factor increases in proportion to the area of windows (Fig. 93, (a)). However the rate of such increase diminishes from $A_3 = 3A_0$ onwards.

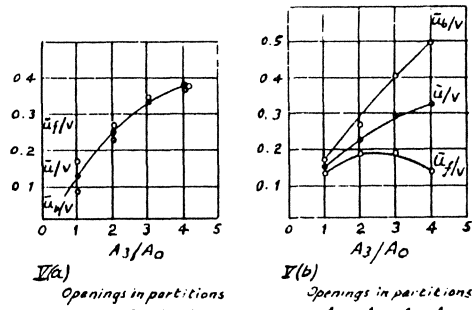


Fig. 93. Sizes of Openings in Partitions and Ventilation of Windows V.

(3) When the openings in the partitions are small ($A_2 = A_0$), the ventilation factor of the windward room is exceedingly small compared with that of the leeward room. (Fig. 93, V(B)). In this case there appears a point of a very large ventilation factor in the leeward room. (Fig. 28, opening form, 414).

(4) When openings in partitions are small, windows larger than the openings produce almost no effect on the windward room. (Fig. 93, V(b) $\bar{u}_f/V$ curve). On the other hand, the ventilation factor of the leeward room increases in proportion to the area of windows. (Fig. 93, V(b), $\bar{u}_b/V$) curve).

(5) If k is obtained from ($\bar{u}/V$) by the equation (86), $\bar{k} = 0.19$ and 0.27 are the results. (Fig. 94).

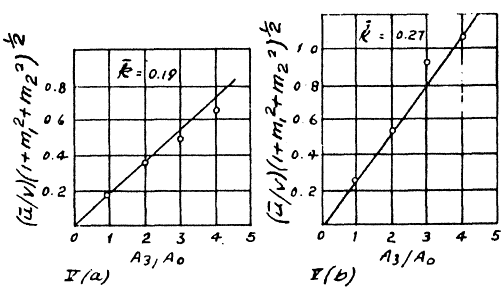


Fig. 94. Values of $\bar{k}$ V(a) and V(b).

6.2.8 The Area of Openings in Partitions and Ventilation, Group VI

The conditions are: The angle of wind direction, $\delta = 0$, the position of the rooms is 20. $A_1 = A_3 = 2A_0$, $A_2 = 4A_0, 3A_0, 2A_0, A_0$ ($m_1 = 1$, $m_2 = 0.5, 0.67, 1, 2$). (Fig. 86, (f)).

(1) The values of the ventilation factor, u/V are given in Table 29 and Fig. 95.

Combinations		Windward Rooms (u_f/V)			Leeward Rooms (u_b/V)			Mean ($\bar{u}/V$) of 2 rooms
		Max	Min	Mean	Max	Min	Mean	
Group VI	020242	0.37	0.20	0.27	0.24	0.22	0.23	0.29
	020232	0.36	0.26	0.29	0.29	0.19	0.23	0.26
	020222	0.32	0.25	0.27	0.36	0.22	0.28	0.28
	020212	0.21	0.17	0.19	0.37	0.22	0.27	0.23

Table 29

Values of Ventilation Factors u/V (VI)

(2) The mean ventilation factors of the windward and leeward rooms are 0.2 - 0.3 and the mean value of the two rooms is very nearly a constant. The maximum is found to be in the neighbourhood of $A_2 = 2A_0$ ($m_2 = 1$) (Fig. 95). Thus from the point of view of ventilation, the most suitable condition is that when the sizes of openings in partitions are the same as those of windows.

(3) Fig. 96 gives the values of $\bar{k}$; $\bar{k} = 0.24$ when obtained from $\bar{u}/V$ by (86).

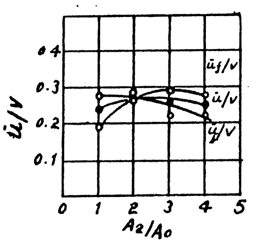


Fig. 95. Area of Openings in Partitions and Ventilation Factors VI.

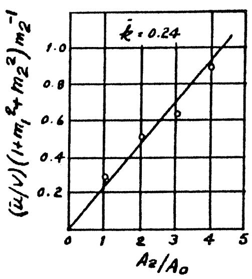


Fig. 96. Values of $\bar{k}$ VI.

6.2.9 Amount of Ventilation

The amount of ventilation is $Q = uA$ (equation (82)). If $\bar{u} = au$ is taken, $\bar{k} = ak$

where $$k = \alpha\ (C_1 - C_3)^{-1/2}\ (A_0/A) \qquad (87)$$

$A_0/A = 75 \times 42.5/225 \times 150 = 0.0945$, and as the wind velocity at the opening is under 3 (m/sec), we arrive at $\alpha = 0.7$ from Table 16 in 5.1.3 of Chapter 5. Reynolds' number for the model in the experiment carried out by Prof. Taniguchi (Ref. 12) was of the order $R_V = 4 \times 10^5$. However, in the present experiment, Reynolds' number is of the order 8×10^4, so we put $C_1 - C_3 = 1.2$, then, $k = 0.06$. The values of k in Groups III - VI are as given in Table 30, and the mean value is 0.21.

From $k = 0.06$, $\bar{k} = 0.21$, we reach $\alpha = 3.5$. That is to say, the mean ventilation factor ($\bar{u}/V$) of unit rooms amounts to approximately 3.5 times as much as the value calculated from equation (86). When the changes in the vertical direction of the distribution of wind velocities in a room is taken into consideration it is quite conceivable that the mean value of the measured values of wind velocities on a level in the centre of a room is larger than the mean wind velocity of a section of the room.

Groups	$\bar{k}$
III	0.22
IV (a)	0.19
IV (b)	0.17
V (a)	0.19
V (b)	0.27
VI	0.24
Mean	0.21

Table 30

Values of $\bar{k}$

There are a number of cases in which $\bar{u}f$ and u_b, the means of the measured values of windward and leeward rooms are not equal (Fig. 86). The writer suggests that this must be due to the fact that the flux tubes are formed in the rooms and the pressure is built up where the mean velocity is small; and the mean value of the two rooms is proportional to the mean wind velocity across a section of the rooms.

Suppose u = the mean wind velocity of a room, V = external wind velocity, ρ, μ = density of air and coefficient of viscosity respectively, A_1, A_2, A_3, A = areas of windward windows, openings in partitions, leeward windows, and section of a room, where the opening ratios are $m_1 = A_3/A_1$, $m_2 = A_3/A_2$, $\lambda_1\ \lambda_2$ = shape factors of buildings, λ_3, λ_4, λ_5, λ_6 = ratios expressing the positions of windward and leeward rooms, then by dimensional analysis,

$$C.\phi_1(R_u)\phi_2(R_V)\phi_3(\lambda_1)\phi_4(\lambda_2) \qquad \phi_8(\lambda_6)\phi_9(u/V)\phi_{10}(m_1)\phi_{11}(m_2)\phi_{12}(A_3/A) = 1 \qquad (88)$$

When the above is compared with (82);

$$C'\phi_1(R_u) = \alpha^{-1}, \quad C''\phi_2(R_V)\phi_3(\lambda_1)\phi_4(\lambda_2) \qquad \phi_8(\lambda_6) = (C_1-C_3)^{1/2}$$

$$\phi_9(u/V) = u/V \quad \phi_{10}(m_1)\phi_{11}(m_2) = (1+m_1^2+m_2^2)^{1/2} \quad \phi_{12}(A_3/A) = A_3/A)^{-1}$$

When R_u, R_V, $\lambda_1 \ldots\ldots \lambda_6$, are the same it is possible to make comparisons regarding other quantities by equation (82) or (86). From the results of experiments, too, it can be seen that $\bar{k}$ is approximately constant. (Table 30). Therefore, this procedure can also be applied to full-size objects. The amount of ventilation itself can be calculated by (82), but there are points of detail on this subject which require fuller studies in the future.

POSTSCRIPT

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