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THE NEUTRAL ZONE IN VENTILATION*

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THE term *neutral zone* has been used by Meier to designate the level, within a room, at which the pressure is just equal to that outside; but so far as the writer knows, it has never been extensively used in ventilation literature. It is the purpose of this paper to explain the relation between the position of the Neutral Zone and the motive heads arising from temperature differences available for causing flow, and to show in a general way how the idea of the Neutral Zone is helpful to a better understanding of several problems of ventilation; and more particularly how it may be applied advantageously in a consideration of the ventilation of large factory buildings by natural means.

In the attainment of this objective, it will be shown among other things:

1. That the head tending to cause flow at any opening, is proportional to the vertical distance of that opening from the Neutral Zone.

2. That the amount of air that may be passed by a given opening is proportional to the square root of the vertical distance of that opening from the Neutral Zone. Therefore, an opening located *at* the Neutral Zone is totally ineffective in passing air; and extreme openings near roof and floor of a building, are most effective.

3. That the position of the Neutral Zone, between roof and floor of a one-story building, is governed by the relative amount of opening provided at top and bottom, and by the difference of temperature between inside and outside air at different levels. With equal area and symmetrical arrangement of openings at top and bottom, and with uniform temperature difference throughout, the Neutral Zone will be at mid-height. If the area provided in upper sidewalls and roof is larger than that near the floor, the Neutral Zone will be displaced toward the roof; and similarly, if the lower area preponderates, the Neutral Zone will be displaced toward the floor. If the temperature difference between inside and outside air is less for the lower levels than for the higher, the Neutral Zone will be displaced toward the roof. In general, the Neutral Zone is displaced toward the group of openings of larger area, and toward the region of higher temperature difference.

The material herein presented has been developed in connection with an investigation of natural ventilation undertaken by the Engineering Research Department of the University of Michigan in cooperation with the Detroit Steel Products Co., Detroit, Mich., extending over a period of about three years.

When the air inside a structure, for example a single story factory building, is

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* Since the presentation of the paper the attention of the author has been directed to an article of similar title that had escaped his search of the literature, by L. Biro, a French engineer, translated and published in the HEATING AND VENTILATING MAGAZINE, June, 1912.

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warmed to a temperature above that of the outside surrounding air, there results an immediate tendency for movement or flow to take place, cool air entering at lower openings, and warm air issuing from upper openings, if any are provided. The chimney and the warm air heating system are more familiar as examples to which the laws of flow have been applied, but the same fundamental theory, of course, applies in the consideration of any problem of flow resulting from a temperature difference. It is proposed to show how a better knowledge of the significance of the Neutral Zone in connection with the theory of flow is essential to the analysis of the less familiar problem of natural ventilation, and may be very

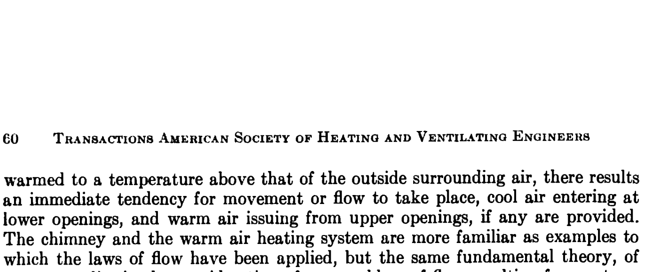

FIG. 1. WARM-AIR COLUMNS PLACED IN ATMOSPHERE OF COOL AIR; SHOWING DIFFERENCE IN PRESSURES WHEN A SINGLE OPENING AT TOP OR BOTTOM IS PROVIDED AS INDICATED BY LIQUID IN GAGES. NO FLOW OCCURRING

helpful in the better understanding of the more familiar examples of the chimney, the warm air furnace, and the gravity hot water heating system.

Pressure Zones Resulting from Temperature Difference

Fig. 1 represents a tall structure filled with warm air, placed in an atmosphere of cooler air. This structure is provided with ports or windows, U and L, located near the top and bottom respectively. It is also furnished with manometers or differential gages, which indicate the relation between inside and outside pressure at the four equi-spaced levels, C, D, E and F.

In Case A (Fig. 1), the upper window U is closed and the lower window L, opened. The pressures at the lower level, F, must be alike inside and outside, since there is direct communication through L, and no flow. The absolute pressure both inside and outside, will be less at the upper level C than at the lower level F; that inside will be less by the weight of the column of warm air; and that outside by the weight of the column of cool air of the same height. Hence, the pressure outside will decrease more rapidly upwardly from the bottom, than that inside. Warm air will be seeking to push its way out of the structure with an increasing intensity from the bottom, or place of equality, toward the top where the full head h (representing the difference between the weights of the columns of cool and warm air of height m) exists, and is manifested in the deflection of the liquid in the uppermost gage.

In Case B (Fig. 1), the upper window U is opened, and the lower one L closed. Again, no flow can take place. Equality of pressure is now established at the upper level C by direct communication between inside and outside through opening U. The absolute pressure, both inside and outside will be greater at the lower level F, by the weights of the respective columns. Since the cool air is heavier, it will be found that the outside pressure increases more rapidly, downwardly from C, than the inside pressure. The increasing excess of outside pressure at the level, C, D, E and F, is illustrated by the increasing deflection of the liquid in the four gages of Fig. 1—Case B, with the full head h now indicated by the lowermost gage. In other words, a vacuum of h inches exists within the building at level F.

In Fig. 2, the lower window L has been opened and in response to the difference of pressure that existed there in Fig. 1—Case B, air begins to flow in at the bottom. The inflow here will tend to raise the pressure all the way up, and cause an excess of pressure inside at the upper opening U, resulting in an outflow there. If the incoming cool air at the bottom be warmed by some heat source to maintain the temperature t_w of the warm column, a permanent condition of flow has been established.

Notwithstanding the fact that the warm air column is now in motion, the total head is no different than it was when the condition was static, as in Fig. 1, because the difference in weights of cool and warm columns is the same as before. With the air in motion, the total available head is used up in overcoming resistance to flow which is opposition to motion. In the case of Fig. 2, the total resistance may be considered as made up of three elements, *viz.*, the resistance at entrance at window L; the resistance of internal obstructions; and the resistance at exit at window U. Of these, the second may be reasonably omitted as a negligible factor in the case of most buildings. For the purposes of this paper, the total opposition to flow will be considered to consist of the inlet and outlet resistances.

If, in Fig. 2, the two openings U and L be of the same area and kind, it is clear that, neglecting change of volume of the air caused by heating, it will take half the total head to squeeze the air in through L, and the other half to squeeze it out through U. Hence the lower gage at F, will indicate a *vacuum* of $^1/_2\ h$, and the upper gage at C, a *pressure* of $^1/_2\ h$, existing within the building.

In Fig. 3—Case A, let the upper window U be partially closed, to such a degree that the resistance there is three times that at L. It will therefore require three-fourths of the available head to get the air out through U, and one-fourth to get it in through L. In Fig. 3—Case B, the lower window L is partially closed, to such a degree, that the resistance there is three times that at U. Here then three-fourths of the available head is required to get the air in at L, and one-fourth to get it out at U. The pressure distribution is illustrated by the levels in the gages in Fig. 3. In Fig. 3—Case A, the gage at level D will indicate rather strong pressure. There may be some doubt about the one at E, but it would in fact indicate a slight pressure, as shall be seen later.

The Neutral Zone

It is apparent from a consideration of Figs. 2 and 3, that there must be some point between U and L, at which, if there should happen to be a gage attached, the indication would be zero. This level is called the *neutral zone*. At all levels below the Neutral Zone, there is a slight vacuum, increasing in magnitude in proportion to the distance from the Neutral Zone; and similarly, at all levels above the Neutral Zone, there is a slight excess of pressure inside over that outside at the same level, increasing with the distance from the Neutral Zone. If another opening should be made in the wall at any point below the Neutral Zone, inflow would occur there; and outflow would take place through any opening made above the Neutral Zone. An opening *at* the level of the Neutral Zone would be totally

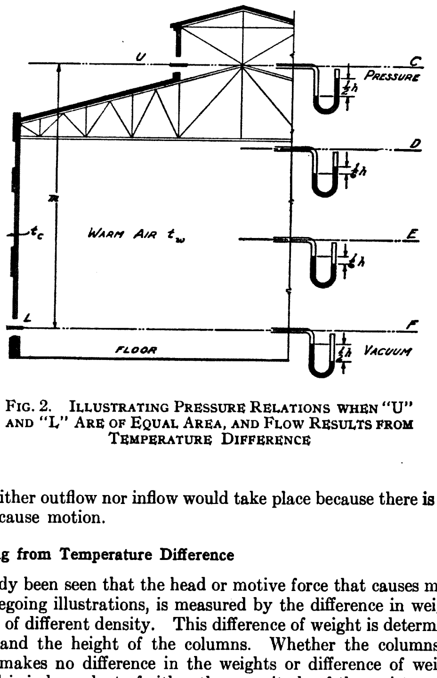

FIG. 2. ILLUSTRATING PRESSURE RELATIONS WHEN "U" AND "L" ARE OF EQUAL AREA, AND FLOW RESULTS FROM TEMPERATURE DIFFERENCE

ineffective; neither outflow nor inflow would take place because there is no pressure difference to cause motion.

Head Resulting from Temperature Difference

It has already been seen that the head or motive force that causes movement of air, in the foregoing illustrations, is measured by the difference in weights of two columns of air of different density. This difference of weight is determined by the temperatures and the height of the columns. Whether the columns are static or in motion makes no difference in the weights or difference of weights. The available head is independent of either the magnitude of the resistance or its distribution. In the case of Fig. 1, the resistance is infinite; in Figs. 2 and 3, it is differently distributed for each case. But in every instance, granting that the temperatures t_c and t_w are alike respectively, the head is the same. Hence the head available to overcome resistance and cause flow, may be computed in terms of temperatures and height of columns.

An expression for head can be derived from the fundamental laws of physics and mechanics, and may be found in various forms especially in literature relating to

the theory of chimneys. For the present purpose, where the application is to problems in ventilation, the writer has derived the expression:

$$h_a = \frac{mD}{T} \quad \text{(1)}$$

Where h_a = head in feet of air caused by difference in weight of the two columns.
D = difference in temperature ($t_w - t_c$, Figs. 1, 2, 3) deg. fahr.
T = average absolute temperature of the two columns $\left(\frac{t_w + t_c}{2} + 460\right)$

Heads are usually measured in inches of water. An inch of water corresponds

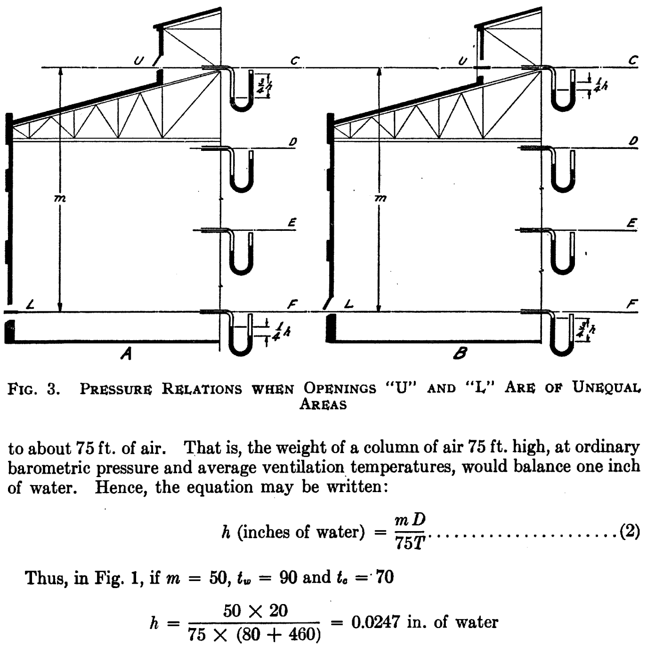

FIG. 3. PRESSURE RELATIONS WHEN OPENINGS "U" AND "L" ARE OF UNEQUAL AREAS

to about 75 ft. of air. That is, the weight of a column of air 75 ft. high, at ordinary barometric pressure and average ventilation temperatures, would balance one inch of water. Hence, the equation may be written:

$$h \text{ (inches of water)} = \frac{mD}{75T} \quad \text{(2)}$$

Thus, in Fig. 1, if $m = 50$, $t_w = 90$ and $t_c = 70$

$$h = \frac{50 \times 20}{75 \times (80 + 460)} = 0.0247 \text{ in. of water}$$

which would be the pressure indicated by the uppermost gage in Fig. 1—Case *A*, and the vacuum indicated by the lowermost gage in Fig. 1—Case *B*.

In Fig. 2, the gage attached at the bottom would indicate one-half of 0.0247 or 0.0123 in. of *vacuum;* and that attached at the top would show 0.0123 in. *pressure.* The total head available to produce flow is 0.0247, the same as in Fig. 1.

The Head at an Opening Is Proportional to Its Distance from the Neutral Zone

Referring again to Fig. 3—Case *B*, it is apparent by an inspection of the indication of the gages, that proceeding from the bottom upward, the state within the structure changes from vacuum to pressure at some level between *D* and *C*, which level is what may be defined as the Neutral Zone. Here an opening could be cut in the wall, and no inflow or outflow would take place, and the originally established flow through the structure would not be disturbed in the least. To go even further, cut the building in two on the Neutral Zone, separate the sections, and, provided the same temperature was maintained in the separate pieces as existed there when

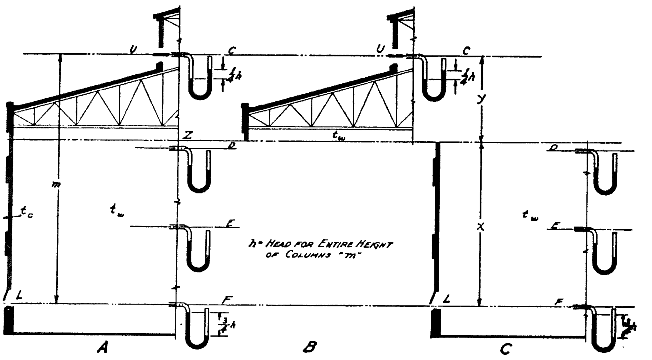

FIG. 4. SHOWING HOW THE TOTAL HEAD IS DISTRIBUTED TO UPPER AND LOWER OPENING IN PROPORTION TO THEIR DISTANCE FROM THE NEUTRAL ZONE

they were united, the flow *Q* through the two sections would be equal to the flow through the original solid structure; and all the gages would go on indicating the same deflections as they did before. Fig. 4 illustrates this idea, where *A* is the same as Fig. 3—Case *B;* while *B* and *C* show the full figure cut across with the sections displaced from each other.

The upper section may be thought of as a complete structure in itself, of height *y*, with an inlet opening so large as to offer practically no resistance to flow. The entire head is the result of the difference in weights of the columns *y* ft. high, or,

$$h_U = \frac{yD}{T} \qquad (3)$$

where h_U = head (in feet of air)
y = height of columns, feet
D = difference in temperature $(t_w - t_c)$
T = average of the two temperatures in deg. fahr. absolute.

This entire head, h_U, is available for overcoming the resistance of the upper opening *U*.

Similarly, for the lower section, Fig. 4—Case *C*, the head available for overcoming the resistance of the lower opening *L*, is h_L, where

$$h_L = \frac{xD}{T} \qquad (4)$$

These statements are true, no matter whether the two sections of the structure are being considered, Fig. 4—Case *B* and 4—Case *C;* or the structure as a whole,

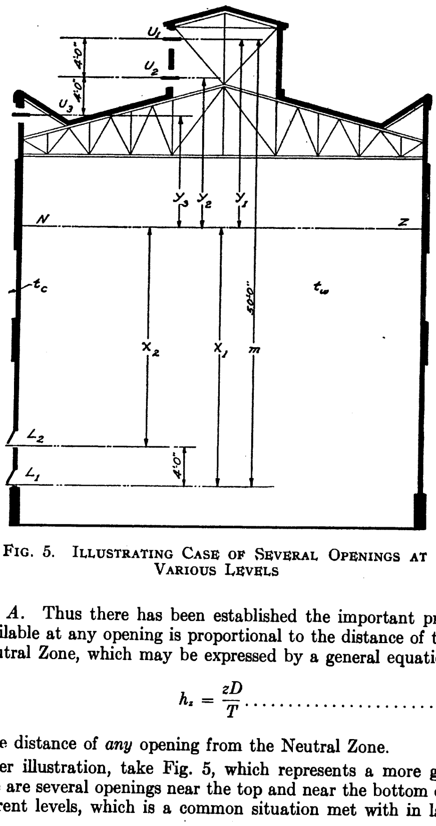

FIG. 5. ILLUSTRATING CASE OF SEVERAL OPENINGS AT VARIOUS LEVELS

Fig. 4—Case *A*. Thus there has been established the important principle that the head available at any opening is proportional to the distance of that opening from the Neutral Zone, which may be expressed by a general equation:

$$h_z = \frac{zD}{T} \qquad (5)$$

where *z* is the distance of *any* opening from the Neutral Zone.

As a further illustration, take Fig. 5, which represents a more general case, wherein there are several openings near the top and near the bottom of the structure, at different levels, which is a common situation met with in large factory buildings.

In Fig. 5, inflow takes place through the two lower openings, L_1 and L_2; and outflow (presumably) through the three upper openings, U_1, U_2 and U_3. The resistance of L_1 and L_2 is much greater than that of U_1, U_2 and U_3. The air has a harder time, so to speak, getting through L_1 and L_2; or it requires a greater motive pressure at the lower openings than at the upper, to push the flowing air through. The Neutral Zone will automatically take such a position that the head at each opening will assume a value such that the total inflow will equal the total outflow, which, of course, is the necessary condition of equilibrium. The head available at any point, or level, is proportional to the distance of that level from the Neutral Zone.

Relation of Flow to Head and Resistance

The amount of air passing through any opening per unit of time is determined by the head or pressure difference on the two sides of the opening, and the resistance of the opening. The relation among these three quantities is similar to that which prevails in electrical circuits where

$$E = IR \qquad (6)$$

wherein E = electromotive force, or electrical head available for pushing current through a conductor
I = current or electrical flow
and R = resistance, or opposition to flow

In the case of air flow, a similar equation applies:

$$H = Q^nR \qquad (7)$$

wherein H = motive pressure or head available for pushing the air through an opening
Q = flow of air
and R = resistance of the opening.

In the use of the equation, the units must be properly chosen or related.

The head H must be expressed in *feet of air*—that is, it is the pressure or weight of a column of air H feet high. If any other substance were under consideration, such as water, then H would be expressed in feet of water.

The flow Q must be expressed in cubic feet per second.

R may be thought of as a characteristic of the opening or conductor through which flow takes place, and is numerically equal to the head in feet necessary to push 1 cu. ft. per sec. through.

The value of the exponent n may vary somewhat for different conditions, but experiments tend to confirm the choice of 2 as a satisfactory value for ventilation work.

The equation then takes the form

$$H = Q^2R \qquad (8)$$

The resistance of an opening is determined by its area and individual peculiarities. The latter factor is usually expressed by a coefficient C, in the equation

$$Q = AVC \qquad (9)$$

where Q = volume of flow per sec.
V = velocity, ft. per sec.
and C = a coefficient, less than unity

The relation between resistance on the one hand, and area and coefficient on the other, is readily found to be:

$$R = \frac{1}{2gA^2C^2} \qquad (10)$$

where R = resistance of a given opening
g = 32.2
A = clear area of opening in sq. ft.
and C = a coefficient expressing individual peculiarities of the opening. For ventilation work, experiments show that C has a value between 0.60 and 0.70.

Calculation of Flow

Armed with the working equations (5), (8) and (10) an attempt at the solution of a problem can be made.

Referring again to Fig. 5, suppose the following information is at hand:

Vertical distance between centers of extreme windows U and L = 50 ft. = m.
Vertical distance between L_1 and L_2, U_1 and U_2, and U_2 and U_3 = 4 ft.
Outside temperature, t_e = 40 deg. fahr.
Inside temperature, t_w = 60 deg. fahr. (assumed uniform)
Area of L_1 = area of L_2 = 50 sq. ft.
Area of U_1 = U_2 = U_3 = 100 sq. ft.

The problem is to determine the amount of air passing through the building per minute.

Applying equation (10)

$$R = \frac{1}{2gA^2C^2} \qquad (11)$$

$g = 32.2$
A (for L_1 and L_2) = 50 sq. ft. $A^2 = 2500$
A (for U_1, U_2 and U_3) = 100 sq. ft. $A^2 = 10{,}000$
C may be taken as 0.65; $C^2 = 0.42$

Whence for each of the lower openings,

$$R = \frac{1}{64.4 \times 2500 \times 0.42} = 0.0000148 \qquad (12)$$

and for each of the upper openings,

$$R = \frac{1}{64.4 \times 10{,}000 \times 0.42} = 0.0000037 \qquad (13)$$

Combining equations (5) and (8)

$$\frac{zD}{T} = Q^2R$$

$$Q^2 = \frac{zD}{RT}$$

and

$$Q = \sqrt{\frac{zD}{RT}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Substituting $D = 60\text{–}40 = 20$ and $T = \dfrac{60 + 40}{2} + 460 = 510$ in (14)

$$Q = \sqrt{\frac{z \times 20}{R \times 510}} = 0.198 \sqrt{\frac{z}{R}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

The Neutral Zone (Fig. 5.) must assume such a position that the total inflow will equal the total outflow. The simplest and easiest solution to determine this position will be found in the assumption of a number of different positions for the Neutral Zone, calculating, for each position, the flow through each of the five openings, by means of equation (15) inserting the value of z appropriate to the assumed location of the Neutral Zone. The correct assumption will be indicated when the total inflow is equal to the total outflow.

The various assumptions made together with the results of the calculations for each, are presented in Table 1. To show how the calculations are made, consider the first assumption. It is certain from an inspection of the problem as illustrated in Fig. 5, that the Neutral Zone will be nearer the extreme upper opening U_1 than to the extreme lower opening L_1. Assume that it is 30 ft. from L_1. This fixes the values of x_1, x_2, y_1, y_2 and y_3. The flow through the opening L_1 is given by equation (15) with value of $z = x_1 = 30$, and with $R = 0.0000148$, eq. (12)

$$Q \text{ for } L_1 = 0.098 \sqrt{\frac{30}{0.0000148}} = 282 \text{ cu. ft. per sec.}$$

Similarly, the flow for L_2 is computed, using $z = x_2 = 26$. The flow for the window U_1 is found by using $z = y_1 = 20$, and $R = 0.0000037$ (eq. 13)

$$Q \text{ for } U_1 = 0.098 \sqrt{\frac{20}{0.0000037}} = 461 \text{ cu. ft. per sec.}$$

and that for U_2 and U_3 are calculated in similar manner using $z = y_2 = 16$, and $z = y_3 = 12$ respectively.

For this first assumption, the total inflow amounts to 545 cu. ft. per sec. and the total outflow, 1229 cu. ft. per sec. This result shows that the Neutral Zone as assumed was too low, and acts as a guide in making the next assumption, represented by the second line of Table 1. The fourth assumption of the Neutral Zone position, 42 ft. above the lowest opening, is found to be too high. The next assumption of 41 ft. is found to give almost exactly equal inflow and outflow, and is therefore correct.

It will not usually happen that the correct position will be found so readily and exactly as in the fifth line of the Table 1. In case this last chosen value had not shown an almost exact equality between inflow and outflow, the correct position of the Neutral Zone could be found by plotting the inflow and outflow values against some distance representing the position of the Neutral Zone, as for example x_1, as is done in Fig. 6.

The solution shows how the excess of opening in the upper part of the building brings the Neutral Zone much nearer the roof. In fact it is seen that it lies only 1 ft. below the center of the window U_3, which makes this window rather ineffective in passing air. The conditions here would be found to be unstable. If there were no motive agency other than temperature differences, there would be inflow, at the lower part of the opening, and outflow at the upper. On the other hand, if there were present any other agency, such as the wind, it would probably be found that there would sometimes be outflow and sometimes inflow. The heads, in the vicinity of the Neutral Zone, are so minute that they may be overcome by the slightest disturbance. A window located near the Neutral Zone contributes but little useful effect.

Several other points of interest and significance may be noted in the solution of the problem. (See last line of Table 1, and Fig. 5.) Although window L_1 is

TABLE 1. SOLUTION OF PROBLEM—SEE FIG. 5

Position of Neutral Zone to Give Following Values of "Z" (Eq. 15)					"Q" for Each Window by Equation 15. $Q = .198\sqrt{\frac{z}{R}}$ "Q" is in Cu Ft. per Sec.					Total Inflow C.F.S.	Total Outflow C.F.S.
X_1	X_2	Y_1	Y_2	Y_3	L_1	L_2	U_1	U_2	U_3		
30	26	20	16	12	282	263	461	412	357	545	1229
35	31	15	11	7	304	286	399	342	272	590	1013
40	36	10	6	2	325	309	325	252	146	634	723
42	38	8	4	0	334	317	291	206	0	651	497
41	37	9	5	1	330	313	309	230	103	643	642

opened to but one-half the effective area of U_1, the flow through L_1 is 330 cu. ft. per sec. as compared to 309 cu. ft. per sec. for U_1, or the ratio is 1.07 to 1.00. The velocity through L_1 is 6.6 ft. per sec., while that through U_1 is 3.1 ft. per sec. The disparity between areas of inlet and outlet openings requires that the activity of the former shall be much greater than the latter, which in turn necessitates the displacement of the Neutral Zone far toward the top, in order to realize the necessary distance to give the required head.

If a draft gage were connected at the level of L_1, its indication could be predicted by equation (2)

$$h = \frac{mD}{75T}$$

wherein m is to be replaced by $x_1 = 41$, the distance from L_1 to the Neutral Zone. Then

$$h = \frac{41 \times 20}{75 \times 510} = 0.0214 \text{ in. of water.}$$

The indications of draft gages if attached on a level with the centers of each of the openings have been computed in similar manner. and are shown in Table 2.

The thing that compels interest about these values of pressure or heads is the minuteness of their magnitude. Yet the aggregate flow maintained by these minute pressures, as worked out in Table 1, is 642 cu. ft. per sec., which is over 38,000 cu. ft. per min. Very small forces, if distributed over large areas, may be productive of enormous flows.

TABLE 2. PRESSURES THAT WOULD BE SHOWN BY DRAFT GAGES AT CENTERS OF OPENINGS. FIG. 5

Opening	Indication of Gage Inches Water	Pressure or Suction
L_1	0.0214	Suction
L_2	0.0193	Suction
U_1	0.0047	Pressure
U_2	0.0026	Pressure
U_3	0.0005	Pressure

Effectiveness of Area of Openings

In terms of quantity of air passing through it, the effectiveness of an opening is proportional to the square root of its distance from the Neutral Zone. Thus if one opening is 9 ft. from the Neutral Zone, and another opening is 36 ft. from the Neutral Zone, all other factors being equal, the second will deliver twice the volume of the first one.

In the example the total flow of 642 cu. ft. per sec., was participated in by all five openings, aggregating 400 sq. ft. in area. This would amount to 3.21 cu. ft. per sec. per sq. ft., as the average activity of the openings. Referring again to Fig. 5, let it now be assumed that the two windows L_1 and L_2 be opened to their full capacity, *viz.*, 100 sq. ft. each, thus giving an aggregate area of 500 sq. ft. instead of 400, as before. Assuming the same temperatures to prevail as in the original problem, *viz.*, 40 and 60 deg. and solving the new situation in the same manner as heretofore described, it is found that the resulting flow will be 1135 cu. ft. per sec. and the Neutral Zone will establish itself at a height of 32 ft. 4 in. from L_1. Thus an increase of area of 100 sq. ft. has increased the flow from 642 to 1135 cu. ft. per sec. resulting in an average activity 4.54 cu. ft. per sec. per sq. ft. of area. The Neutral Zone has been brought down from 41 ft. to 32 ft. 4 in.

As another supposition, let the opening U_3 (Fig. 5.) be closed, leaving L_1, L_2, U_1 and U_2 each equal to 100 sq. ft. The Neutral Zone will now lie at the level of mid-height, and the flow is easily computed and found to be 987 cu. ft. per sec. With an aggregate of 400 sq. ft. of area, this flow represents an average activity of 4.98 cu. ft. per sec. per sq. ft. of area.

Finally, if the two windows L_2 and U_2 be closed, leaving only the extreme openings effective, the flow will be 515 cu. ft. per sec. which represents an activity of 5.15 cu. ft. per sec. per sq. ft.

The example and its variations show that the effectiveness of openings as represented by the average flow per square foot of opening, is a maximum when the distribution of area above and below is symmetrical, resulting in the location of the Neutral Zone at the mid-point between; and that the extreme uppermost and lowermost openings are the most effective in flow, as would, of course, be expected. In other words, for maximum flow or ventilation, the areas of inflow and outflow openings should be equal, and should be located as near the bottom and top of a building as possible.

Case of Non-Uniform Temperatures at Different Levels

In the example discussed above, it was assumed that the temperatures both inside and outside the building were uniform throughout the height. While the outside temperature, in actual practice, is likely to conform to this assumption, it is possible that the inside temperature may vary. If data are available giving the temperatures at various heights the problem is still easily capable of solution, but requires a little more labor in the calculations. The procedure is exactly like that which resulted in the figures presented in Table 1, except that for each assumption made for the position of the Neutral Zone, the average difference of temperature for the section of the building between the Neutral Zone, and the opening for which flow is to be computed, must be used, resulting in a different value of D and T (of equation 5) for each different opening. Non-uniformity of temperature will result in a displacement of the Neutral Zone from midposition even when the area of openings is symmetrically disposed in the upper and lower parts of the building. Space does not permit the presentation of an example to show in detail how non-uniform temperatures may be handled.

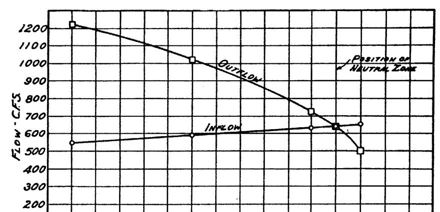

FIG. 6. PLOTTING OF VALUES OF FLOW FOR VARIOUS ASSUMPTIONS OF TABLE 1 TO FIND THE POSITION OF THE NEUTRAL ZONE

Example of Application of Equation of Flow to an Actual Building

The foundry used for instructional purposes in the University of Michigan is located on the 4th floor of the East Engineering Building. The cross section and principal dimensions are represented in Fig. 7. A test was made one morning, while pouring was going on, the inflow and outflow of air being measured by anemometers at the openings. The area and vertical location of the openings in use are shown in Fig. 7. The average inside temperature was 59 deg., and the outside temperature, 20 deg. The openings were all on the leeward side of the building from the wind, so that the ventilation may be attributed to the temperature difference effect almost entirely. On this assumption, the flow can be calculated as in the previous example, and compared with the measured quantity.

In Table 3, the numbers in the first column, headed Z_A, represent the assumed distance of the Neutral Zone from the lowermost opening A (Fig. 7) for each trial. The distances to the other openings are shown in the next three columns. The flow is calculated for each opening for each trial position of the Neutral Zone, by means of equation (14).

Values of Q lying to the left of the heavy line in the Table represents inflow; those to the right, outflow.

TABLE 3. COMPUTED VALUES OF Q FOR VARIOUS POSITIONS OF NEUTRAL LEVEL
Fig. 7

z_A	z_B	z_C	z_D	Q_A	Q_B	Q_C	Q_D	Total In	Total Out
12	7.5	10.5	12	135	200	202	36	135	438
14	5.5	8.5	10	146	171	183	33	146	387
16	3.5	6.5	8	156	137	160	29	157	326
17	2.5	5.5	7	161	116	147	27	161	290
18	1.5	4.5	6	166	90	133	25	166	248
19	.5	3.5	5	170	51	117	23	170	191
20	− .5	2.5	4	175	51	99	21	226	120
21	−1.5	1.5	3	179	90	77	18	269	95
22	−2.5	.5	2	183	116	44	15	299	59

The figures for total flow are plotted against the corresponding values of Z_A, to determine the position of the Neutral Zone that will represent equality of inflow and outflow. Figure 8 shows this work, and from it the Neutral Zone is found

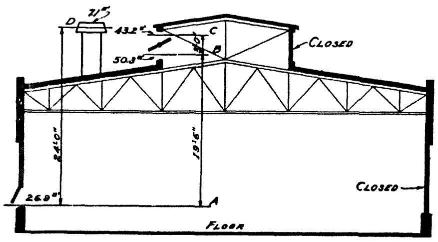

FIG. 7. SECTION THROUGH FOUNDRY AT UNIVERSITY OF MICHIGAN SHOWING AREAS AND VERTICAL DISTANCES

to lie 19 ft. 3 in. above the lower opening A, Fig. 7; and the flow is found to be 171 cu. ft. per sec., or 10,260 cu. ft. per min.

The actual flow as measured by the anemometers was found to be 12,500 cu. ft. per min. The agreement is within about 18 per cent, which is sufficiently close to show that the method of calculation is capable of practical use in predicting with some success, the flow of air resulting from temperature difference alone, in a simple building.

It is to be noted that the Neutral Zone lies only 3 in. below the lower opening of the monitor sash. The calculation is confirmed by the fact that at these openings the flow was observed to be generally out, but was at some times in, thus indicating an instability due to the near presence of the Neutral Zone.

Using the position of the Neutral Level as determined on Fig. 8, the flow for the several individual openings is found to be as follows:

Lower (sidewall) sash, opening A, Fig. 7, 171 cu. ft. per sec. *in*
Lower opening of monitor sash, B, Fig. 7, 36 cu. ft. per sec. *out*
Upper opening of monitor sash, C, Fig. 7, 113 cu. ft. per sec. *out*
Ventilator, opening D, Fig. 7, 22 cu. ft. per sec. *out*

Although the opening B, Fig. 7, is the largest of the four, it is not very effective in ventilation. The cause is to be found in the preponderance of area of upper

openings in use. There is a total of 100.6 sq. ft. of opening at the top against 26.9 sq. ft. below. As pointed out before, the most effective use of ventilating openings results from a nearly equal distribution of area of openings in upper and lower part of building.

Another test was made in this building, wherein the calculated results checked the observed within about 7 per cent.

Other Applications

In the foregoing examples, the objective has been to determine the flow from given data of temperature, vertical distances, and area of openings. It is apparent that, for given data regarding flow, temperatures, and vertical distances, the same principles can be employed to determine required areas. In some cases

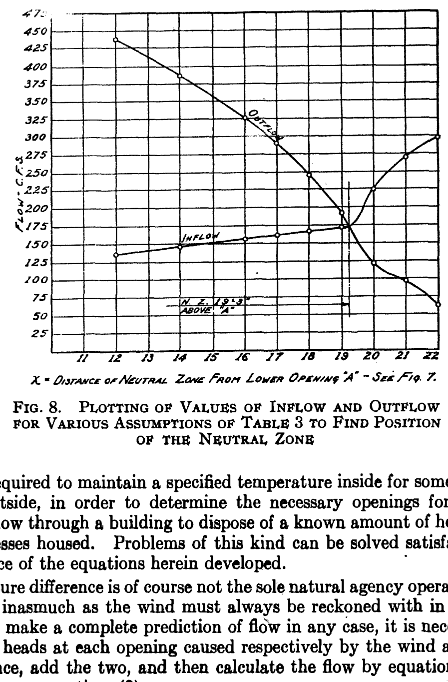

FIG. 8. PLOTTING OF VALUES OF INFLOW AND OUTFLOW FOR VARIOUS ASSUMPTIONS OF TABLE 3 TO FIND POSITION OF THE NEUTRAL ZONE

it may be required to maintain a specified temperature inside for some stated temperature outside, in order to determine the necessary openings for a sufficient amount of flow through a building to dispose of a known amount of heat, liberated in the processes housed. Problems of this kind can be solved satisfactorily with the assistance of the equations herein developed.

Temperature difference is of course not the sole natural agency operating to cause ventilation, inasmuch as the wind must always be reckoned with in more or less degree. To make a complete prediction of flow in any case, it is necessary to determine the heads at each opening caused respectively by the wind and temperature difference, add the two, and then calculate the flow by equation (16) which is the same as equation (8).

$$Q = \sqrt{\frac{h_t}{R}} \qquad (16)$$

where h_t is the *sum* of the heads caused by temperature difference and the wind.

The pressures or heads arising from the effect of the wind constitute another study and cannot be taken up here.

In a gravity hot-water system, or warm-air heating plant, it is evident that there must be a Neutral Zone somewhere within the vertical limits of the installation—a level at which the pressures in the cold and warm legs of the system are exactly equal. Problems of this kind are very difficult of solution because of the necessity of taking into account the friction head or resistances of the risers themselves. But the knowledge of the presence of a Neutral Zone—a place at which no cross flow can take place—and of the fact that its positions may be varied by the manipulation of resistances in the upper and lower part of the system, may often be helpful in a general way.

DISCUSSION

A. C. WILLARD: The Society owes a debt of thanks to Prof. Emswiler for this very able presentation of a very fundamental principle in both heating and ventilation. I don't believe that I have heard a paper that exceeds it in its importance in direct application to the advancement of the science of heating and ventilation in any meeting of the Society. I don't know whether Prof. Emswiler knows it or not, but his paper is of great interest to us in the field of warm-air gravity heating. The principles he has shown are fundamental to the operation of all gravity warm-air heating systems. They are, of course, fundamental in the determination of the in-leakages. The out-leakages which take place in a building are a result of the difference in temperature or density of the inside and outside air.

I congratulate the Society on having secured such a paper and congratulate Prof. Emswiler on the admirable presentation of such a complicated phenomenon as is shown here in a very direct and at the same time comprehensive application of these principles to specific examples. He has not only shown how the principles may be applied but he has checked up his results with actual tests in a practical building.