Air Infiltration through revolving doors

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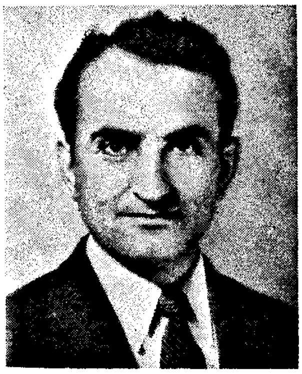

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Air infiltration through doors may cause discomfort in areas near the doors, and thus it is desirable to know the rate of infiltration for proper sizing of the heating and cooling equipment. A recent research (1) supplied comprehensive information on air infiltration through swinging doors, but only limited data (2) are available on air infiltration rates through revolving doors. The purpose of the present investigation is to provide additional information on this subject. The research has been carried out at the ASHRAE Research Laboratory under the guidance of the former Research Advisory Committee on Heating and Air-Conditioning Loads. Experiments were made both under heating and cooling conditions. With the motor-driven revolving door, the door speed and temperature and pressure differences between indoors and outdoors were recognized as significant factors influencing the air-infiltration rate. With manually operated doors, however, additional information regarding a representative traffic pattern and the corresponding average door rpm was needed. The amount of air turbulence inside and outside, and the condition of the door seals would influence infiltration to a certain extent. The research was planned to determine the influence of all these variables on air infiltration.

TEST SETUP

A plan view of the test setup is shown in Fig. 1. A revolving door, 6 ft - 4 in. diam and 6 ft - 10 in. high was installed just inside a double door entrance to the Laboratory. When the swinging doors were opened, a typical revolving door entrance was available for testing. The door was motor driven and its speed could be adjusted by means of a variable-pitch pulley. The door could also be operated manually.

A plywood partition was erected across the entrance back of the door, and all cracks in the test room were caulked to make the enclosure as nearly air tight as possible.

The exhaust system E served several functions. It provided a means of producing any desired pressure differential across the revolving door, it exhausted the infiltration air which, in a normal

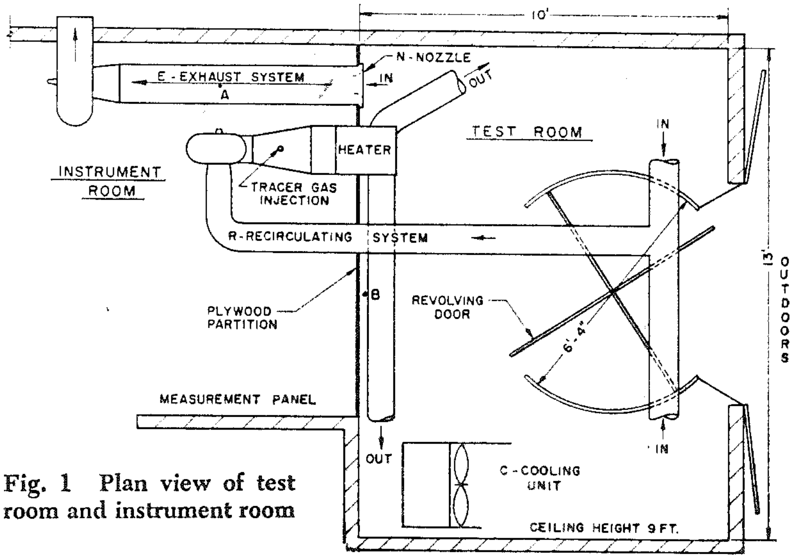


Fig. 1 Plan view of test room and instrument room

L. F. Schutrum was Research Supervisor, C. M. Humphreys was Assistant Director of Research and J. T. Baker was a Research Engineer at the ASHRAE Research Laboratory. N. Ozisik is with the Oak Ridge National Laboratory. This paper was presented at the ASHRAE 68th Annual Meeting in Denver, Colo., June 26-28, 1961.

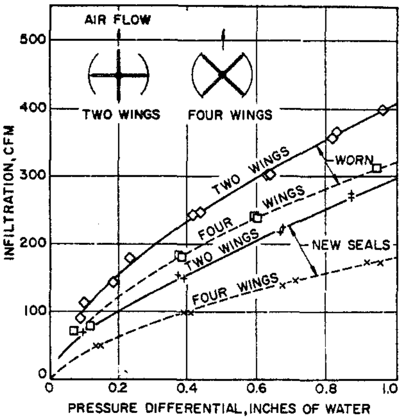


Fig. 2 Infiltration through new and worn* door seals (door not revolving)

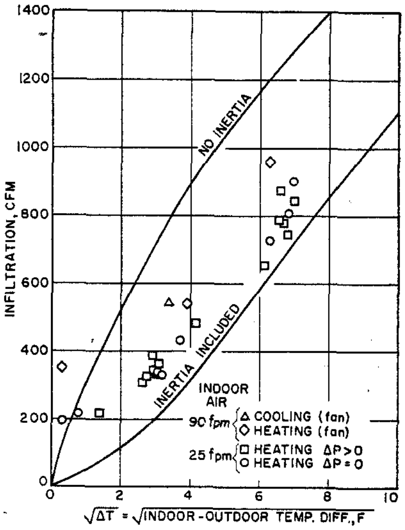


Fig. 3 Observed data and calculated curves of infiltration through revolving door at 10 rpm (air leakages deducted)

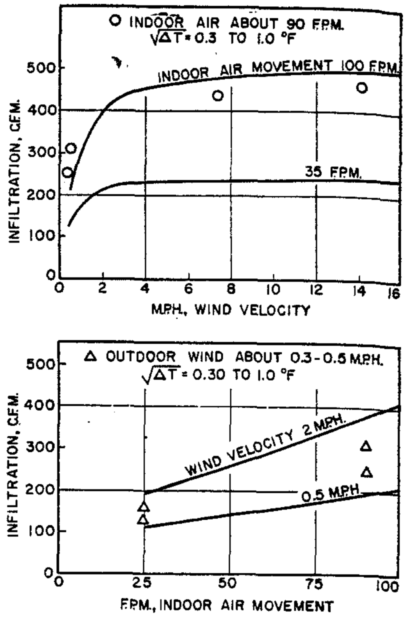


Fig. 4 Effect of wind and indoor air movement on infiltration for small temperature differences and door speed of 5 rpm (air leakages deducted)

installation, would diffuse to other parts of the building, and a nozzle at the duct entrance provided a means of measuring the quantity of the exhausted air.

The recirculating system R also served several purposes. The air drawn from the test room was discharged through a heating coil, thus providing a means of controlling the temperature in the test room during the heating season. The tracer gas was injected into this system between the fan discharge and the heating coil. The fan handled sufficient air, and the supply and return ducts were so located, that the tracer gas was well distributed and the air temperature in the space was reasonably uniform.

A cooling system also was provided to permit a reduction of the air temperature in the test room during the summer tests. This system recirculated air within the space.

After all equipment was installed and all cracks had been caulked, the revolving door opening was sealed and tests were made to determine the tightness of the test room at various pressure differentials. The uncontrolled leakage rate at a pressure differential of 0.5 in. of water was approximately 40 cfm.

Methods of measuring infiltration air – Outside air entered the test room by infiltration through the revolving door, and an equivalent amount left the space either through the exhaust system E or back out through the revolving door. These two routes are shown diagrammatically in Fig. 1-A of Appendix A. The problem was to devise measurement methods by which both of these flows could be determined. It was decided that this could best be accomplished by measuring the total infiltration by the tracer gas technique, and measuring the flow through the exhaust duct by means of a nozzle. The flow back through the door could then be determined by difference.

In applying the tracer gas method of measurement, the tracer gas, hydrogen in this case, was injected into the recirculating system as previously mentioned, and was distributed uniformly through the test room. The gas was supplied at a uniform rate which was measured accurately by two all-glass rotameters of different sizes which had been calibrated previously.

The hydrogen concentration in the room air was measured with a katharometer having three sensing elements. This instrument operates by detecting changes in the thermal conductivity of the mixture due to the presence of the tracer gas. The thermal conductivity of hydrogen is approximately seven times that of air, and the instrument is capable of detecting quite small amounts of the tracer. The maximum concentration of hydrogen used in the tests was approximately 1%, which is well below the lower limit of flammability.

The scale of the katharometer was graduated to read in per cent of helium. It was therefore necessary to recalibrate the instrument for hydrogen. This was done by mixing known volumes of air and hydrogen in a large container, and recirculating the mixture through the sensing elements of the instrument.

A preliminary survey indicated that the concentration of hydrogen was quite uniform throughout the test room except in an area within about 3 ft of the revolving door opening, where the mixing of the room air and infiltration air was taking place. In all later tests, the hydrogen concentration was measured at the 72-in. level at point A in the test room and at point B in the exhaust duct. In tests with the exhaust fan operating, the concentration at both points was essentially the same (see Fig. 1).

Rapid diffusion of hydrogen into the air in the inside segment of the door would introduce errors in the results. However, estimates indicated that this diffusion rate was quite small. The method of calculating the infiltration rate from the tracer gas concentrations is explained in Appendix A.

* **Note: Although worn, the seals provided good contact with adjacent surfaces.**

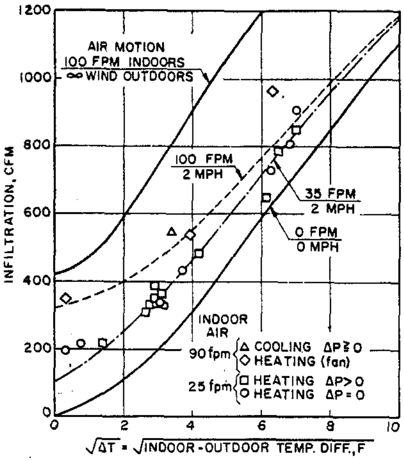


Fig. 5 Infiltration through revolving door at 10 rpm (air leakage through seals deducted)

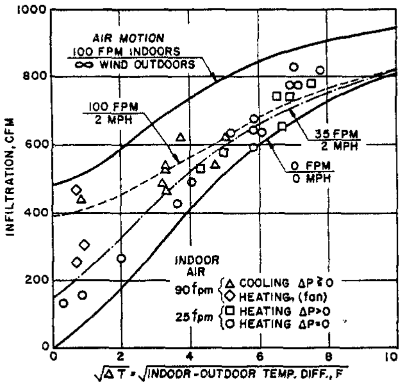


Fig. 6 Infiltration through revolving door at 5 rpm (air leakage through seals deducted)

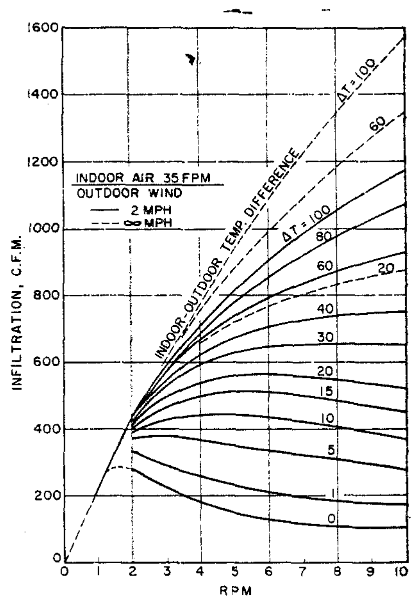


Fig. 7 Infiltration vs. rpm and indoor-outdoor air temperature difference (air leakage past seals deducted)

Flow in the exhaust system was determined by a nozzle located at the duct inlet as shown in Fig. 1. The nozzle size was varied from 1 to 7 in., depending upon the rate of flow to be measured.

Other instrumentation—Differential pressures were measured with draft gauges. The outdoor pressure was obtained with a small static tube extending approximately 3 in. from the face of the wall.

The air temperature at several locations and elevations in the test room was sensed by copper-constantan thermocouples. These were connected to an indicating electronic type potentiometer.

A vane type anemometer located about 5 ft outside the door opening was used to measure the wind velocity. Air velocities in the test room were measured with a heated-thermocouple type anemometer about 3 ft away from the door.

TEST PROCEDURE

After all equipment was in operation and final adjustments were made for door speed, room air temperature and pressure, enough time was allowed for the room air temperature to reach steady conditions. This usually required from one to two hr. Hydrogen was then introduced into the room at a rate which usually would give a reading on the upper half of the katharometer scale, which for hydrogen covered a range from 0 to 0.7%. The actual test would be started, about 15 min later, after the hydrogen concentration level had become stable.

During the 15-min test period, air temperatures and pressures, and rotameter and katharometer readings were taken at fixed intervals. The wind velocity and the door speed also were recorded.

Tests were made under both heating and cooling conditions. Indoor-outdoor air temperature differences up to 60 F could be obtained in winter, while in summer the indoor temperature could be held as much as 30 F below the outside air.

The test program was planned to permit the evaluation of all of the important variables, including door speed, indoor-outdoor temperature and pressure differentials, indoor air motion and outdoor wind.

Analysis of air infiltration through revolving doors – For the purpose of analysis, air infiltrating through a revolving door can be separated into two components: One, component A, is the infiltration through the cracks between the door housing and door wings. The amount of this component depends upon the width and length of crack and the pressure difference between indoors and outdoors.

The other component, B, is the air infiltration related to door movement. When a segment of the revolving door filled with cold outdoor air is turned to the warm room side, circulation starts between the room and the segment air due to the density difference. A similar air exchange takes place at the opposite segment of the door with the outdoor air. The amount of this component of infiltration depends upon indoor-outdoor temperature difference, door speed and door size. Furthermore, indoor air motion and outdoor wind were expected to influence this infiltration. An analysis of this problem and the derivation of an analytical equation for calculating air infiltration related to the door movement is included within Appendix B.

TEST RESULTS

Infiltration Component A: Air leakage past door seals due to pressure differential – Infiltration past door seals depends upon the closeness of fit and the pressure differential. To investigate the magnitude of this infiltration, tests were made with two sets of new seals and one set of worn seals. The door was not revolving for these tests but was adjusted so that either two wings or four wings of the door were touching the door housing. Fig. 2 shows the magnitude of infiltration for pressure differentials up to 1 in. of water. These infiltration rates were corrected for room air leakage. With both new and used seals there were no visible cracks. Where visible, crack size can be estimated and the infiltration may be found from Fig. 10 of Reference 1. Data on pressure differentials for buildings can be found from the same reference.

Infiltration Component B: Air exchange related to door movement—Experiments were made with constant door speeds of 1, 2, 5 and 10 rpm, for various indoor-outdoor air temperature differences. The effect of indoor-outdoor pressure difference on the door movement component of infiltration was investigated in some of the tests by operating the exhaust fan and creating a pressure difference up to 1 in. of water while the door revolved. The air infiltration rates, obtained under the above conditions, were adjusted for infiltration past seals (two-wing contact) and test room leakage due to pressure difference, and the results were plotted in Fig. 3 as a function of indoor-outdoor air temperature difference for a constant door speed of 10 rpm.

These plotted values were found to be practically independent of the pressure differential. This is shown in Fig. 3 by the proximity of the squares and circles which are the symbols for tests with and without pressure difference. The upper curve of Fig. 3 shows calculated infiltration rates neglecting the inertia of the air, and assuming still air conditions both indoors and outdoors. In calculating the lower curve the effect of inertia was included. This curve follows the observed data but lies below the points.

However, in the experiments, air motion indoors and wind outdoors were expected to increase the infiltration. Moreover, summer data showed higher infiltration rates than the winter data. The only difference in the test setup was the cooling blower used in the summer tests which caused higher indoor air velocities. The blower was then used for heating tests (coil not cooled) and the effect of air velocity on infiltration was verified. The experimental points in Fig. 3, representing the data with indoor air movement averaging about 90 fpm with the door stationary (triangles for summer and diamonds for winter data), are higher than those in which the average velocities were about 25 fpm (squares and circles).

Wind velocities 5 ft outside the door were quite low, usually less than 2 mph, while at about 10 ft from the door limited data show the velocity to be about twice as high. The data in Fig. 4, for quite small indoor-outdoor temperature differences, show the effect of wind velocity and indoor air movement on infiltration rates. The curves were calculated as described in Appendix B, based on the assumption that the heads due to the average non-directional air movement and wind velocities have the same effect on infiltration as equal heads due to temperature differences. The trends, if not precisely the magnitude, of the calculated curves in Fig. 4 are in agreement, and thus this premise was assumed to approximately represent the effect of wind and air motion.

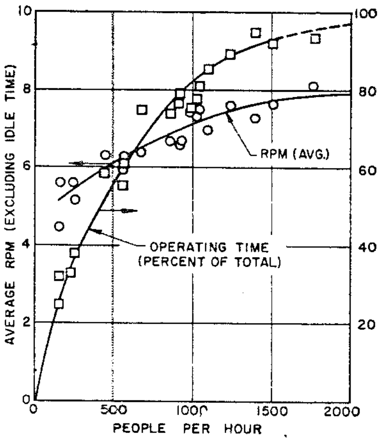


Fig. 8 Operating time and average rpm vs. traffic rate for seven manually operated revolving doors

Figs. 5 and 6 show experimental points, and curves calculated for various indoor air movement and outdoor wind velocities. The approximate indoor air movement for the test points is indicated by the symbols; however, the wind velocities are not identified.

The infiltration rates shown by the solid curves in Fig. 7 are for an indoor air movement of about 35 fpm and a wind velocity of 2 mph. The maximum wind velocity normal to the entrances at the curb line was reported by T. C. Min[1] to be about 2 mph when the wind velocities at the U. S. Weather Bureau were 20 mph. The dashed curves represent the infiltration with extremely high wind velocities which might cause one hundred per cent air exchange in the outside segment of the door.

FIELD TESTS

Fig. 7 shows the infiltration which may be expected as a function of temperature difference and constant rpm of the door. Thus, it shows the performance of a motor-operated revolving door. To obtain information on manually operated revolving doors, a series of 19 field tests was made on seven revolving doors in Cleveland. Data recorded by two observers included the elapsed stop watch time for a given number of door revolutions (50 or 100), time during this period when the door was idle, and a count of the number of people passing through in each direction. The traffic rates varied from 160 to 1770 people per hr. The two curves of regression in Fig. 8 show the relationship found from the field tests between traffic rate, and average rpm and operating time.

Infiltration (Component B) through manually-operated and motor-driven revolving doors — The infiltration through manually operated doors for a given traffic rate was taken as the product of the operating time from Fig. 8 and the infiltration from Fig. 7 determined for the average rpm given in Fig. 8. To substantiate this method, three tests were conducted at the Laboratory with summer cooling conditions and with Laboratory personnel passing through the revolving door, manually operated, at traffic rates ranging from 1075 to 1975 people per hr. While this random traffic pattern was maintained, the tracer gas was being used to measure the infiltration. The observed infiltration, 400-450 cfm, was lower by about 10% on the average than that predicted.

The infiltration through manually operated revolving doors is shown in Fig. 9. The wind velocity was taken as 2 mph, but a few dashed curves for maximum wind velocity are given to show the probable upper limit of infiltration.

For motor-driven doors the infiltration rates can be found from Fig. 7.

EFFECT OF PEOPLE

In a series of tests the doors were motor operated with none, one, two or four of the door segments occupied by people walking around continuously without leaving the space. The infiltration under these conditions was found to be lower by approximately the volume of the people occupying the space. However, when a person steps into the door space, he displaces part of the air in the space, and when he leaves the space on the opposite side of the door, an equal volume of air must replace him. This effectively increases the infiltration, counteracting the decrease caused by the occupancy of the door space. Calculations show that the effect of people on infiltration is small and can be neglected.

Example of infiltration calculation—

Given: A building has a pressure differential of 0.46 in. of water when the indoor air is maintained at 75 F and the outdoor at zero F. Find: The infiltration through a manual revolving door when the traffic rate is 1000 people per hr.

Solution: From Fig. 9 the infiltration rate due to the temperature difference of 75 F is 750 cfm. The infiltration through door seals due to the pressure differential of 0.46 in. of water is 250 cfm from Fig. 2 for two wings and worn seals. The total infiltration is 750 + 250 or 1000 cfm.

Second Example—

Given: The same conditions as in the previous example except that the door is motor driven and operates at a constant speed of 10 rpm.

Solution: The infiltration due to a temperature difference of 75 F is 1040 cfm as taken from Fig. 7. The infiltration due to a pressure difference of 0.46 in. of water is the same as in the first example, making the total 1040 + 250 or 1290 cfm.

DISCUSSION

All calculated infiltration curves and experimental data were based on the standard air density of 0.075 lb per cu ft. The calculated curves were not adjusted for the change in volume of the infiltration air due to temperature change as it passes from the outdoors to the indoors. Moreover, the infiltration rates found in the various figures which are a function of temperature difference were based on winter conditions. The same temperature differences for summer conditions would correspond to slightly lower density differences. It was felt that the refinements for these changes in air density were not necessary and would only complicate the presentation of the results.

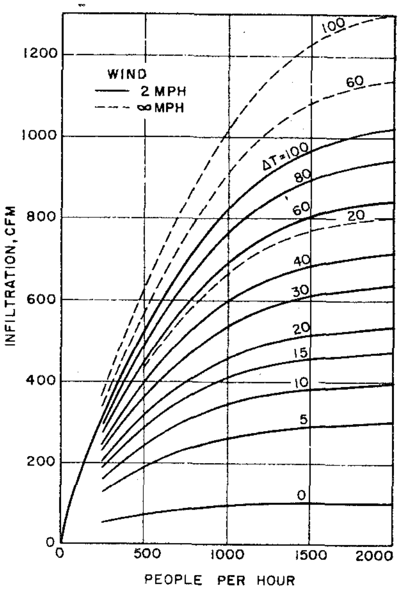


Fig. 9 Infiltration through manually operated revolving doors (air movement 35 fpm indoors, air leakage past door seals deducted)

One would expect that the motion of the door would tend to increase the crack area between door seals and the adjacent surfaces and thus increase the air leakage past the door seals due to pressure difference. The data showed only insignificant changes in crack leakage with door movement.

The effect of air movement indoors and wind outdoors on infiltration was not rigorously investigated, as this would likely require an extensive research project in itself. However, the assumption that air velocity heads in the boundary spaces were equivalent in effect to heads produced by temperature difference is a correction in the proper direction to the infiltration calculated for still-air conditions.

The centrifugal force of the air in the door segment was estimated from the difference in density of the incoming and outgoing air of the segment and the door speed. This effect was neglected in the final analysis since the magnitude of the force even at the higher rpm (10) was less than 10% of the temperature head.

In a few tests, heated air was introduced into the inside segment of the revolving door, through the opening provided for a luminaire in the ceiling of the revolving door housing. The rate of air entering through this opening was about 250 cfm. With but extremely limited data, a definite conclusion cannot be drawn; however, the infiltration rates deduced from these tests at 10 rpm were close to the values given by the upper curve of Fig. 5.

CONCLUSIONS

Infiltration through a revolving door can be estimated by combining the air leakage past the door seals with the infiltration related to the revolving of the door. The magnitude of air leakage through the seals of the door is the result of the pressure differential across the building entrance and the size of the openings at the seal. Revolving the door causes an exchange of indoor and outdoor air of approximately equal volume. The amount of this air exchange depends upon the door speed and the temperature differential and somewhat upon the wind and indoor air velocities.

Infiltration due to air leakage past the seals of the door is given in the paper as a function of the indoor-outdoor pressure differential. Infiltration related to the door movement also is given for a motor-driven revolving door, and for a manually operated door for traffic rates up to 2000 people per hr.

Data given in this paper are based on the use of door seals which provide good contact with the adjacent surfaces. If seals deteriorate to the point that good contact is not maintained, leakage past the seals will increase greatly.

ACKNOWLEDGMENT

The authors recognize the valuable guidance of Messrs. A. M. Simpson and R. G. Chapman in setting up the research program, and also wish to thank the Revolving Door Div of the International Steel Door Company for its cooperation in supplying the revolving door for these experiments. Helpful suggestions from the staff of the Laboratory are acknowledged gratefully.

APPENDIX A

Infiltration rates from tracer gas measurement

The hydrogen and air flow-circuits in the test room are shown in Fig. 1-A. The hydrogen flow paths are designated as Q_{HT} the total steady rate of hydrogen introduced into the room, Q_{HD} the rate of hydrogen flowing out of the room through the duct, and Q_{HO} the net rate of hydrogen passing out through the revolving door. The air entering the test chamber is Q_{Ai} through the revolving door; and Q_L the leakage through walls, etc. Air leaves the chamber via the revolving door Q_{AO} and the exhaust duct Q_{AD}. C_s and C_D are the concentrations of hydrogen in the space and in the exhaust duct.

By volume, balances on

hydrogen $Q_{HT} = Q_{HO} + Q_{HD}$ A-1

and on air $Q_{AI} = Q_{AO} + Q_{AD} - Q_L$ A-2

The measured concentrations are

$$\text{in space } C_s = \frac{Q_{HO}}{Q_{AO} + Q_{HO}} \qquad \text{A-3}$$

where from Eq. A-3 and A-1

$$Q_{AO} = \left(\frac{1 - C_s}{C_s}\right) Q_{HO} = \left(\frac{1 - C_s}{C_s}\right) (Q_{HT} - Q_{HD}) \qquad \text{A-4}$$

and in duct

$$C_D = \frac{Q_{HD}}{Q_{AD} + Q_{HD}} = \frac{Q_{HD}}{Q_D} \qquad \text{A-5}$$

from which

$$Q_{HD} = C_D\, Q_D \qquad \text{A-6}$$

from A-5 and A-6

$$Q_{AD} = (1 - C_D) \frac{Q_{HD}}{C_D} = (1 - C_D)\, Q_D \qquad \text{A-7}$$

Substituting Eq. A-6 into A-4

$$Q_{AO} = \left(\frac{1 - C_s}{C_s}\right) (Q_{HT} - C_D\, Q_D) \qquad \text{A-8}$$

and substituting Eq. A-7 and A-8 into A-2

$$Q_{Ai} = \left(\frac{1 - C_s}{C_s}\right)(Q_{HT} - C_D\, Q_D) + Q_D\,(1 - C_D) - Q_L \qquad \text{A-9}$$

The infiltration was determined from Eq. A-9 for observed values of C_s and C_D from katharometer measurements, Q_{HT} from rotometer readings, and Q_D from nozzle information. Q_L was determined by measurement and its relation to indoor-outdoor pressure differences. For tests without pressure differences the exhaust volume Q_D was zero and Q_L was assumed to be zero.

APPENDIX B

Calculation of air infiltration component B through a revolving door

Let a revolving door having 4 segments rotate at a uniform speed, N, in the direction shown in Fig. 1-B. Assume outside air is colder than room air.

Consider a quarter-section OAB having its leading edge OA along ox reference axis $\theta = 0$. At this moment, assume that air in the segment has a uniform temperature between indoor and outdoor air temperatures. At time θ let the segment be at position OA_1, and the volume of warm air entering into the segment during the time interval θ be q. Assume air displacement is taking place as the result of buoyancy due to cold air in the segment and warm air in the room, and that warm air entering the segment is collecting in a uniform layer at the top of the segment. At the time θ, the rate of change of q can be expressed as follows:

$$\frac{dq}{d\theta} = CA\sqrt{2gh} \qquad \text{B-1}$$

where

A = area of opening
h = head of air
C = flow coefficient

In this equation, both A and h are functions of θ and q. Therefore, in order to solve equation B-1, A and h are to be expressed in terms of q and θ. As area, A, first increases and then decreases during a complete cycle, the equation can be solved separately for the two time intervals defined as follows:

1. "Opening-cycle" corresponding to the time interval:

$$\theta = 0 \text{ to } \theta = \frac{1}{4N}$$

2. "Closing-cycle" corresponding to the time interval:

$$\theta = \frac{1}{4N} \text{ to } \theta = \frac{1}{2N}$$

First, consider the opening cycle. For this cycle, h and A can be related to q and θ as follows:

$$h = h_o \frac{V - q}{V} \qquad \text{B-2}$$

$$A = \tfrac{1}{2} L\,(2\pi RN\theta)\,\frac{V - q}{V} \qquad \text{B-3}$$

where

h_o = head when $\theta = 0$
V = Volume of the door segment

Substituting B-2 and B-3 in B-1:

$$\frac{dq}{d\theta} = CL\pi RN\theta\,\frac{V - q}{V}\sqrt{2\,gh_o\,\frac{V - q}{V}} \qquad \text{B-4}$$

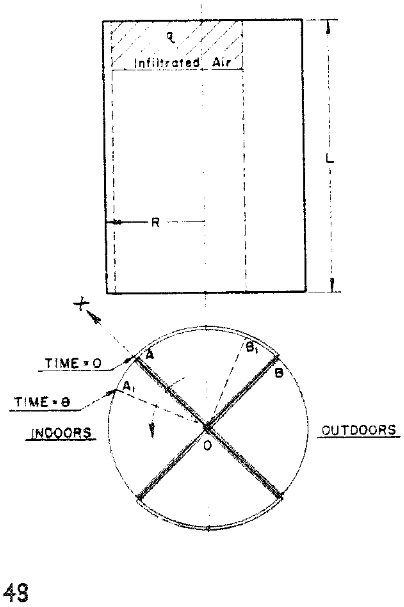
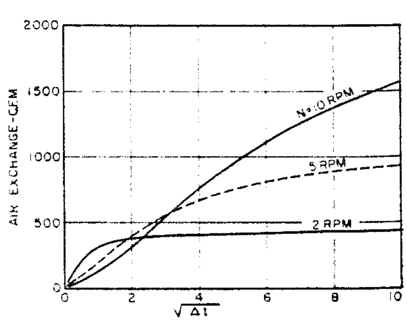


Fig. 2B Air exchange from one side of revolving door into door segment (includes inertia effect)



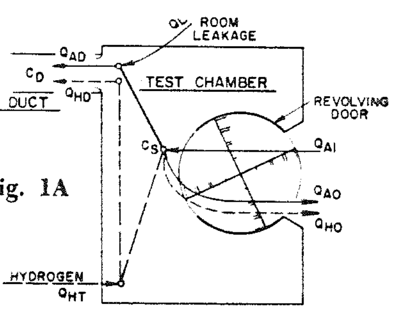
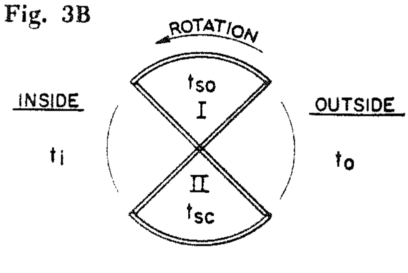


Fig. 1A

Fig. 3B



During the closing-cycle the time interval is $\frac{1}{4N} < \theta \leqq \frac{1}{2N}$.

For convenience take $\frac{1}{4N}$ as zero θ for reference purpose, thus the value of A for this closing cycle is

$$A = \tfrac{1}{2} L\, 2\pi RN \left(\frac{1}{4N} - \theta \right) \frac{V-q}{V} \qquad \text{B-5}$$

and equation B-4 becomes

$$\frac{dq}{d\theta} = CL\pi RN \left(\frac{1}{4N} - \theta \right) \frac{V-q}{V} \sqrt{2 g h_o \frac{V-q}{V}} \qquad \text{B-6}$$

Inertia effect—In the foregoing derivation the inertia of air in the segment, that is, the head lost in accelerating this mass of air from initially zero to some finite velocity, was not considered. In a door segment, the inertia head at a time θ can be approximated as follows:

$$h_i = \frac{1}{2} \frac{L}{g} \frac{dv}{d\theta} \qquad \text{B-7}$$

where L/2 is used to be consistent with h_o, which is described later

since

$$vA_s = \frac{dq}{d\theta} \text{ or } \frac{dv}{d\theta} = \frac{1}{A_s} \frac{d^2q}{d\theta^2}$$

and

$$A_s = \frac{V}{L}$$

then

$$h_i = \frac{L^2}{2gV} \frac{d^2q}{d\theta^2} \qquad \text{B-8}$$

and the actual head causing infiltration at any time θ would be the buoyancy head given by equation B-2 less the inertia head given by equation B-8, that is

$$\text{Actual head} = h - h_i = h_o \frac{V-q}{V} - \frac{L^2}{2gV} \frac{d^2q}{d\theta^2} \qquad \text{B-9}$$

Equation E-4 for the opening cycle becomes:

$$\frac{dq}{d\theta} = K\theta \frac{V-q}{V} \sqrt{\frac{V-q}{V} - \frac{L^2}{2gVh_o} \frac{d^2q}{d\theta^2}} \qquad \text{B-10}$$

and for the closing cycle

$$\frac{dq}{d\theta} = K \left(\frac{1}{4N} - \theta \right) \frac{V-q}{V} \sqrt{\frac{V-q}{V} - \frac{L^2}{2gVh_o} \frac{d^2q}{d\theta^2}}$$

where

$$K = CL\pi RN\sqrt{2gh_o} \qquad \text{B-11}$$

The head at the beginning of the opening cycle is

$$h_o = \tfrac{1}{2} L \frac{\rho_{so} - \rho_i}{\rho} \qquad \text{B-12}$$

where

ρ_{so} = density of air in the door segment at the beginning of the opening cycle

ρ_i = density of air in room

ρ = reference density of air 0.075.

Fig. 2-B shows the air exchange rates for all four segments as calculated by equations B-10 and B-11 for assumed values of air temperature in the segment and indoors or outdoors. Note it does not represent the net infiltration but merely the amount of air entering or leaving the door segments.

In Equation B-12 the determination of ρ_{so}, the density of the air in the door segment, for a given indoor-outdoor temperature difference, requires a knowledge of the air temperature in the space. Thus in Fig. 3-B, t_{sc} is the air-space temperature just after closing. By inspection of the figure, equations can be written as

$$t_{so} = f_o t_o + (1 - f_o) t_{sc} \qquad \text{B-13}$$

and

$$t_{sc} = f_i t_i + (1 - f_i) t_{so} \qquad \text{B-14}$$

where

f_o = (Air displacement as fraction of segment volume when segment is exposed to outdoors) =

$$\frac{q_o + q_c}{V} \text{ outdoors} \qquad \text{B-15}$$

f_i = (Air displacement as fraction of segment volume when segment is exposed to indoors) =

$$\frac{q_o + q_c}{V} \text{ indoors} \qquad \text{B-16}$$

Combining equations B-13 and B-14

$$t_{sc} = \frac{f_i t_i + (1 - f_i) f_o t_o}{1 - (1 - f_o)(1 - f_i)} \qquad \text{B-17}$$

and

$$t_{so} = \frac{f_o t_o + (1 - f_o) f_i t_i}{1 - (1 - f_o)(1 - f_i)} \qquad \text{B-18}$$

The temperature of Segment I depends upon the relative quantity of indoor air m_I, and outdoor air, m_o in the segment.

$$t_{so} = \frac{t_i m_I + t_o m_o}{m_I + m_o} = \frac{t_i m_I + t_o m_o}{V \text{ (volume of segment)}} \qquad \text{B-19}$$

and similarly

$$t_{sc} = \frac{t_i m_{II} + t_o m'_o}{m_{II} + m'_o} = \frac{t_i m_{II} + t_o m'_o}{V} \qquad \text{B-20}$$

From Equations B-18 and B-19 the amount of indoor air in Segment I is

$$m_I = \frac{f_i (1 - f_o) V}{1 - (1 - f_o)(1 - f_i)} \qquad \text{B-21}$$

where for convenience, t_o was assumed to be zero.

Similarly from Equations B-17 and B-20 the amount of indoor air in Segment II is

$$m_{II} = \frac{f_i V}{1 - (1 - f_o)(1 - f_i)} \qquad \text{B-22}$$

The difference in the quantity of indoor air in the outgoing and incoming segments is the net infiltration. Hence,

Infiltration per segment per revolution $= m_{II} - m_I = \frac{f_o f_i V}{1 - (1 - f_o)(1 - f_i)}$ and the infiltration rate through the door becomes B-23

$$Q = \frac{4 N f_i f_o V}{1 - (1 - f_o)(1 - f_i)}, \text{ cfm} \qquad \text{B-24}$$

In addition to knowing the infiltration through the revolving door the corresponding indoor-outdoor temperature difference must be found. By subtracting both sides of Equation B-18 from t_i it becomes

$$(t_i - t_{so}) = \frac{f_o}{1 - (1 - f_o)(1 - f_i)} (t_i - t_o) \qquad \text{B-25}$$

Also by subtracting t_o from both sides of Equation B-17 and dividing this result by Equation B-25, an equation is found which may help in visualizing some of the temperature and infiltration relationships.

$$\frac{t_{sc} - t_o}{t_i - t_{so}} = \frac{f_i}{f_o} \qquad \text{B-26}$$

Fig. 2-B shows air displacement rates for the entire door (i.e. 4 segments) and for (N) revolutions of the door as a function of ΔT. For a given ΔT the (f) values can be determined from Fig. 2-B with the following relationship:

$$f = \frac{\text{cfm from Fig. 2-B}}{4VN} \qquad \text{B-27}$$

where 4V was taken as 218 cu ft for the revolving door used in the tests.

For a given value of $t_i - t_{so}$, the net infiltration rate Q, and the corresponding indoor-outdoor temperature difference $(t_i - t_o)$ can be determined as follows:

1. Assume $t_i - t_{so}$ and obtain cfm (inside) from Fig. 2-B and determine f_i from Equation B-27.
2. Assume f_o. Where buoyance effects alone determine the infiltration, it is logical that $f_o = f_i$.
3. Knowing f_i and f_o, determine infiltration from Equation B-24 and $t_i - t_o$ from B-25.

Effect of turbulence and wind—By definition, the factors f_o and f_i represent the fractional air displacement of the segment volume when the segment is exposed to outdoors and indoors, respectively. This air displacement is caused by the temperature difference, in the absence of any external air turbulence or wind. Any external air movement will increase the value of f_o or f_i.

An approximate solution to the effect of air movement on infiltration was made by assuming that the average nondirectional air velocity head $\frac{v^2}{2g}$, was equivalent in its effect on infiltration to a buoyancy head of equal magnitude. For convenience, since curves of infiltration rates were plotted against the square root of the temperature difference between door segment air and room air, Fig. 2-B, the velocity heads were converted to temperature difference heads. Thus ΔT_T and ΔT_W were designated indoor turbulence and outdoor wind equivalent temperature heads.

To solve for the infiltration through the revolving door with a turbulence head inside of ΔT_T and wind outdoor equivalent to ΔT_W a trial and error solution was used as follows:

1. Assume $(t_i - t_{so})$ and ΔT_T.
2. Find cfm_i and thus (f_i) from Fig. 2-B for $\sqrt{(t_i - t_{so}) + \Delta T_T}$
3. Assume f_o.
4. Find $\sqrt{(t_{sc} - t_o) + \Delta T_W}$ from Fig. 2-B for assumed (f_o).
5. Calculate $(t_{sc} - t_o)$ from Equation B-26 if $[(t_{sc} - t_o)$ from Step 5$] > [(t_{sc} - t_o + \Delta T_W)$ from Step 4$]$ then a new value of (f_o) in Step 3 is required.
6. Solve for $\Delta T_W = [(t_{sc} - t_o) + \Delta T_W] - [t_{sc} - t_o]$.
7. Calculate $(t_i - t_o)$ from Equation B-25.
8. Calculate infiltration from Equation B-24.

From this procedure the indoor-outdoor temperature differential was found in Step 7, (reference t_o = zero) for the infiltration rate determined in Step 8, turbulence indoors of ΔT_T and wind outdoors of ΔT_W. In this manner the curves of Fig. 7 were constructed.

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2. Infiltration Problem of Multiple Entrances by A. M. Simpson and K. B. Atkinson (ASHVE Journal Section, Heating, Piping & Air Conditioning, Vol. 8, No. 6, June, 1936, p. 345-351)

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