# AIR INFILTRATION — THERMAL BEHAVIOUR OF DOOR FRAMES

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# ABSTRACT

## AIR INFILTRATION — THERMAL BEHAVIOUR OF DOOR FRAMES

by

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The present work deals with air infiltration and thermal behaviour of door frames. The main purpose is to simulate exterior temperature and wind pressure conditions under which door or window frames could be tested for air leakage and thermal behaviour.

For the completion of this work, two tasks were undertaken, the first being the modification and the calibration of the test equipment for the achievement of test conditions, and the second the tests on a wooden door frame. The first test is under isothermal and pressure differential, and the second under differential pressure and temperature conditions. Finally, thermal deformations on the door were measured, such as warping and bowing under pressure and temperature differential conditions.

These tests were conducted on behalf of the Bureau de Normalization du Quebec for the development of standards on Air Leakage and Thermal Behaviour of Door Frames.

## ACKNOWLEDGEMENTS

*I am greatly indebted to my supervisor, Professor C. Marsh, for his contribution and I sincerely thank him for instructing me during the course of this work.*

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Montreal, P.Q., Canada
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Eleni Adamidis

*To*

*my Mother*

*and*

*the memory of my*

*beloved Father*

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# 1. INTRODUCTION

Air leakage through building enclosures has certain implications with respect to overall performance of the building. Air flow through building openings is a result of wind action or chimneys.

It is well known that air infiltration and exfiltration will affect the building environment for human comfort a great deal. Controlling the building environment will decrease the heating load during the winter and the cooling load during the summer. As a result, energy costs regardint that aspect will decrease as well.

Another implication in relation to the performance of buildings is the extent to which air leakage is responsible for serious condensation problems which contribute to the deterioration of building structures.

How these implications could be eliminated or minimized is a matter of undertstanding the characteristics of air leakage, the distribution of pressure across building enclosures, the resulting pattern of air flow and the behaviour of elements of building enclosures. Being aware of all these, a good design and careful construction will resolve the air leakage problems and improve the overall building performance.

Exterior door frames are one of the most important elements of building enclosures that create sources of air infiltration and exfiltration in buldings. For this reason, it is important to know their behaviour in order to improve their performance.

The purpose of the present work is to test exterior door or window frames for air infiltration and thermal behaviour. It commences with the apparatus and its calibration. By the calibration, the extraneous air leakage ($Q_L$) escaping from the interior chamber of the apparatus has been determined for the various pressure levels in the chamber.

In continuation, two tests have been conducted on a wooden exterior door. The first test was under isothermal conditions and differential pressure, and the second under differential pressure and temperature across the specimen. Humidity measurements were not made but it was assumed that during the first test (under isothermal conditions and differential pressure) the humidity across the specimen was constant.

The total flow ($Q_T$) through the specimen was measured in both tests by a flowmeter and corrected for exfiltration from the interior chamber. Finally, the deformations on the wooden door (warping and bowing) due to differential temperature, were measured.

## 2. APPARATUS

The apparatus consists of two chambers (Fig. 2.1), the chamber representing the exterior (cold box), and the chamber representing the interior (hot box). The exterior chamber is to simulate the outside building temperature and wind pressure conditions whereas the interior simulates the inside building conditions. Between the two chambers there is a panel to which the specimen is attached.

The exterior chamber includes in it refrigeration coils for the achievement of low temperature conditions. In addition, there is a fan for air circulation purposes near the top of the interior face of the exterior chamber. The refrigeration coils are positioned in a shaft through which the air circulates aided by the fan. Also, the exterior chamber includes one thermostat sensor at the bottom and two thermocouples, one being at the top and the other at the bottom of the chamber.

The inlet A to the exterior chamber, illustrated in the same figure, is for compressed air flow to create a differential pressure between the two chambers.

In the interior chamber there is a lamp to keep the temperature of the interior chamber constant while the refrigeration system is on. The fan in the same chamber is to circulate the air to ensure uniform temperature. There is one thermostat sensor at the bottom and three thermocouples in the interior chamber. One thermocouple is attached to the top, one at the bottom and another on the surface of the door at mid-height.

In the outlet B of the interior chamber a flow meter is inserted to measure the air passing through the specimen. Finally, there are two manometer tubes inserted to the two chambers for the measurement of their differential pressure and of the pressure of the interior chamber separately.

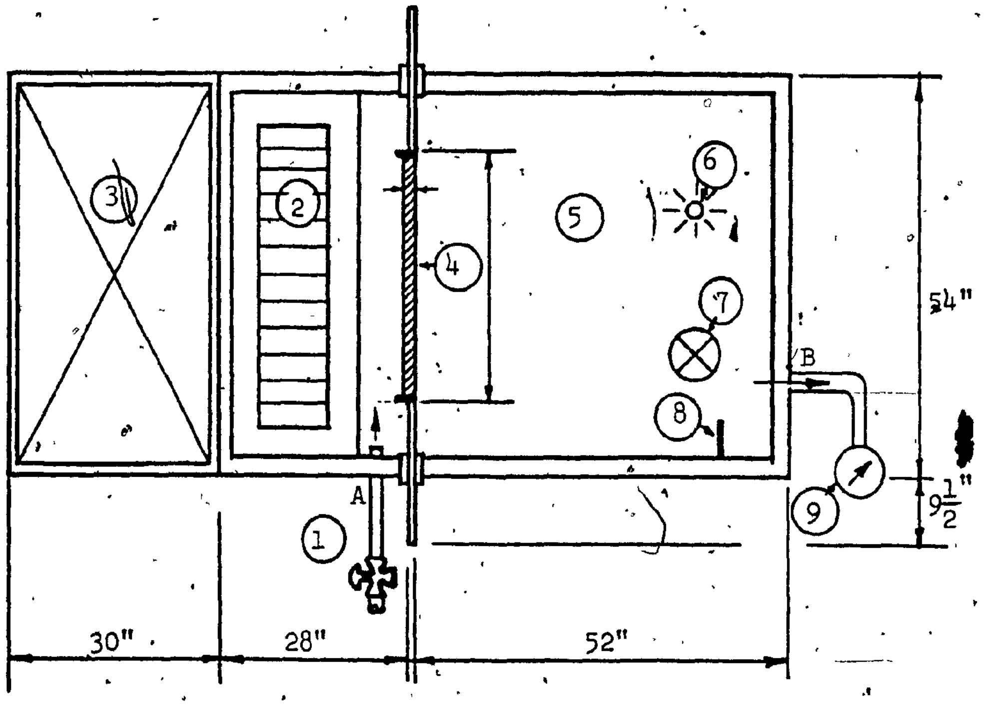


*Fig. 2.1 — Horizontal Cross-Section of the Apparatus*

Identification of Parts

1. Control valve
2. Refrigeration coils of exterior chamber
3. Compartment of refrigeration motor
4. Test specimen
5. Interior chamber
6. Heating lamp
7. Fan for air circulation
8. Thermostat sensor
9. Flow meter
   A. air flow inlet
   B. air flow outlet

# 3. CALIBRATION OF INTERIOR CHAMBER

## 3.1 MEASUREMENTS

The hot box was closed with a plywood panel as illustrated in Fig. 3.1. The pressure in the box was increased up to 5 inches of water (at $T = 24^{o}C$) with compressed air device. At 5 inches of water the compressed air flow was cut off and as the pressure in the box dropped to zero, time and pressure readings were taken (see Table 3.1). Based on these readings the rate of air loss as a function of pressure was determined.

## 3.2 ANALYSIS FOR AIR LEAKAGE[6]

The density of air contained in the chamber increases directly proportionally with pressure.

According to the equation of state of ideal gases, the following relation exists:

$$Pv = RT \quad \quad (3.1)$$

where —

P = absolute pressure

v = specific volume ($v = 1/\rho$, $\rho$ = density)

T = absolute temperature

R = gas constant

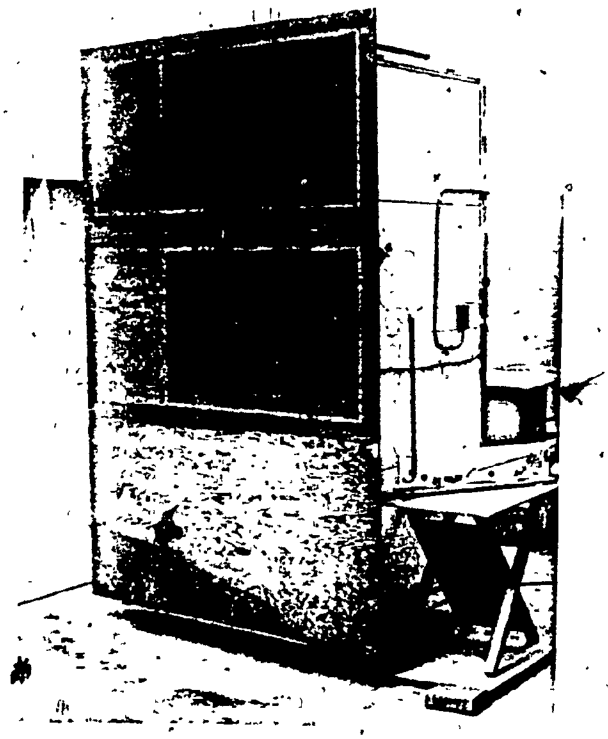

*Fig. 3.1 — Interior Chamber*

TABLE 3.1 — DEPRESSURIZATION MEASUREMENTS ON TIME AND PRESSURE

| h in inches of of water | t in sec. | t in sec. | $t_{ave.}$ in sec. | $ln\ h$ |
|---|---|---|---|---|
| 5.0 | | | | |
| 4.5 | 7 | 7 | 7 | 1.504 |
| 4.0 | 14 | 14 | 14 | 1.386 |
| 3.5 | 23 | 22 | 22.5 | 1.253 |
| 3.0 | 31 | 31 | 31 | 1.099 |
| 2.5 | 42 | 42 | 42 | 0.916 |
| 2.0 | 55 | 55 | 55 | 0.693 |
| 1.5 | 72 | 71 | 71.5 | 0.405 |
| 1.0 | 94 | 92 | 93 | 0.0 |
| 0.5 | 133 | 133 | 133 | -0.693 |
| 0.3 | 170 | 170 | 170 | -1.204 |

The units of R can be determined from the equation when the other units are known. For instance, for P in pounds per square foot, $\rho$ in slugs per cubic foot and T ($^{0}F + 459.6$) in degrees Rankine ($^{0}R$)

$$R = (lb/ft^2)(ft^3/slug \times {}^{0}R) = ft.\ lb./(slug \times {}^{0}R)$$

for $\rho$ in pounds-mass per cubic foot

$$R = ft \times lb/(lb_m \times {}^{0}R)(m \times kg/(kg_m \times {}^{0}R)$$

In our particular case, since the volume of the chamber remains constant whereas the mass of air inside it changes, Boyle's Law applies (derived from equation 3.1, for T and R constant). Thus,

$$P = m \times constant \qquad (3.2)$$

where —

m = mass of air

From equation (3.2) if the pressure in the chamber changes from $P_o$ to $P_i$, then

$$P_o/P_i = m_o/m_i$$

$$= V_o\rho_o/V_i\rho_i$$

$$= V_o\rho_o/V_{ie}\rho_o$$

therefore —

$$V_{ie} = V_oP_i/P_o \qquad (3.3)$$

where —

$P_o$ = initial pressure in chamber, atmospheric pressure

= 34.3 ft of water

$P_i$ = absolute pressure above $P_o$

$m_o$ = mass of air in chamber when $P = P_o$

$m_i$ = mass of air in chamber when $P = P_i$

$V_o$ = the volume of the chamber with room air density

= 130 cu. ft.

$\rho_o$ = room air density, chamber air density at $P = P_o$

$V_i$ = the volume of air in chamber with $\rho = \rho_i$

$\rho_i$ = air density in the chamber when $P = P_i$

$V_{ie}$ = expanded volume of air with room air density when $P_i$ pressure is introduced in the chamber.

Note that the temperature inside the interior chamber was constant throughout the calibration and it was the same as the room temperature ($T = 24^oC$)

Equation (3.3) can be transformed to:

$$V_{ie} = \frac{V_o}{P_o}(P_o + h), \quad \text{or}$$

$$V = V_o + \frac{V_o}{P_o} h \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

where —

$h$ = the manometer reading in inches of water

$V = V_{ie}$

Using the values of $P_0$ and $V_0$ as given previously, equation (3.4) becomes

$$V = 130 + 0.32h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.5)$$

In equation (3.5), V is expressed in cu. ft. whereas h in inches of water. In addition, equation (3.5) is represented by Fig. 3.2 and the observations illustrated on Table 3.1 by Fig. 3.3 (see experimental points). Looking at the experimental points of Fig. 3.3, one can predict that the equation of the "best fit" curve could be represented by an exponential decay function such as:

$$h = C_1 e^{-C_2 t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.6)$$

The constants $C_1$ and $C_2$ could be calculated by the use of the experimental observations in the following manner. Taking the natural logarithm of both sides of equation (3.6), the following relation exists:

$$l_n h = l_n C_1 - C_2 t$$

Let —

$l_n h = y$

$l_n h C_1 = a$

$C_2 = b$

$t = x$

then —

$y = a + bx$

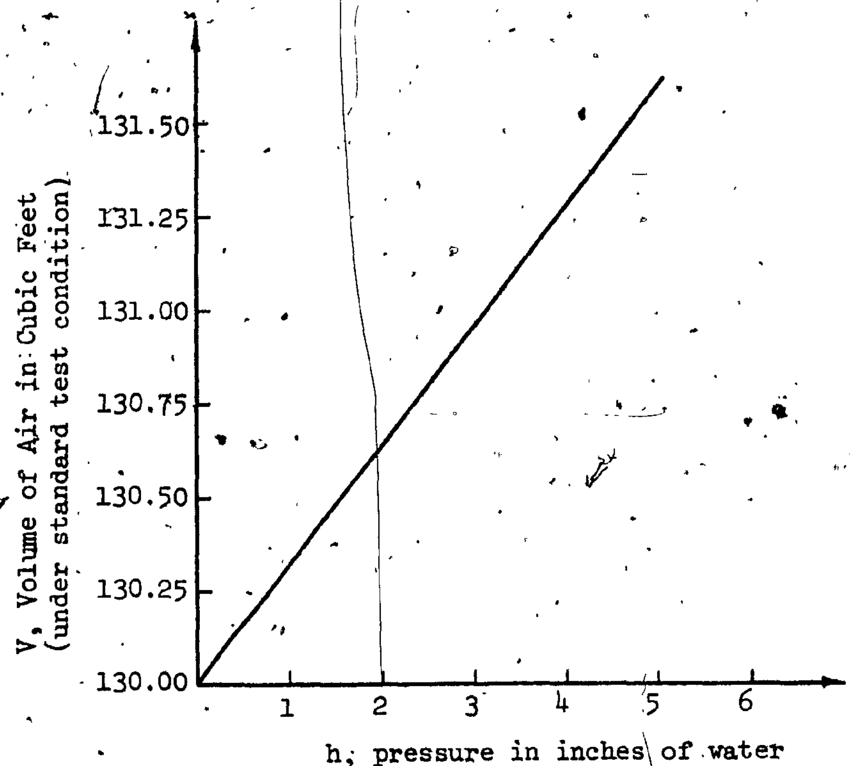


*Fig. 3.2 — Air Volume-Pressure Variation.*

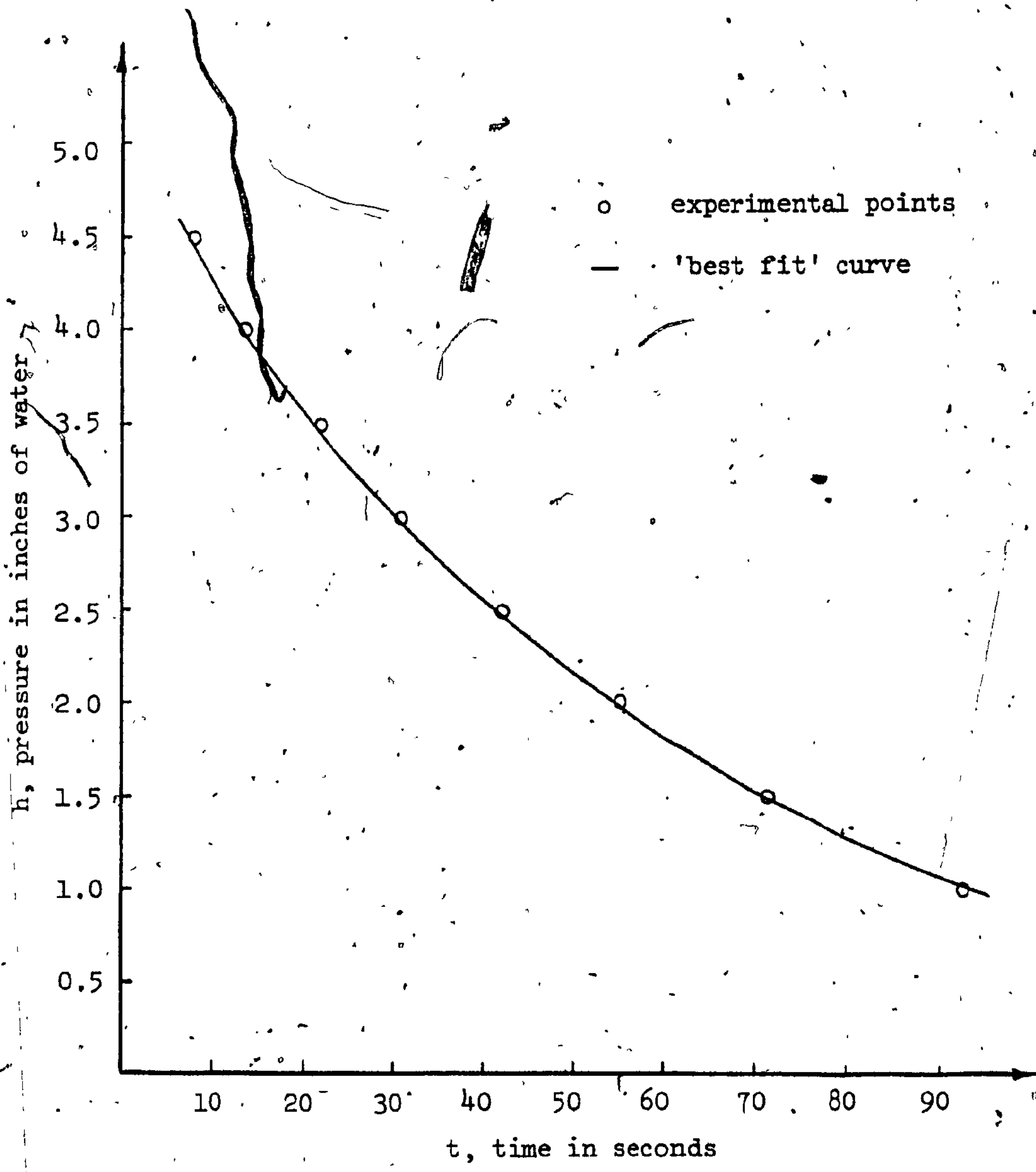


*Fig. 3.3 — Pressure Drop-Time Variation (experimental and 'best fit' curve)*

Using linear regression analysis with the results of Table 3.1, the constants a and b can be estimated and then from these, the constants $C_1$ and $C_2$. The two latter constants were found to be:

$$C_1 = 5.053$$

$$C_2 = 0.017$$

By substituting the values of $C_1$ and $C_2$ back to the equation (3.6), we have:

$$h = 5.053\ e^{-0.017t} \quad \ldots\ldots\ldots\ldots \quad (3.7)$$

As can be seen from Fig. 3.3, the points due to observation do not deviate much from the curve represented by the "best fit" curve of the exponential function of equation (3.7), illustrated in the same figure.

Equation (3.7) gives fall in pressure from which the leakage through the interior chamber is calculated in the following manner.

By substituting equation (3.7) into (3.5):

$$V = 130 + 0.32(5.053^{-0.017t})$$

$$= 130 + 1.62\ e^{-0.017t} \quad \ldots\ldots\ldots\ldots \quad (3.8)$$

The above rate is then:

$$dV/dt = -Q_L \quad \ldots\ldots\ldots\ldots \quad (3.9)$$

where —

$Q_L$ = air leakage from the interior chamber

$V$ = volume of air under standard test conditions

The negative sign in equation (3.9) is due to the fact that zero time was taken at maximum value of air mass in the chamber (depressurization process).

By differentiating equation (3.8) with respect to time and substituting it into equation (3.9), then —

$$Q_L = 0.027\ e^{-0.017t} \qquad (3.10)$$

From equation (3.7), by taking the natural logarithm of both sides of the equation and solving for t, we have —

$$t = 95.29 - 58.82\ l_n h$$

Substituting the value of t into equation (3.10), the relationship between air leakage and pressure is:

$$Q_L = 0.0054h \qquad (3.11)$$

Equation (3.11) is represented by Fig. 3.4. From this figure one can read the theortical leakage ($Q_L$) of the interior chamber for various pressure levels. Note that when the calibration was performed the room temperature was 24°C. To minimize the error in calculating the theoretical air leakage ($Q_L$) when tests are performed, the room temperature should be close to 24°C.

The value of $Q_L$ is added to the measured flow $Q_M$ to give the total flow $Q_T$ from the exterior chamber to the interior chamber.

Therefore,

$$Q_T = Q_L + Q_M \qquad (3.12)$$

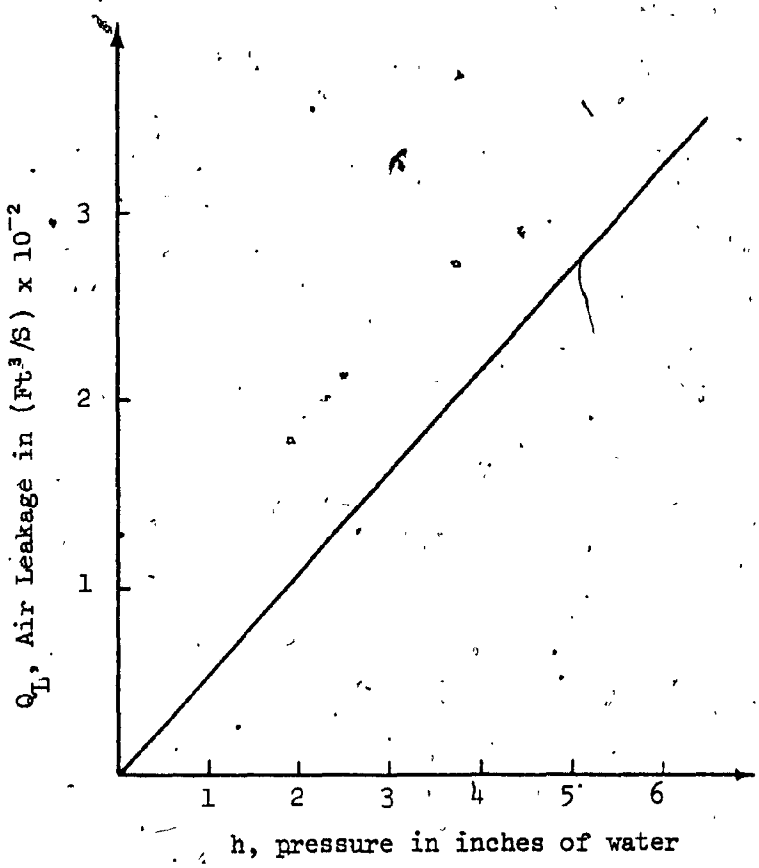


*Fig. 3.4 — Air Leakage-Pressure Variation.*

# 4. TEST SPECIMEN AND INITIAL OBSERVATIONS

The specimen is a test door prehung in its frame on a closure panel as illustrated in Fig. 4.1. The original dimensions of the door were as follows:

height. . . . . . . . . . . . . . . . 80.53" (2.05 m)

length. . . . . . . . . . . . . . . . 33.81" (0.86 m)

thickness. . . . . . . . . . . . . . . 1.75" (4.4 cm)

Before the test, measurements on bowing and warping were made. Figures 4.2 and 4.3 illustrate their maximum values. The measurement of bowing were obtained by the aid of a stretched string and a ruler, whereas the measurements of warping by the aid of a plumb. The plumb's position is illustrated in Fig. 4.3 by the dotted lines. In addition, maximum gaps between the frame and the door specimen were measured with the aid of a ruler and are illustrated in Fig. 4.4.

*Fig. 4.1 — Test Specimen.*

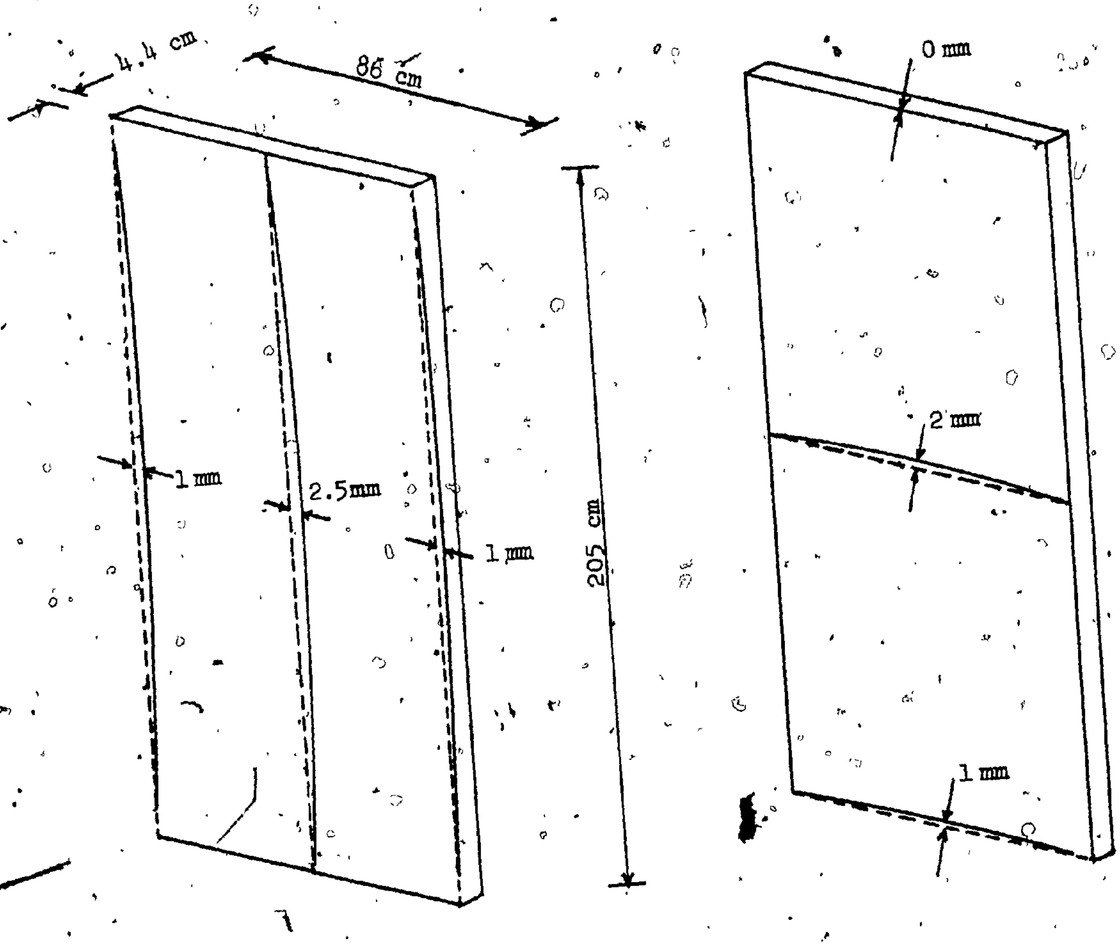


*Fig. 4.2 — Observations on Bowing Before Testing.*

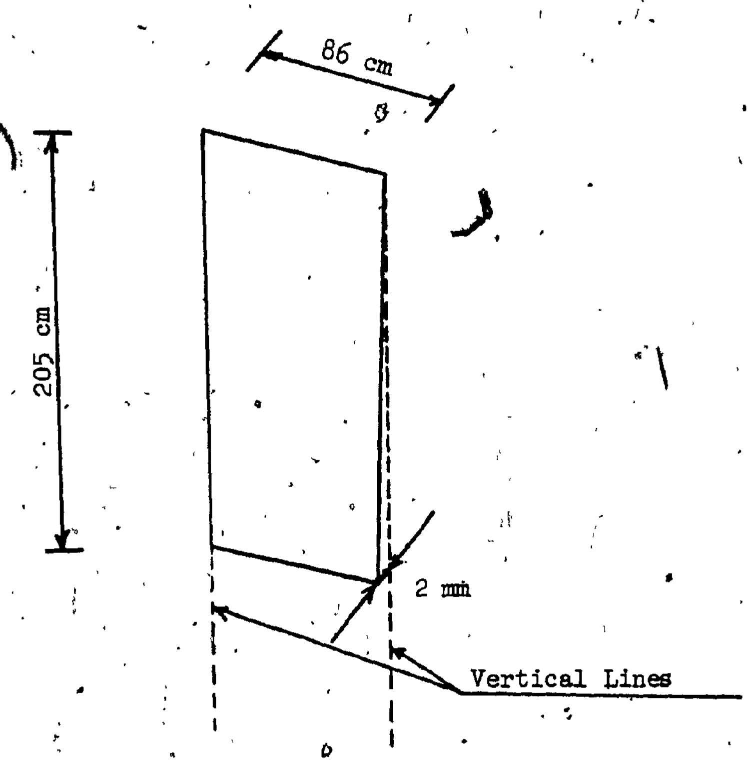


*Fig. 4.3 — Observations on Warping Before Testing.*

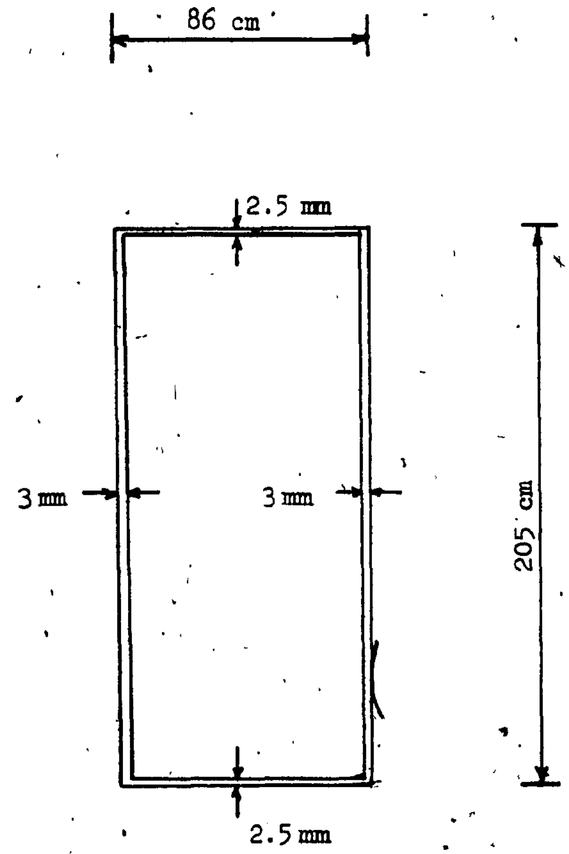


*Fig. 4.4 — Maximum Gaps Between Frame and Door Specimen.*

# 5. TEST PROCEDURES

## 5.1 TEST UNDER ISOTHERMAL CONDITIONS

The specimen of Fig. 4.7 was positioned between the two chambers of the apparatus as illustrated in Fig. 5.1 (for horizontal cross section details of the apparatus see Fig. 2.1).

The conditions of air for this test were:

Pressure: 31.05 in. Hg (105.1 kPa)

Temperature: 75°F (24°C)

Air Density: 0.0731 lb/ft³ (1.171 kg/m³)

By introducing compressed air into the exterior chamber a differential pressure between the two chambers was created. Air flow out from the interior chamber was measured for differential pressures of up to 150 Pa. Table 5.1 gives the measured air flow ($Q_M$) and the corresponding pressure (P)

## 5.2 TEST UNDER DIFFERENTIAL TEMPERATURE

The ambient conditions for air in this test were approximately the same as in the previous test.

By the aid of the refrigeration system, the temperature in the exterior chamber was reduced to -16°C (average temperature with a fluctuation of ± 1°C). In the other chamber the temperature was kept to 24°C

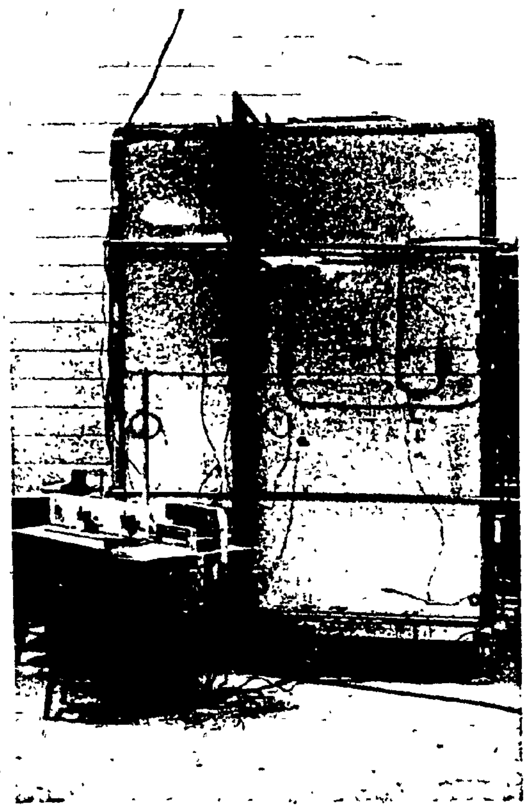

*Fig. 5.1 — Set Up of Apparatus for Testing.*

TABLE 5.1 — AIR FLOW-PRESSURE MEASUREMENTS UNDER ISOTHERMAL CONDITIONS

| ΔP Differential pressure in Pascals ($P_a$) | ΔP Differential pressure in in. of water | P Pressure of interior chamber in in. of water | $Q_M$ Air Flow in gr/sec |
|---|---|---|---|
| 25 | 0.1 | 0.012 | 2.39 |
| 50 | 0.2 | 0.024 | 3.23 |
| 75 | 0.3 | 0.036 | 3.83 |
| 100 | 0.4 | 0.048 | 4.38 |
| 125 | 0.5 | 0.057 | 4.74 |
| 150 | 0.6 | 0.066 | 5.12 |

(average temperature with a fluctuation of $\pm$ 2°C). For seven days the door specimen was under the differential temperature. After 7 days, the measured air flow ($Q_M$) out from the interior chamber was found to be 3.83 gr/sec for a differential pressure of 75 Pa (0.3 in. of water). Under these conditions the pressure in the interior chamber was measured to be 9 Pa above the atmospheric pressure.

## 5.3 THERMAL DEFORMATIONS

Right after the measurements in 5.2, thermal deformation measurements of bowing and warping were taken on the door specimen. These new deformations are illustrated in Figs. 5.2 and 5.3.

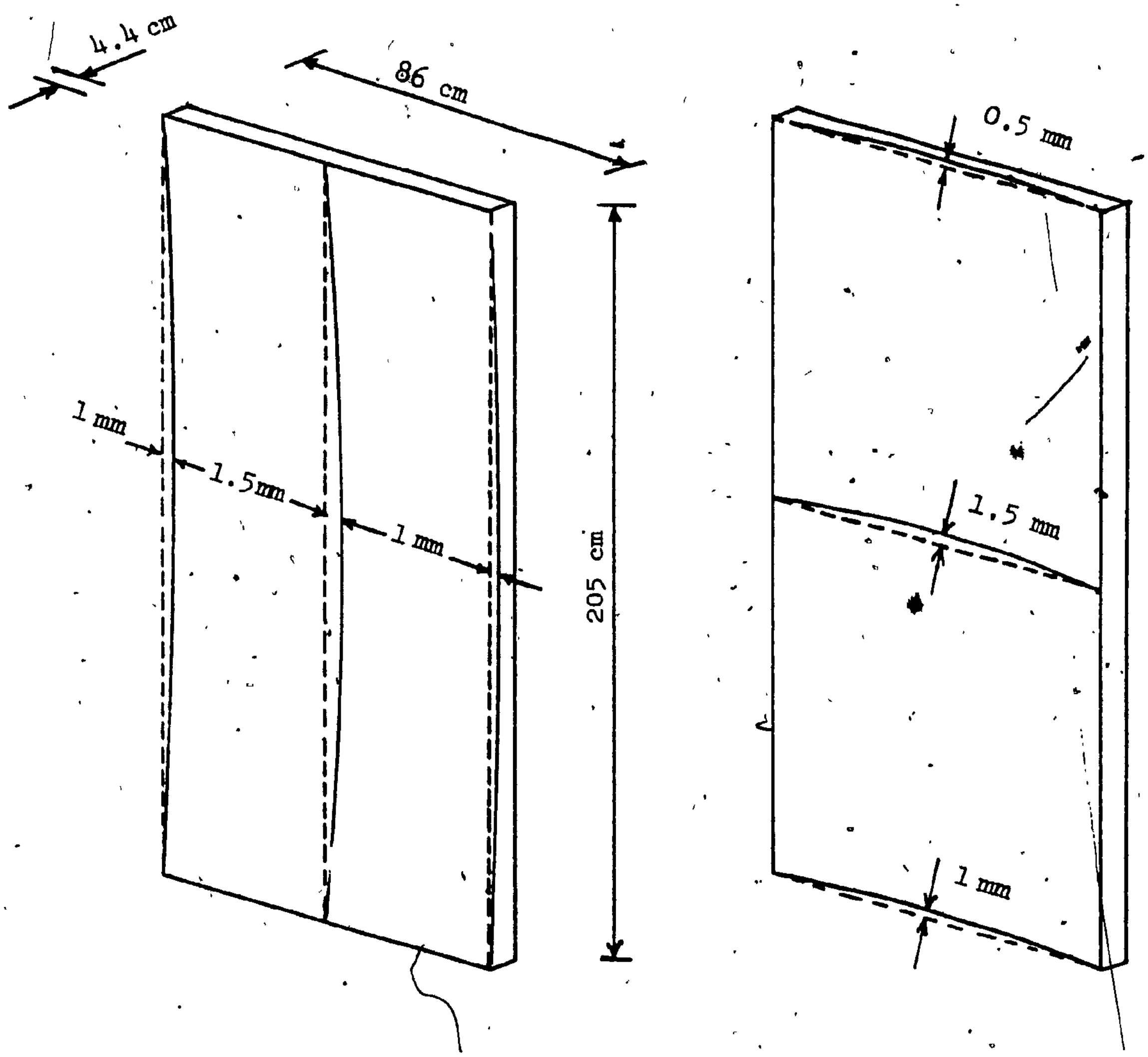


*Fig. 5.2 — Thermal Deformations (Bowing)*

A reduction of 1 mm of bowing was observed at the center of the door in the vertical direction and a reduction of 0.5 mm in the horizontal. (See Figures 4.2 and 5.2).

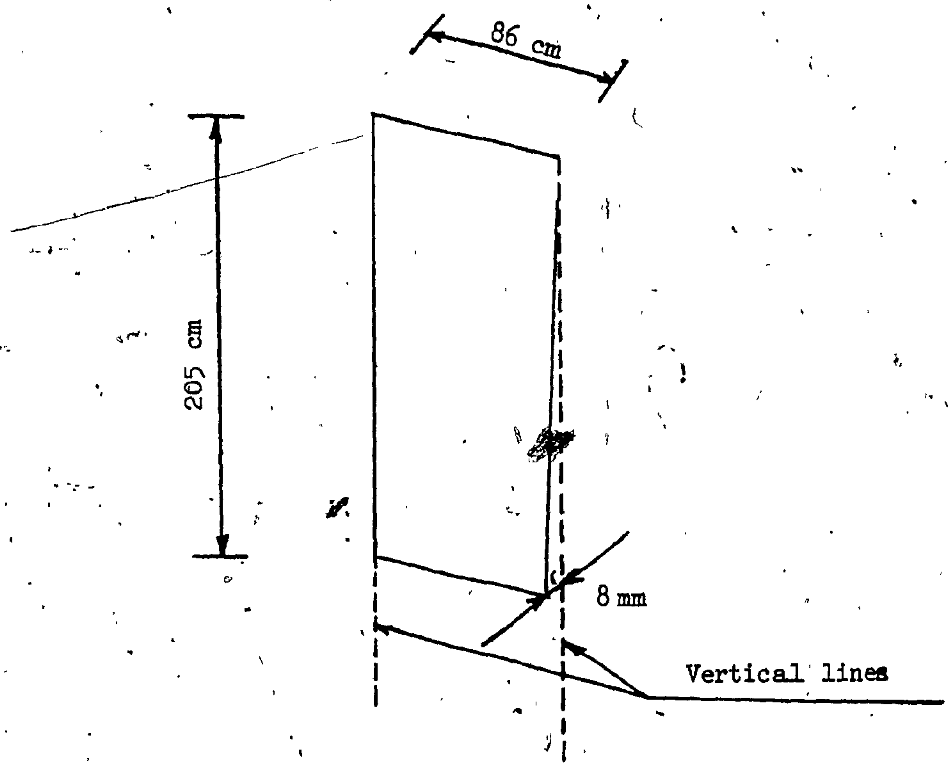


*Fig. 5.3 — Thermal Deformations.*

In addition, regarding warping, an increase of 6 mm was recorded. (See Figures 4.3 and 5.3).

# 6. ANALYSIS OF RESULTS

The measured air flow ($Q_M$) under isothermal conditions given in Section 5.1 added to the leakage ($Q_L$) gave the total air flow ($Q_T$) through the specimen for various pressure differentials. These total air flows were calculated by the aid of the following equations as illustrated in Section 3.

$$Q_L = 0.0054\ h \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6.1)$$

$$Q_T = Q_L + Q_M \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6.2)$$

In addition, the total air infiltration per unit length of the door perimeter was calculated for each pressure difference. These results are illustrated in the last column of Table 6.1. Furthermore, Fig. 6.1 illustrates the variation of total air flow per unit length of door perimeter with respect to pressure difference (h), across the specimen.

Under differential pressure of 75 Pa and differential temperature with -16 $\pm 1^{0}$C in the exterior chamber and 24 $\pm$ $2^{0}$C in the interior) the total air flow was found to be 7.48 x $10^{-4}$ ($m^3$/sec)/m, which is 25% higher than in the isothermal condition case. (See Table 6.1).

In addition, from the observations (sections 4 and 5.3) on deformations (bowing and warping), it is concluded that after the door

Table 6.1 — TOTAL AIR FLOW CALCULATIONS

| | ΔP in (Pascals) | $Q_M \times 10^{-3}$ in ($m^3$/sec) | $Q_L \times 10^{-6}$ in ($m^3$/sec) | $Q_T^* \times 10^{-3}$ in ($m^3$/sec) | $(Q_T^†/L) \times 10^{-4}$ in ($m^3$/sec)/m |
|---|---|---|---|---|---|
| Isothermal | 25 | 2.04 | 1.80 | 2.04 | 3.50 |
| | 50 | 2.76 | 3.66 | 2.76 | 4.76 |
| | 75 | 3.27 | 5.50 | 3.28 | 5.64 |
| | 100 | 3.74 | 7.34 | 3.75 | 6.46 |
| | 125 | 4.05 | 8.70 | 4.06 | 6.99 |
| | 150 | 4.39 | 10.10 | 4.39 | 7.55 |
| Differential Temperature | 75 | 4.34 | 10.00 | 4.35 | 7.48 |

* $Q_T = Q_M + Q_L$

† L = Length of door perimeter = 5.809 m

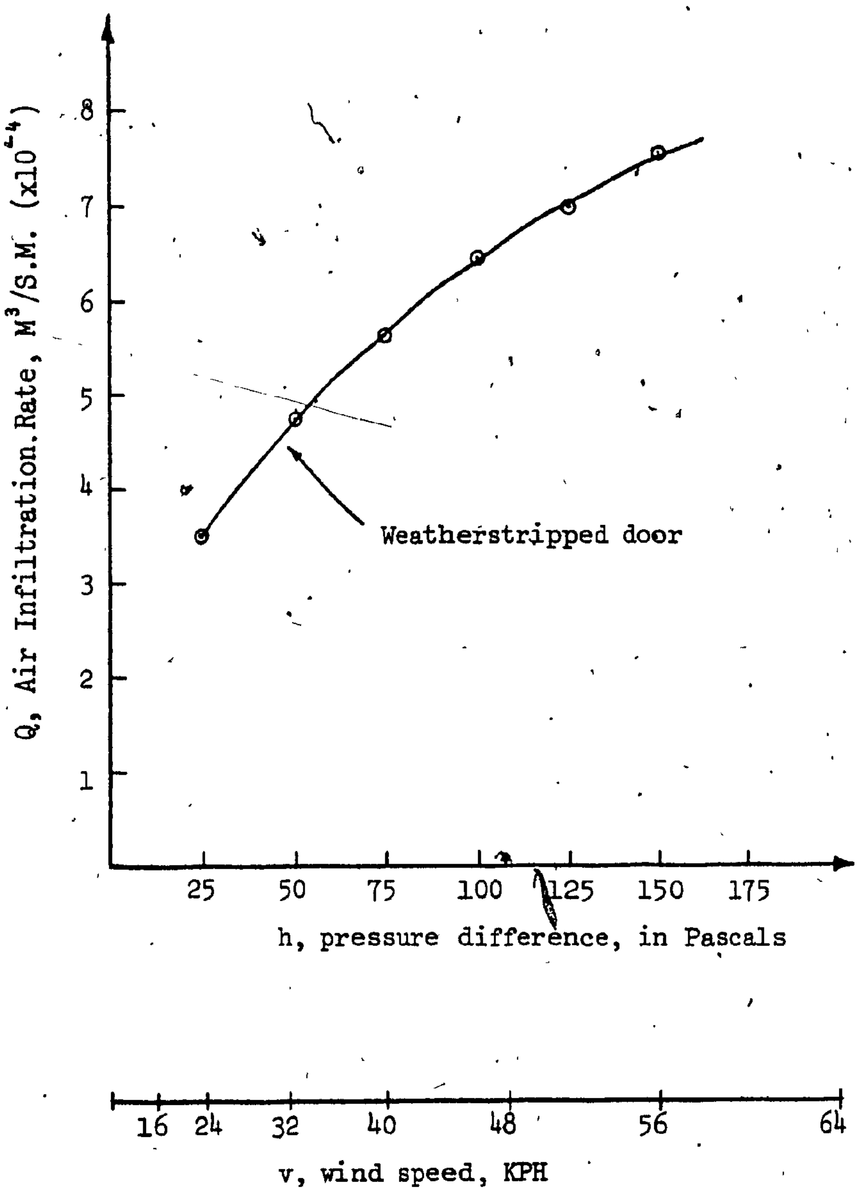


*Fig. 6.1 — Door Air Infiltration Characteristics.*

specimen has been exposed to differential temperature for 7 days, the bowing was reduced whereas its warping was increased (see Figs. 4.2, 4.3, 5.2 and 5.3). In addition, twenty-four hours from the time the refrigeration system was set on, the temperature on the interior surface of the door specimen was recorded to be 22$^{o}$C.

# 7. CONCLUSIONS AND COMMENTS

There is no doubt that air leakage affects the building performance several ways. Heat load and building relative humidity are affected by overall air infiltration and ventilation rates.

Since doors represent one of the major sources of air leakage much consideration must be given to their design and construction. The designer before undertaking the task to design door frames and especially their tolerances, should be aware of the behaviour of door elements under pressure and temperature differentials. That is to say, for certain gaps around doors, with or without weatherstripping, and for various wind speeds the quantity of air infiltration should be known. With this knowledge, the designer can design accordingly for heating and air conditioning loading. But, if the air leakage is above acceptable levels, the air tightness of the door frames could be increased for a better overall building performance.

For satisfactory design of door frames with respect to air leakage, tests have been performed in the past on doors. Window, elevator shaft walls, stair shaft walls, etc. To my knowledge, those tests were under isothermal conditions. The present research on door frames extends the tests to differential temperatures as well.

The method adopted in Section 3 for the estimation of the extraneous air leakage ($Q_L$) out from the interior chamber differs from that mentioned in ASTM E283-73.[1] In the present Method for extraneous air leakage, $Q_L$ could be measured by the aid of a manometer only (see equation 3.11, section 3) whereas in the ASTM E283-73 by the aid of a flowmeter. In case of a compressible flow (with variable air density), measurements of air density through the specimen and through the flowmeter are required in ASTM E283-73 method. With the present method, direct measurements of air density are not required. The measured air flow ($Q_M$) out from the interior chamber is measured in gr/sec and converted to $m^3$/sec with relative humidity 50% and Temperature 24$^oC$.

The air infiltration rate Q, as illustrated in Fig. 6.1, was very low compared to 0.02 $m^2$/s for 2 mm gaps which means that the weather-stripping was effective. In addition, in the test under differential pressure and temperature the total air infiltration rate was higher than the corresponding (for pressure difference of 75 Pa) rate in the isothermal case. Another observation which is of importance to be mentioned is that after the door has been exposed to differential temperature for 7 days, its bowing has been reduced whereas its warping has been increased.

Finally, it is hoped that the present testing method for air infiltration and thermal behaviour will lead to a better understanding of the behaviour of door or window frames under differential pressure and temperature and consequently, to a better design for the achievement of satisfactory performance of the overall building structure.

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