COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS
OF SMOKE CONTROL IN TALL BUILDINGS

VOLUME ONE

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To

MOTHER
COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN BUILDINGS

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ABSTRACT

The work described in this thesis deals with the effects of wind building leakage characteristics on the internal pressure distribution in tall buildings. The effects of temperature difference (stack effect) and mechanical ventilation have been ignored generally to simplify the problem.

The work consists of three major parts: wind tunnel model studies, full pressure measurements and computer analysis of both the model and full scale buildings.

A 32-cell model building of five storeys high was built for the wind tunnel. A programme of pressure measurements (internal and external) in the wind tunnel has been carried out with different wind orientations and with varying external and internal leakage characteristics of the model. Fire pressure in a room was simulated by creating a pressure difference of 10.0N/m² across the room door in some of the measurements. The results are described in Chapters 2 and 3 (volume I).

Chapter 2 deals with the effect of external leakage on internal pressures. It has been concluded that provided the internal door leakage is small and uniform, the internal pressures are independent of external leakage, within the range investigated. Under these conditions the internal pressures are a direct reflection of prevailing outside wing induced pressures. For smoke control purposes the pressure differences across the shaft door are important.
and are measured at each level.

In chapter 3, the pressure measurements for varying internal leakage are presented. Inside a building the leakage change is associated with the opening and closing of doors. Results for three door opening combinations are described, for floors 2 and 4.

Fire pressure simulation results are presented in Chapter 4. The internal measurements of pressures were made on floors 2 and 4 varying wind directions. The fire pressure was simulated in room 6 on the floor.

The full scale measurements were carried out on a ten storey building belonging to the University (Darwin Building). The measurements include both the wind and stack effect. The results are presented in Chapter 5.

The leakage characteristics of the Darwin Building were obtained by measuring the gaps around each of the doors and windows on every floor. These measurements were used for the computer analysis. The leakage characteristics of the model were also based on these measurements. The computer prediction for both the cases (full scale and model) are presented in Chapter 6. These results show good comparisons with the measurements, considering the difficulties with the pressure measurements and assumption made in the computer program.
Volume II of the thesis contains full discussion of the model measurement results for all configurations, including those with and without the fire pressure simulation. The content of Volume II is the extension of Chapter 3 and 4 of Volume I.

Baldev S Kandola

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ACKNOWLEDGEMENTS:

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The author values the discussions with the staff of Fire Research Station over the past years.

Last but not least Mrs Jean Mills and Miss Maureen Gray are thanked for typing the script.

BALDEV S. KANDOLA

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O the Winds' chariot! What power what glory!
Crashing it goes with the voice of thunder.
It touches heaven and turns its face red;
As it moves it gathers all the dust of the Earth.

- Rg Veda

The Wind led the blazing fire to wander within the buildings and residences;
With the contact of the breeze, the fire gained great velocity.

- Ramayana
COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN TALL BUILDINGS

CHAPTER ONE

GENERAL INTRODUCTION
CHAPTER 1

COMPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN TALL BUILDINGS.

1.0 General Introduction

The study of the influences of wind on buildings and their surroundings have received a great deal of attention from the Building Aerodynamists, over the past couple of decades (1.1, 1.2, 1.3, 1.5). A vast amount of data has been collected for all possible building shapes subjected to various wind conditions, both from wind tunnel and full scale studies (1.6, 1.7, 1.8, 1.9, 1.10). It has been found that wind tunnel simulation of full scale buildings provide a very good guide to the pressures to be expected on real buildings (1.11, 1.12, 1.13, 1.14, 1.15, 1.16).

The phenomenon of internal air flows in buildings, caused by the external wind, has not been investigated fully (1.18). Apart from the outside wind, the internal flows are also influenced by the internal temperature distribution. The steady state flow pattern can change dramatically due to thermal inequilibrium caused by the sudden changes in temperature (e.g. by a fire) in any part of the building. Any smoke or toxic gases produced by the fire flow away from it and when cooled sufficiently are taken to other parts of the buildings, by the pre-existing flows.
The problem is more serious in the case of tall buildings, where once smoke gets into the vertical shafts, it can spread very quickly to other floors. Since vertical shafts are the major means of escape in fire situations, they must be kept smoke free.

1.1 Fire and Tall Buildings

Fire in tall buildings present many problems not encountered in other small buildings. Evacuation of the occupants and fire fighting are among the major problems.

The building heights are such that the fire brigade rescue ladders are of no use. At the most these ladders are only capable of reaching up to heights of six or seven floors. As modern high rise buildings are as high as 100 storeys, some other method of rescue is required.

The tragic incidences of fires (1.22, 1.23, 1.24) in tall buildings over the past years, especially in South America, show how the safety aspects have been overlooked in the design feature. In the United Kingdom the Fire and Loss statistics (Published Annually, BRE) show that in 1971, for example, over 50% of the fatalities in fires were attributed directly to the inhalation of smoke and toxic gases. A more recent survey (1.25) shows that casualties associated with furniture and furnishings about 70% of the fatalities were caused by smoke and toxic gases. The apparent increase with death rate is attributable to the increased use of synthetic materials for domestic purposes.
1.2 Production and Nature of Smoke and Toxic gases:

The amount of smoke produced in a fire depends on:

(i) The nature of combustible material

(ii) Conditions of burning.

A number of methods are available for measuring the smoke production properties of materials (1.28). The material under test is subjected to heating or burning and the smoke produced measured. The results for several materials obtained from small scale experiments are summarized in reference (1.27). A calculation method to assess the smoke hazard of domestic furnishings is developed by Robertson (1.26).

In real fires, smoke is produced from the burning of a combination of several materials, in which case the smoke generated may be different from when these materials burn individually. The results for the tests carried out on such materials can be found in references (1.30 and 1.31).

It has been found that almost all combustible materials used in buildings are based on element carbon. When these materials burn, poisonous gases such as Carbon monoxide (CO) and Carbon dioxide (CO$_2$) are produced with high concentration. Measurements on experimental compartment fires (1.32) show that the concentration of CO is more than 10%. An exposure to this level of concentration can cause death in a very short time.
In real fire situations, the effectiveness of a smoke control system depends on the amount of smoke produced, at least in the initial stages of fire. It is necessary, therefore, for a complete analysis of the smoke control problem to assess the amount of smoke production of a compartment when on fire.

1.3 Evacuation Time:

Any smoke control method installed in a building must ensure that no smoke gets into (or a certain level of concentration is not exceeded) the escape routes from the moment a fire is detected until all the occupants are in a place of safety. This time period or the Evacuation Time, depends on many factors (1.34).

For a given building it is

(i) proportional to the total number of occupants.

(ii) inversely proportional to the width of the escape routes.

For average healthy occupants, the evacuation time increases with the building height. For other buildings where the occupants require assistance (such as hospitals or old people's homes) the evacuation time will be higher. Apart from these factors people's behaviour under stress is also important— an organised evacuation can considerably decrease the time. The measurements (1.34) have shown that a flow rate of 1 person per metre width can avoid panic per second.
1.4 Mechanism of Smoke Movement Within Tall Buildings.

A building is, essentially, an enclosure designed to maintain a different environment from that outside. For example, in winter conditions, the internal temperature is maintained at a higher value than the surroundings. These buildings are ventilated naturally (i.e. high window leakage) or mechanically (i.e. no window leakage). Such buildings present different problems under fire situations.

When fire occurs in a building the spread of smoke is influenced by:

(i) Stack Effect

(ii) Wind Effect

(iii) Fire

(iv) Mechanical Ventilation

(i) The Stack effect in tall buildings.

Stack effect is the name given to a flow of air resulting from the difference in external and internal temperature. If, for example, the internal temperature is higher than the external, the inside hot air of low density rises up the building and is replaced by the cold air of high density flowing from the outside through lower levels. At some height above the ground level there exists a plane where internal and external pressures are the same and no flow results in or out of the building. This plane is usually referred to as the neutral pressure plane. The position of this plane depends on the leakage characteristics of the building as well as the internal and external temperatures. (1.35, 1.36, 1.37, 1.38, 1.39).
Fig 1.4.1: Stack effect in a tall building.

Under such circumstances fire occurring below the neutral pressure plane can result in smoke spreading to other floors above the plane. To prevent this from happening, the shaft pressure is raised (shaft pressurisation) so that it is higher than the pressure on the fire floor (1.40, 1.41, 1.45, 1.48).

A simple mathematical analysis of stack effect in a shaft is given by McGuire and Tamura (1.46). From this analysis the height of the neutral plane is given by

\[ \frac{H_T}{H_B} = \left( \frac{T_1}{T_o} \right)^{\frac{1}{2}} \]  

...1.41

where \( H_T \) = height of top of shaft above neutral plane.

\( H_B \) = height of neutral plane above bottom of shaft.

\( T_1 \) = average inside temperature.

\( T_o \) = average outside temperature.
The analysis assumes that the shaft leakage is uniform.

(ii) **Wind Effect:**

Apart from the stack effect, outside wind is another major factor which influences the internal flow pattern within a building.

Buildings act as bluff bodies placed in the terrestrial turbulent boundary layer (1.13, 1.14, 1.21). If wind flows normal to one side of the building, that side is subjected to positive pressures (i.e. higher than the atmospheric pressure) while other three sides together with the roof experience negative pressures (i.e. lower than the atmospheric pressure).

![Wind-induced Pressure Distribution](image)

Figure 1.4.2: Wind Induced pressure distribution:

Under such a pressure distribution, air flows into the building through the leakage paths on the windward side (i.e. side with positive pressures) and leaves the building through the leakage paths on other sides. Since the outside wind speed and direction vary considerably, spatially as well as temporally, the internal
flow pattern can be very complex. Any fire occurring in a room with window openings to the windward side can result in smoke spreading to other parts of the building. In real building wind and stack effects are present at the same time resulting in a very complicated internal flow pattern.

The wind induced pressure distribution on building surface is usually expressed in terms of a pressure coefficient defined as.

\[ C_{p_o} = \frac{P-P_0}{\frac{1}{2} \rho V_H^2} \]  

...1.4.2

where \( P \) = total pressure at a point  
\( P_0 \) = static pressure at that point  
\( V_H \) = wind speed at the building height  
\( \rho \) = air density.

(iii) Fire:

When fire occurs in a room or compartment, its temperature rises to a value much higher than the surroundings (i.e. rest of the building average temp). This gives rise to very high pressure differences across the leakage paths into the room (such as doors and windows). Neutral pressure planes exist for these doors and windows, resulting in cold air flowing into the fire room below the plane and hot smoke flowing out above the neutral pressure plane.
Figure 1.4.3. Flow pattern in a fire room

If the room door leads into a corridor, the smoke flowing out at the top of the door forms a hot layer under the ceiling in the corridor, with smoke moving towards the shaft and cold air beneath the layer moving towards the fire room. By the time smoke gets to the shaft it is cooled sufficiently to be carried to other parts of the building by pre-existing flows.

(iv) Mechanical Ventilation:

In the normal operation of a ventilation system is to inject and extract air from the various parts of the building. In fire situations this can cause smoke to spread very quickly to other parts. It is therefore a normal practice to shut off all mechanical ventilation systems when a fire is detected.

1.5 Building Leakage Characteristics:

For buildings relying on natural ventilation, the only source of
outside fresh air is through the leakage paths in the outside walls (such as doors and windows). It is also through these leakages that the great amount of heat loss occurs. To achieve the desired conditions in a building it is important to know its leakage characteristics. Apart from that, the internal pressure distribution is also a function of the leakage characteristics, which is important for the smoke control purposes.

To assess the total building leakage, is not an easy task in view of the sizes involved. One way of overcoming this problem is to estimate the leakage through major components.

**Window Leakage:**

In a building the window leakage can vary considerably due to the opening and closing of these windows. Several methods are available to test the windows under laboratory conditions (1.54, 1.55, 1.67, 1.58, 1.60, 1.61). In these tests windows are subjected to various pressure differences, when closed, and the infiltration rate measured. More recently a European standard method has been developed for air permeability test of windows (1.57).

For crack around closed windows, the following relationship seems to hold for the mass flow rate and the pressure difference.

\[ M = \sqrt{\frac{\Delta P}{R_c}} \]

...1.5.1
where \( M \) = mass flow rate

\[ \Delta P = \text{pressure difference across the crack} \]

\[ R_f = \text{flow resistance of the opening} \]

\[ = \frac{1}{2\rho (C_d A_e)^2} \]

where \( A_e \) = area of the crack

\( C_d \) = flow coefficient (0.65)

\( \rho \) = air density

It has been found that for tall buildings the total window leakage area does not amount to more than about 2% of the wall area.

**Leakage Through Walls:**

Various wall constructions (such as plastered and unplastered brick walls) can be tested in the laboratory (1.69, 1.70) to measure their leakage. It has been found (ASHRAE Handbook of Fundamental Chapter 25) that the leakage through walls is very small compared with that through the windows. Similar Canadian Studies can be found in references (1.7., 1.72, 1.73, 1.74).

**Door Leakage:**

The cracks around doors differ from the types of doors. The measurements have shown that the cracks around doors do not exceed about 2% of the door area. This has been confirmed by the measurements on Darwin Building, described in this thesis. Relationship 1.51. holds for doors as well.
1.6 Force Required to open a door:

If shaft pressurisations is to be used for smoke control purposes, the pressure difference must not exceed to make door opening impossible. Studies (1.45) have shown that a normal person can exert a force of 90N to open a door. If 45N is allowed for any self-closing mechanism, the available force is about 45N. For an average door this is equivalent to a pressure difference of 50N/m². Any pressurisation system then must not create pressure difference higher than this value anywhere within the building. To ensure this, a knowledge of the pressure distribution in a building is required before the pressurisation is switched on.

It is not practicable to make pressure measurements on every building where a pressurisation system may be installed.

Hence wind tunnel studies and/or a calculation method is necessary to predict the pressure distribution in a building under all possible environmental conditions. A 32-cell model used for wind tunnel studies is described below.
1.7 Description of Model:

To investigate the effects of wind on the internal pressure distribution, a fire storey model was constructed with six rooms on each floor. All rooms have their door openings to a common corridor (C) which is connected to the shaft(s) by a similar door. The floor plan is shown in figure 1.7.1.

![Diagram of the five-storey model](image-url)
View from Duct

View from Top

Plate 1 Wind tunnel Model
The overall dimensions are 425 x 425 x 505 mm high. A vertical duct (D) contains measuring tubes and input ducts. These are required for fire pressure simulation and corridor (C) or shaft(s) pressurisation. Rooms on each floor have their window openings to side T and R and that way only these two walls contain leakages. The other two walls are sealed effectively but do contain pressure taps for external pressure measurements and sealed removable panels for the necessary manipulation of internal doors (see plate 1).

All rooms are of the same volume. 'Doors' to the corridor contain holes to represent defined leakage areas and each door is sealed to the corridor wall by a tubular seal (PVC) and kept in place by a turnbuckle arrangement. All doors are removable. 'Windows' to each room are represented by removable perspex panels, each with a number of holes to simulate representative leakage areas. Walls T and R contained leakage areas; all other walls, floor and roof surfaces were regarded as impermeable.

Door and Window Leakages:

As shown in the earlier section, in real buildings the external total window leakage represents about 1.5-2.1% of the wall area.

For each of the rooms, as well as the shaft on side T, four holes each of diameter 8.0 mm were made so that when all holes were open the total leakage area added up to 2.0% of the wall T area.
The reasons for having four holes instead of one were:

(i) to ensure flow similarity through the holes

(ii) to vary the total leakage easily by taping up various holes.

Since the duct is internally sealed from the rest of the building, no holes were made in the duct area. The leakage holes on side R were made so that the total leakage area was 2% of side R minus duct area. Again four holes each of diameter 9.15 mm were drilled. This way when all holes were open on both sides T and R, the leakage areas were the same.

From the full scale measurements on Darwin Building it was evident that the total crack area around any door was not more than 1.5% of the door area. Three holes each of diameter 3.6 mm were drilled on each door.

The combination of side T, R and Door leakages are expressed in the form of a table.

<table>
<thead>
<tr>
<th>T</th>
<th>D</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>m</td>
<td>η</td>
</tr>
</tbody>
</table>

where λ is the percentage leakage of side T

m is the percentage leakage of Door D

η is the percentage leakage of side R
A parameter called the leakage Ratio, $R_L$, was defined to combine T and R leakage.

$$R_L = \frac{\text{Side T leakage area}}{\text{side R leakage area}}$$

Wind incidence $\alpha$ is defined as the angle between the wind direction and normal to side T.

Flow Simularity and Tunnel Blockage:

The usual definition of Reynolds's number is written as:

$$Re = \frac{Vd}{\nu}$$ …1.7.1

where $V$ is the air velocity (m/s)

$d$ - some characteristic length (m)

$\nu$ - Kinematic viscosity of air = $\frac{\mu}{\rho}$ (m$^2$/s)

For air at 15° and at normal atmospheric pressure

$$\nu = 1.46 \times 10^{-5} \text{ m}^2/\text{s}$$
Mass rate of flow through small leakage is given by

\[ M = \frac{\Delta P}{\sqrt{R}} \]  \quad \ldots 1.7.2

where \( R \) is the flow resistance given by

\[ R = \frac{1}{2\rho (C_dA_e)^2} \]  \quad \ldots 1.7.3

where \( \Delta p \) = pressure difference across the opening
\( A_e \) = area of opening
\( C_d \) = discharge coefficient (=0.65)

\[ M = \sqrt{2\rho \Delta P \cdot C_d A_e} \]  \quad \ldots 1.7.4

or the volume flow rate, \( Q \) is given by

\[ Q = \frac{M}{\rho} = \sqrt{\frac{2\Delta P}{\rho} \cdot C_d A_e} \]  \quad \ldots 1.7.5

If the mean flow velocity through the crack is \( V \) then the volume flow rate can also be written as:

\[ Q = A_e V \]  \quad \ldots 1.7.6
\[ V = C_d \frac{2\Delta P}{\rho} \]  \quad \ldots 1.7.7

Equation 1.7.1 becomes

\[ Re = C_d \frac{2\Delta P}{\rho} \frac{d}{y} \]  \quad \ldots 1.7.8
By definition

$$\Delta p = \frac{1}{2} \rho \gamma H \Delta C_p$$

$$= q \cdot \Delta C_p$$

$$Re = \frac{C_d d}{\gamma} \sqrt{\frac{2q \Delta C_p}{\rho}}$$

Generally for cracks around windows equivalent diameter is used in defining Re

$$i.e. \quad d_e = 4 \frac{\gamma}{h}$$

where $\gamma$ is the hydraulic radius defined as

$$\gamma = \frac{Cross-sectional \ area \ of \ opening}{perimeter \ length \ of \ opening}$$

for a long thin crack of width c, and length L

$$\gamma = \frac{cL}{2(c+L)}$$

then $Re = \frac{V}{\gamma} \frac{4cL}{2(c+L)}$

It has been found that for each of the leakage holes in the model $Re < 1000$. From the full scale measurements made on the Darwin Building and in reference (1.75), it was found that $Re$ was less than 1000.
**Tunnel Blockage Effect**

The model area when at $\alpha=0^\circ$ is about 12% of the tunnel working section area; and this figure at $\alpha=45^\circ$ is about 17%.

Earlier investigations have shown (1.79, 1.75) that for closed working section tunnels, corrections to measurements are required due to blockage effects if the model area is greater than about 10% of the tunnel cross-sectional area. This limit does not hold for open jet tunnels (1.76, 1.77, 1.78, 1.79, 1.80, 1.81), where it is much higher than this. Accordingly no such corrections are made in the present results.

**1.8 Program of Measurements**

1. Measurements were made to investigate the effect of outside leakage and internal pressures. Internal pressures (shaft corridor and Rooms) on all floors with varying $R_L$, constant door leakage and with $\alpha=0^\circ$, 45°, 90°.

2. Effect of Internal and External leakages.

Two external leakage configurations were investigated.

<table>
<thead>
<tr>
<th>Leakage (a)</th>
<th>Leakage (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T D R</td>
<td>T D R</td>
</tr>
<tr>
<td>1.5 1.5 1.5</td>
<td>1.5* 1.5 1.5</td>
</tr>
</tbody>
</table>
Fig 1.6.1: Definition of Leakages (a) and (b)
Leakage (a) is with

1.5% Side T leakage (i.e. three holes open)
1.5% Door Leakage  (i.e. three holes open)
1.5% Side R Leakage (i.e. three holes open)

Leakage (b)

1.5%* means that all holes in the shaft are closed except for one on floor 1 which represents the main entrance door leakage. Other leakages are the same as for Leakage (a).

See Also Fig. 1.8.1.

For these leakage configurations (a) and (b) pressure measurements were made on floors 2 and 4 at constant $R_L$ for various internal door opening configurations. This was repeated for wind incidences $0^\circ \leq \alpha \leq 315^\circ$ at steps of $45^\circ$.

3. The above measurements were repeated with a fire pressure in room 6, on the floor concerned.

The internal door opening configurations were:

(i) All internal doors closed (all closed)
(ii) Shaft door opened on the floor concerned ('s' open)
(iii) Room 6 door opened on the floor concerned ('6' open)
(iv) Shaft and Room 6 doors opened together on the floor concerned ('s'+ '6') open. See fig 1.8.2.
Fig 1.8.2: Program of Model Pressure Measurements.
1.9 Wind Tunnel Characteristics:

The pressure measurements were made in the low speed open-jet type industrial wind tunnel at the Department of Civil Engineering and Building Science, University of Edinburgh. The open jet was 1.07m by 1.52m with a working table of 1.75m by 1.53m. A uniform section 1.75m was added to the outlet of the original tunnel to accommodate the elliptical wedge turbulence generators - They were used to produce the same wind turbulence as found in the real atmosphere. The General layout is shown in fig 1.9.1.

Velocity Profile and Turbulence Intensity:

The measurements of wind tunnel velocity profile and turbulence intensity were made at six different positions on the working table in the absence of the model. Positions A, A', A and A were the four corners of the model, A the centre and A the mid-position of A A'.

The velocity profile at position A is shown in fig 1.9.2, which shows that it approximates to a power law profile of exponent 0.32.
Fig 1.9.1 Wind Tunnel and Model Layout. units: mm
\[
\frac{V}{V_{\text{max}}} = \left(\frac{Z}{Z_{\text{max}}}\right)^{0.32}
\]

Fig 1.9.2: Wind Tunnel Velocity Profile, Position A5.
Fig 1.9.3: Wind Tunnel Turbulence Intensity
The variation of turbulence intensity of positions $A_1$, $A_2$, $A_3$, $A_4$ and $A_5$ is shown in fig 1.93. These measurements show that the turbulence intensity profiles do not vary a great deal and are very similar to the atmospheric values (1.82, 1.83, 1.84).

1.10 Fire Simulation:

Because the model could not be subjected to very high temperatures the fire could not be simulated by increasing the temperature of one of the rooms. Instead, as some of the earlier studies on the nature of fire in a compartment have shown, (see the Introduction to Chapter 4) the designated room pressure was raised so as to create a pressure difference of $10N/m^2$ across the door under calm conditions.

1.11 Full Scale Measurements:

In order to compare the wind tunnel results with those of real buildings, measurements were also made on a ten storey building (Darwin Building) belonging to the University of Edinburgh (see Plate 2). Because of the complexity of the building internal layout, considerably practical problems were encountered. The full description and discussion of Results appear in Chapter 5.

1.12 The Computer Program:

The computer program used for the prediction of internal pressure distribution, is a modified version of the 'Smoke Movement' program
View from NW

Measuring apparatus

Plate 2: Darwin Building
developed by SCICON for the Fire Research Station. The analysis of the wind tunnel and full scale results show a good agreement with the computer prediction in view of the simplifying assumptions made in the program. Possible improvements to the program are suggested in Chapter 7. The analysis of results is shown in Chapter 6.


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CHAPTER TWO

THE EFFECT OF OUTSIDE LEAKAGE ON INTERNAL PRESSURES AT VARYING WIND DIRECTIONS.
CHAPTER 2

EFFECT OF OUTSIDE LEAKAGE ON INTERNAL PRESSURES AT VARYING WIND DIRECTIONS.

2.0 Introduction

In real buildings many factors influence the distribution of internal pressures. By far the most important are the wind and temperature effects. In the wind tunnel experiments the latter is most difficult to simulate, hence it has been ignored to simplify the present problem.

In leaky buildings, the internal pressures are highly dependent on the wind induced pressure distribution on the periphery of the building. This distribution is a function of the type of wind as well as the shape and size of the building itself. A vast amount of data has been collected, both from the full-scale and wind tunnel experiments in many countries, as has been discussed earlier (page 7). In all these experiments, the irregularities of the walls have been ignored. Hardly any work exists which takes these factors into account.

Windows are of considerable size in all tall buildings. The walls therefore act as permeable surfaces which allow the air to continue to flow into the building at varying velocities, instead of coming to a stop or flowing along the surface in various directions. These windows act as "sinks" distributed evenly on the wall surface, which modify the velocity distribution on the wall. This may result in
a different outside pressure distribution.

To investigate the effect of leakage on pressure distribution, a cubical model was constructed with wall leakage variations between 0.5 per cent and 2 per cent of the wall area, and tested in the wind tunnel. The model details and the results are described in Ref 2.

This study showed that provided the leakage does not exceed the 2 per cent value, the outside pressures remain unchanged, i.e. the walls can be regarded as non-permeable. Whereas the external pressures are independent of the leakage, the internal pressures are highly dependent on it. (See Appendix A, also Ref 2, 1 and 5).

The present 32-cell model is much more complex than any of the earlier models investigated, which consisted of very simple interior partitions. The models used in Ref 5 were simply divided into two open floors, i.e. no partitions on individual floors. The present model, as described earlier, consisted of six rooms as well as a corridor and shaft on each of the five floors.

In such a model there are a large number of internal and external leakage combinations, resulting from the opening and closing of 'doors' and 'windows'. This change in the leakage characteristics of the model can considerably modify the internal pressure distribution. Matters are made still more complex by the changing wind direction. This means that for any possible leakage combination, there are a
large number of possible wind directions. Evidently, to explore all these possibilities is neither feasible nor a wise thing to undertake. In such circumstances, what can be done is to find out the extreme limits of the problem. In other words, we investigate the lowest and highest range of internal and external pressures caused by several wind directions. By fixing one or more of the parameters, the influence of the others can be investigated.

The major parameters are:-

(i) External leakage
(ii) Internal leakage
(iii) Wind direction.

(i) Effect of external leakage: This is investigated by fixing the other two parameters. The internal leakage is kept constant, by closing all the doors, with only having leakage equivalent to the crack round them. For one particular wind direction the external leakage can be changed and its effect on internal pressures measured.

The changing of outside leakage also presents problems. Two opposite walls (T and R) are given varying leakages from 0.5 per cent to 2 per cent of the wall area. It may be that in real buildings the outside leakage varies from floor to floor. This again leads us into very large number of leakage combinations on the two walls and the problem becomes even more complex if leakage on all four walls is considered.
### Table 2.1: Outside Leakage Combinations

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To overcome this difficulty in the present studies, the same leakage is assigned to all windows on a wall and a leakage ratio parameter ($R_L$) is defined as follows (see Appendix A).

$$R_L = \frac{A_T}{A_R}$$

where $A_T$ = total window leakage area on wall T

$A_R$ = total window leakage area on wall R.

Pressure measurements were made in:-

(a) All rooms
(b) Corridor, and
(c) Shaft

on each floor level for sixteen different leakage combinations ($0.25 < R_L < 4$) shown in Table 2.1. These measurements were repeated for wind angles, $\alpha = 0^\circ, 45^\circ$ and $90^\circ$. To correlate these measurements to the outside wall pressures, outside pressure measurements were also made for the above wind incidences on walls T and R.
2.1 Discussion of Results

2.1.1 Wind Incidence, $\alpha = 0^\circ$

2.1.1.1 External pressures
The mean pressures vary quite considerably from point to point on all walls. The results obtained in this case are comparable to other published works (4, 6, 7, 8, 10, 13). For zero wind incidence the flow is normal to wall T. On this wall, then, the highest pressures occur in the vicinity of the stagnation point which itself occurs at about the 4/5th height of the model (i.e. at the 4th level) (See Fig 2.2a). The pressure increases up to that height and starts to decrease towards the roof. The lateral variation from the stagnation point is also quite considerable.

Wall R on the other hand is in the wake region of the building and experiences negative pressures (suction). These negative pressures are remarkably uniform in comparison with side T. The size of shed vortices varies with height which results in slight pressure variations (see Fig 2.2(b)). From this Figure, it can be said that up to half the height (i.e. to 3rd floor) the value $C_{p_o} = -0.14$ is fairly uniform. On the upper half its value is about $C_{p_o} = -0.19$. However, for the whole surface, it will not be wrong to assume the value $C_{p_o} = -0.16$. In contrast, the same is not true about side R.
Outside Pressure Distribution ($C_{p_0}$)

$\alpha = 0$

Side $T$

Floor 5
Floor 4
Floor 3
Floor 2
Floor 1

(a)

(b)

Fig 2.2: Outside Pressure Distribution ($C_{p_0}$), $\alpha = 0^\circ$
2.1.1.2 Internal Pressures

The internal pressures are very much a function of the outside pressures, as well as the size of the relative leakages.

On the whole, air enters the building through the leakage holes in side T and leaves through those in side R. The internal pressures adjust themselves so as to make inflow equal outflow. This is also true of the partitions within the building, which results in a variation of pressures from one cell to another.

2.1.1.3 Corridor Pressures

The corridor is one volume on a floor which connects the shaft to the rooms. In this way, each floor is inter-connected by the shaft. Any drastic pressure changes occurring on one floor can influence the pressures on other floors.

On a floor, air enters the corridor through shaft door and through the doors of rooms 1, 2 and 3, which are at positive pressures, and it leaves through the doors of rooms 4, 5 and 6 which are at negative pressures. In this way the leakage through which air enters (four doors) is greater than that through which it leaves (three doors). Consequently, the corridor pressure is dominated by the positive pressures which results in the high pressure difference across rooms 4, 5 and 6 doors.

Because of the nature of outside flow on side T, and since the wind velocity is very small near the ground level, the magnitude of corridor pressure on floor 1 is the smallest (see Fig 2.3). Floor 4 is in the region of stagnation pressure height which causes the
Fig 2.3: Shaft and Corridor Pressures for Varying $R_L$, $\alpha = 0^\circ$. 
maximum corridor pressure on this floor. The pressure contours on wall T show that there is a pressure decrease towards the roof and the corridor pressure decreases accordingly.

Fig 2.3 also shows the variation of corridor pressures with the outside leakage ratio, $R_L$. It is clear that outside leakage ratio does not alter the corridor pressures significantly. At the most the maximum pressure coefficient difference is only about 0.05, for the range of leakage ratio shown. It will not be wrong to assume that at least the corridor pressures are independent of $R_L$.

2.1.1.4 Shaft Pressures

The shaft runs all along the height of the model with its leakage openings onto side T. Any flow from one floor to the other occurs only through the shaft, at least internally, even though under certain circumstances, air can also flow from one floor to the other externally.

The shaft is located on the extreme right hand side of side T (Fig 2.2(a)). From the pressure contours it is clear that the shaft is subjected to $C_{p_0}$ values ranging from about 0.3 to 0.7. Since it is a continuous volume all along the height, its mean pressure is within these two limits. Measurements on each floor level confirmed this.

Fig 2.3 shows that the shaft pressure is always higher than the corridor pressure and that for any particular leakage configuration it is the same on each floor level.
Except for the leakage ratio $R_L = 0.5$, the shaft pressure can be assumed to be independent of $R_L$ and its mean value is about $C_p = 0.55$. The drop in pressure for the $R_L = 0.5$ case is not so significant as the flow still occurs from shaft into corridor.

2.1.1.5 **Room Pressures**

The relative location of rooms on all floors is shown in Fig 2.2. Because the door leakages are much smaller than the window leakages, the respective room pressures are determined by the prevailing wind pressures on walls.

As rooms 1, 2 and 3 have their window openings on to side T, which has a complicated pressure pattern, their pressures vary from room to room as well as from floor to floor. This is not true for other rooms 4, 5 and 6 whose windows are exposed to side R, which has a very uniform pressure distribution.

The general feature of pressure on side T is that in the region of rooms 1 and 2, pressure is the highest on each floor and decreases towards the side walls. This means that the room 3 pressure is considerably lower than that in rooms 1 and 2. The relative magnitude of room pressures is shown in Fig 2.4. The increase in room pressures with height is a reflection of the outside pressure distribution on side T.

The pressures in rooms 4, 5 and 6 are fairly constant on all floors, as is evident from Fig 2.4. Slight variations are attributable to outside pressure variations on side R.
Fig 2.4: Variation of Room Pressures with Height, $\alpha = 0^\circ$. 
Fig 2.5: Room Pressure Variation with $R_L$, Floor 1, $\alpha = 0^\circ$. 
Fig 2.6: Room Pressure Variation with $R_L$, Floor 2, $\alpha = 0^\circ$. 
Fig 2.7: Room Pressure Variation with $R_L$, Floor 3, $\alpha = 0^\circ$. 
Fig 2.8: Room Pressure Variation with $R_L$, Floor 4, $\alpha = 0^\circ$. 
Fig 2.9: Room Pressure Variation with $R_L$, Floor 5, $\alpha = 0^\circ$. 

Legend:
- $+$ Room (1)
- $\times$ Room (2)
- $\bullet$ Room (3)
- $\circ$ Room (4)
- $\triangle$ Room (5)
- $\square$ Room (6)
The room pressure variations with leakage ratio, $R_L$, on each floor, are shown in Figs 2.5 to 2.9. Comparison of these figures shows that the highest pressures occur in rooms (1) and (2) on floors 4 and 5. These results also show that the room pressures are independent of $R_L$.

2.1.2 Wind Incidence, $\alpha = 45^\circ$

2.1.2.1 External Pressures

Measurements made for this wind incidence show that, as before, the outside pressure distribution on side T is quite complex, whereas on side R, it is uniform (see Fig 2.10). This time there is no stagnation point on side T, but the highest pressures still occur at about the same height (4th floor level). The pressure coefficient is highest at the top left hand corner of side T and it decreases due to air slowing down as it travels along the wall. From the figure it is clear that in the region of the shaft the outside pressure is lowest on the surface. The average value is about $C_p = 0.30$.

No general mathematical expression is possible to describe the outside pressure distribution exactly but it can be seen that for, at least, the central part of the wall, the variation with height can be taken to be constant (i.e. $C_{p0} = 0.40$).
Outside Pressure Distribution \( (C_{p_0}) \)

\[ \alpha = 45 \]
Side R, on the other hand, is still in the wake region. Because of the sharp edge of room 4 to the wind, size of eddy generated at this corner is larger than in the case of zero wind, which gives rise to a higher negative pressure on side R. Fig 2.10(b) shows that the average $C_{p_0}$ value is about -0.20.

2.1.2.2. Internal Pressures

From the relative outside pressure distribution on two of the leaky sides, T and R, it can be said that, as in the previous case, air enters the model through side T and leaves through side R.

The outside pressures decrease from room 3 towards the shaft on any floor, on side T, which means that on a floor the internal pressures are highest in room 3 and lowest in the shaft, considering only the openings to side T. Rooms 4, 5 and 6 pressures are expected to be very nearly equal and negative to conform to the prevailing negative pressures on side R. The corridor pressures again attain an equilibrium value, so that inflow equals outflow.

2.1.2.3 Corridor Pressures

Fig 2.11 shows the measurements of corridor pressures on each floor for four different leakage ratios. It is clear that the variation with leakage ratio is very small as in the previous case. Because of the reduced magnitude of pressure on side T, the corridor pressure drops on all floors accordingly. The combined effect of positive pressures on the first floor is reduced and the corridor assumes slightly negative pressure values. For floors 2, 3 and 5, the corridor pressures are very nearly the same, which is evident from
Fig. 2.11 Shaft and Corridor pressures, $\alpha = 45^\circ$
outside pressure distribution: higher pressure on floor 4 can be explained similarly. With the exception of floor 1, the corridor pressure on the other floors can be assumed to have the same value (i.e. $C_p = 0.075$) without any great loss of accuracy. From Fig 2.11 it is also clear that the shaft pressure always remains greater than that of the corridor, which results in air flowing into the corridor on all floors.

2.1.2.3 Shaft Pressures

Pressures measured in the shaft at each level showed that all values were the same. Fig 2.11 shows the measured results which, when compared with the zero wind case (Fig 2.3), show a considerable drop. This time the values for $R_L = 0.5$ are not different from the rest. Again, for the range of $R_L$ values ($0.25 < R_L < 4$) investigated, the shaft pressures are independent of $R_L$. The average pressure coefficient is about 0.15.

2.1.2.4 Room Pressures

To conform to the outside pressure distribution on both the leaky walls, the room pressures differ quite considerably from those for the $\alpha = 0^\circ$ case. From the relative location of rooms and pressure contours on side T, rooms of approximately equal pressures can easily be identified. The contours with values $C_p = 0.45$ and $C_p = 0.15$ pass over the windows of:-
Fig 2.12: Variation of Room Pressures with Height, $\alpha = 45^\circ$. 
Fig. 2.12a  Room pressures, $\alpha = 45^\circ$
Fig. 2.12b  Room pressures, $\alpha = 45$
Hence pressures in these rooms must be the same. The measurements of room pressures shown in Fig 2.12 confirm this conclusion. Although the pressures in this figure are only for $R_L = 1.0$, for other leakage ratios, values do not differ a great deal, as will be shown later. Other rooms -

- Room 2 Floor 2
- Room 1 Floor 4

with similar pressures, can also be identified from Fig 2.10 and compared to those in Fig 2.12.

The measurements for other rooms, i.e. 4, 5 and 6 are shown in Figures 2.12(a) and 2.12(b). With the exception of the leakage combination - 1.5 1.5 0.5 - the pressures in these rooms are almost constant. It was noticed during the measurements that the pressures varied quite considerably and slowly with time, hence to select a mean value was not really justified. In view of this difficulty the results for rooms 4, 5 and 6 in Figs 2.12(a) and (b) are quite good.

The measurements for different leakages are shown in Figs 2.13 to 2.17. The results for rooms 4, 5 and 6 do not convincingly show that they are independent of $R_L$: this is due to the reasons
Fig 2.13: Room Pressure Variation with $R_L$, Floor 1, $\alpha = 45^\circ$. 
Fig 2.14: Room Pressure Variation with $R_L$, Floor 2, $\alpha = 45^\circ$. 
Fig 2.15: Room Pressure Variation with $R_L$. Floor 3, $\alpha = 45^\circ$. 
Fig 2.16: Room Pressure Variation with $R_L$, Floor 4, $\alpha = 45^\circ$. 
Fig 2.17: Room Pressure Variation with $R_L$, Floor 5, $\alpha = 45^\circ$. 

FLOOR 5
explained earlier. For the other three rooms on each floor, there is no doubt and no significant error will be introduced by this assumption.

2.1.3 Wind Incidence, $\alpha = 90^\circ$

2.1.3.1 External Pressures

Both the leaky sides, T and R, experience negative pressures which are of the same order of magnitude and similar distribution (see Fig 2.18). The maximum suction (i.e. highest negative pressure) occurs in the region of rooms 3 and 4 on the fifth floor. The figure shows that in the central region of each side there are only very slight variations with height. Pressures in the four corner regions of both the sides vary drastically. This variation is associated with the size of vortices. Also, the velocity of air decreases downwind, which results in lower negative values of pressure. The variation with height in the leading edge regions is due to the wind profile. There are no stagnation points in this case. Ideally the shape and position of contours must be the same for both walls. Slight dissimilarities apparent from Fig 2.18(a) and (b) are probably due to mis-alignment of the model with the flow, in other words, the flow is not exactly at $90^\circ$. It seems to be a few degrees greater than $90^\circ$. 
Outside Pressure Distribution ($C_{p_o}$)

$\alpha = 90^\circ$

Fig 2.18: Outside Pressure Distribution, $C_{p_o}$, $\alpha = 90^\circ$. 
Fig 2.19: Shaft and Corridor pressures for varying $R_L$, $\alpha = 90^\circ$
2.1.3.2 Internal Pressures

The inside flow pattern is completely different from either of the previous two angles investigated. Both the available leakages of sides T and R are subjected to negative pressures of comparable magnitude. There is no inflow or outflow of the earlier type. Because of the nature of outside pressure distribution, the rooms with openings to any one of the walls experience quite different pressures. From Fig 2.18 it is clear that the outside pressure contours on both the sides T and R are nearly similar. Comparison of these contours shows that on any one floor the outside pressure for the opposing rooms (e.g. 1 and 6, 2 and 5, 3 and 4) is very nearly the same. For this reason the internal pressures in these rooms are nearly of the same order of magnitude (compare Figs 2.20 and 2.21). Because of the relative magnitude of the internal room, corridor and shaft pressures, there is a tendency for the air to flow from the shaft into the corridor and from the corridor into each of the rooms on a floor.

It was found that the pressure measurements did not fully describe the internal flow pattern. The smoke tests revealed very complex internal flows. The results are discussed in more detail in Vol II. It was found that there was no simple kind of inflow and outflow as seen for the previous two wind directions (namely \( \alpha = 0^\circ, 45^\circ \)). Fluctuating room pressures caused the inflow and outflow to occur through the room windows, which was not reflected in the pressure measurements. Some type of flow pattern was found to exist in the
Fig 2.20: Variation of Room Pressures with Height, $\alpha = 90^\circ$. 

$R_L = 1.0$

$\alpha = 90^\circ$
Fig 2.21: Variation of Room Pressures with Height, $\alpha = 90^\circ$. 

$R_L = 1.0$

$\alpha = 90^\circ$
shaft, with air entering the shaft through window leakage holes at lower levels and leaving through the holes at upper levels.

2.1.3.3 Corridor Pressures

The corridor pressure on each floor is highly dominated by the prevailing pressures in rooms as well as in the shaft. As all rooms are subjected to very high negative pressures, the corridor pressure is likewise negative. Fig 2.19 shows the measured values on each floor. It is noticed that on each floor the magnitude of negative corridor pressure is greater than that of the shaft. This results in a flow from the shaft into each of the corridors.

![Diagram](image)

Fig 2.1.3.3: Internal and External Flow Pattern

The figure also shows that the variation with the leakage ratio $R_L$ is similar to that in the case of previous two wind directions investigated. No significant error will be introduced if the pressures are assumed to be independent of $R_L$. 
2.1.3.4 Shaft Pressures

The outside pressures in the shaft region are the highest (i.e. less negative) than anywhere else on side T. This results in the higher (i.e. lower negative) internal shaft pressures than the corridors on each floor. The results plotted in Fig 2.19 show that, as before, the shaft pressures do not change very much with the leakage ratio $R_L$.

2.1.3.4 Room Pressures

All rooms on all floors are subjected to negative pressures of varying magnitudes. As in the case of $\alpha = 45^\circ$ wind direction, the rooms experiencing the same pressures can be identified from the outside pressure contour diagrams of Fig 2.18. On side T, for example, the contour ($C_{p_0} = -0.60$) passes over the outside of room on all floors with some interference from contour $C_{p_0} = -0.65$ on floors 3, 4 and 5, and from contour $C_{p_0} = -0.40$ on floors 1 and 5. This results in slightly lower room pressures on floors 1 and 2 and slightly higher on floors 3 and 4. On floor 5 it drops slightly due to the effect of contour $C_{p_0} = -0.40$. These conclusions are confirmed by the room pressure measurements shown in Fig 2.20.

Pressures in room vary considerably from one floor to another. The high negative values on floors 2, 3 and 4 can be explained in terms of the outside pressure contours (compare Figs 2.17 and 2.20).

On floors 1 and 5, room pressures are the same due to the
Fig 2.22: Room Pressure Variation with $R_L$, Floor 1, $\alpha = 90^\circ$. 
Fig 2.23: Room Pressure Variation with $R_L$, Floor 2, $\alpha = 90^\circ$. 
Fig 2.24: Room Pressure Variation with $R_L$, Floor 3, $\alpha = 90^\circ$. 

FLOOR 3
Fig 2.25: Room Pressure Variation with $R_L$, Floor 4, $\alpha = 90^\circ$. 
Fig 2.26: Room Pressure Variation with $R_L$, Floor 5, $\alpha = 90^\circ$. 
similarity of outside pressure contours (Fig 2.18). Room 3, on the other hand, is in the leading edge region, where marked pressure variations occur with height. This is reflected in the room 3 pressures with the highest negative value on floor 5.

Rooms 4, 5 and 6 pressures can be explained in a similar way by comparing Figs 2.17(b) and 2.21. Room 1 and 6 pressures are very close to the corridor pressures, and the pressure fluctuations result in reversal of flow through these room doors. For full discussion see Vol II.

The variation of room pressures with the outside leakage ratio, $R_L$, is shown in Figs 2.22 to 2.26 for all floors. These results show that the pressures are independent of $R_L$. 
2.1.4 Combined Discussion

In the foregoing discussion the variations and relations of internal and external pressures have been discussed for three different wind incidences. The emphasis has been on the effect of external leakage ratio.

The same results can be replotted to compare the change with respect to wind incidence. Three wind directions are not enough to work out any accurate empirical law relating wind incidence to internal pressures.

Fig 2.27 shows the corridor pressure variation with wind incidence on each of the floors. On the first floor, where the magnitude of pressures is relatively small, the corridor pressure changes to negative at about 30° wind incidence. For other floors, this limit increases to about 50°. After this limit has been reached, pressure drops rather fast and reaches its lowest value \( Cp = -0.5 \) at 90°.

Fig 2.28 shows the same results with wind incidence as a parameter.

The shaft pressures on the other hand continue to drop at the same rate, i.e. there is no change in gradient. Therefore the shaft pressure varies in a linear fashion according to the following relationship:

\[
C_{p_i} = -0.0083 \alpha + 0.55
\]

where \( \alpha \) = wind incidence in degrees.

This holds true for any leakage ratio \( R_L \). From the figure, it is clear that the shaft pressures change to negative at about \( \alpha = 60^\circ \).
Comparison of Figures 2.28 and 2.30 shows that the shaft pressure remains positive for higher incidences than the corridor pressure, which confirms the conclusion drawn from Figs 2.27 and 2.29.

Fig 2.31 shows that the shaft pressures are independent of $R_L$.

2.1.5 Conclusions
Provided the relative internal leakage remains constant (i.e. all doors closed) the inside pressures are independent of outside leakage ratio $R_L$. The internal pressures are a direct reflection of the outside wind induced wall pressures, which in turn are highly dependent on wind direction and building shape and size.

A complex internal flow pattern results at wind incidence of $\alpha = 90^\circ$, with air flowing from the shaft and some of the rooms into the corridor, which is not directly obvious from the external pressure distribution.

The shaft pressures are a linear function of wind incidence for $0^\circ \leq \alpha \leq 90^\circ$. 
Fig 2.27: Corridor Pressures on Each Floor.
Fig 2.28: Corridor Pressure Changes with Wind Incidence and $R_L$. 
Fig 2.29: Shaft Pressure with $\alpha$. 

Shaft

$C_{p_i}$

0.6

0.4

0.2

0.0

-0.2

-0.4

0° 45° 90°
Fig 2.30: Shaft Pressures for Varying $R_L$ and $\alpha$. 

- $R_L = 0.5$
- $R_L = 1.0$
- $R_L = 1.5$
- $R_L = 2.0$
Fig 2.31: Shaft Pressure Variation with $R_L$ and $\alpha$. 

- $\alpha = 0^\circ$ 
- $\alpha = 45^\circ$ 
- $\alpha = 90^\circ$
References and Bibliography


CHAPTER THREE

THE EFFECT OF VARYING SHAFT LEAKAGE
AND INTERNAL DOOR OPENINGS ON INTERNAL PRESSURES.
Chapter 3

THE EFFECT OF VARYING SHAFT LEAKAGE AND INTERNAL DOOR OPENINGS ON INTERNAL PRESSURES.

Introduction

3.0 In many existing tall buildings the shaft is either sealed or it contains openable windows at each floor level. These windows when open serve to ventilate the shaft when no mechanical ventilation is present, but in the case of fire, the varying shaft leakage can considerably influence the working of a pressurisation system. On the other hand, if a building is not equipped with such a system, it is necessary to investigate how the shaft pressures change with the change in shaft window leakage for any given wind direction. In this section the results of the measurements for two shaft leakage combinations are presented and discussed.

Under the normal use of a building, the internal leakage varies continuously due to the opening and closing of doors, giving rise to varying flow patterns. Under fire situations, the fire room door opening can prove to be most dangerous from the smoke and fire spread points of view.

The influence of a combination of door openings is also investigated. The resulting change in internal pressures is measured and discussed.
3.1 Discussion of Results

3.1.1 Internal room pressures

All rooms on all floors have equal window leakage (1.5 per cent of the wall area) and equal (but different from window) door leakage (1.5 per cent of the door area). To achieve flow similarity, three leakage holes were drilled instead of a large one, as explained earlier (see chapter 1). Full details of room pressure measurements are given in Volume II.

3.1.1.1 Leakage configuration (a) [1.5 1.5 1.5]

Analysis of all the room pressure measurements given in Volume II shows that the room pressures are independent of shaft leakage variations. Even for the door opening configuration investigated, the room pressure changes are negligibly small, hence these changes are ignored (see Volume II).

The basic room pressure measurements are shown in Figs 3.1 and 3.2 on floors 2 and 4 respectively. Since all room leakage characteristics are kept constant, the internal pressures are very much a reflection of external pressures which themselves are a function of wind direction (for a given wind and building shape).

Rooms 1, 2, and 3 have their window openings on to side T, while those of rooms 4, 5 and 6 are on to side R (see Fig 17.1). It is expected, therefore, that the respective room pressures are determined by the wind induced pressures on these walls.
For zero wind \((a = 0^\circ)\) normal to side T, the outside wind-induced pressures are shown in Fig 3.3 II. From this it is clear that the highest outside pressures occur over the region of room 1 window on floor 4. Room 1 then experiences highest pressure at \(a = 0^\circ\). When the wind incidence is changed the stagnation point moves towards room 3, but still stays at floor 4 level. As the stagnation point moves this way the pressure contours of smaller values cross the window of room 1 and the pressure inside the room decreases. The outside pressure contours for \(a = 45^\circ\) are shown in Fig 3.4 II. From this figure it is clear that the stagnation point has just passed over the edge of room 3 on floor 4, and that on this floor room 1 is subjected to low pressures determined by contours \(C_p = 0.35\) and 0.4. This is confirmed by Fig 3.1 which shows that \(C_p_1\) (Room 1, \(a = 45^\circ\)) = 0.31.

On the other hand, since rooms 4, 5 and 6 have their window openings on to side R, which is in the wake region, and because the window leakage is larger than door leakage, the room pressures are dominated by the prevailing wind pressures on side R. The average pressure on this side is negative \((C_p = -0.20)\) and the room pressures are still negative. Fig 3.1 shows the room pressures for all wind directions.

As the wind angle is increased the pressures on both sides (T and R) continue to decrease, until at \(a = 90^\circ\), both these walls are subjected to very high negative pressures. As air passes over
Floor 2 - ROOM PRESSURE.
All Doors Closed.

Fig. 3.1: Room Pressure ($Cp_1$) Variation with Wind Incidence ($\alpha$), Floor 2.
Floor 4 - ROOM PRESSURES
All Doors Closed.

Fig 3.2: Room Pressure ($C_{p_i}$) Variation with Wind Incidence ($\alpha$), Floor 4.
the corners of rooms 3 and 4, there is a sudden geometric discontinuity and as the fluid particles are unable to follow the surface, they leave it (separation point) and accelerate. This results in very high suction pressures developing outside rooms 3 and 4. These particles slow down as they travel downwind and the suction pressure decreases. Fig 3.5 II shows the measured pressure contours for $\alpha = 90^\circ$. At this angle then, all room pressures are negative and vary from one room to another. This kind of negative pressure distribution results in a very complicated flow pattern (see Vol II). From Figs 3.1 and 3.2 it is clear that the drop in room pressures between $\alpha = 45^\circ$ and $90^\circ$ is very fast compared with that between $\alpha = 0^\circ$ and $45^\circ$. This is a direct consequence of the outside pressure variation.

With a further increase in wind incidence towards $\alpha = 135^\circ$, the outside wall pressures on sides T and R begin to increase again. At wind direction of $\alpha = 135^\circ$, the pressures on the most part of side R become positive while on side T, even though there is an increase, they still remain negative (see Fig 3.6 II). This means that while rooms 4, 5 and 6 pressures are positive, those of 1, 2 and 3 are still negative. Small variations in pressures on side T are reflected in the actual room pressure measurements. On the other hand, on side R, the highest pressure occurs in room 4 on floor 4, for this particular wind direction.

Further increase in wind incidence makes the negative pressure disappear altogether from side R and at $\alpha = 180^\circ$, the stagnation
point appears on side R, with the highest pressure in room 5 on floor 4. The outside pressure contours are similar to those for $\alpha = 0^\circ$, only the sides T and R change places. Rooms 1, 2 and 3 pressures in this case are the same as rooms 4, 5 and 6 pressures for $\alpha = 0^\circ$.

As the wind direction continues to change, the room pressures change accordingly, repeating the previous pattern. From Figs. 3.1 and 3.2, it is clear that the minimum pressure occurs at $\alpha = 270^\circ$ and starts to increase again as wind moves towards its starting point of $\alpha = 0^\circ$.

From these figures it can be said that the rooms 1, 2, 3 and 4, 5 and 6 are out of phase by $180^\circ$. In each room the pressure variation is sinusoidal with its positive maximum points at $\alpha = 0^\circ$, $180^\circ$ and $360^\circ$, and negative minimum points at $90^\circ$ and $270^\circ$. The magnitude of these maximum and minimums is a function of the relative leakage sizes of doors and windows.

3.1.1.2 Leakage Configuration (b) 1.5* 1.5 1.5

Pressure measurements in all rooms on floors 2 and 4 showed that they were similar to those for leakage (a). Any variations were negligible, hence a similar discussion would be relevant to results from leakage (b). The results are shown in Volume II for all wind directions.
3.1.2 **Internal Corridor Pressures.**

On each floor, the corridor forms the link between each room and the shaft. The corridor pressures are therefore very much influenced both by the changes in room and shaft pressures.

3.1.2.1 **Leakage Configuration (a) 1.5 1.5 1.5 : Basic pressure distribution (all doors closed).**

Since all rooms are connected to each other and the shaft through the corridor, the pressure on a floor adjusts itself in such a way as to make inflow equal to outflow. For zero wind incidence, because of the prevailing high positive wind pressures in rooms 1, 2, 3 and the shaft, air enters the corridor through the leakage holes of these doors and leaves through the leakage holes of rooms 4, 5 and 6 doors. Because of the higher positive pressure leakage (for doors) the corridor pressure becomes positive.

The pressures measured on each floor are shown in Fig 3.10. Once again they too are a reflection of the outside wind pressures on walls T and R. For zero wind ($\alpha = 0^\circ$) the maximum corridor pressure occurs on floor 4.

Fig 3.10 also shows that the highest corridor pressures are experienced on all floors at zero wind ($\alpha = 0^\circ$) than any other wind direction. As the outside pressures decrease due to the increase in wind angle, the corridor pressures also decrease. It is also noticed that the average corridor pressures for $\alpha = 45^\circ$ and $180^\circ$ are very nearly equal. This is due to the internal leakage asymmetry.
Fig 3.10: Corridor Pressure (Cp₁) Variations with Wind Incidence (α), Leakage (a).
The corridor pressures for $\alpha = 225^\circ$ and $\alpha = 135^\circ$ are also very nearly similar (see Fig 2.10). This is because the pressure distribution on side R does not change drastically for the two wind directions. The small differences are due to the fact that for $\alpha = 225^\circ$, the place of room 4 is taken by the duct (D). For this angle the combined effect of the positive pressures in room 4, 5 and 6 is less than for $\alpha = 135^\circ$. The influence of the negative pressure on side then dominates, and the corridor pressures for $\alpha = 225^\circ$ are slightly less than for $\alpha = 135^\circ$.

At wind incidence $\alpha = 270^\circ$, the outside flow conditions on sides T and R are very nearly similar. In this case the shaft and duct corners facing the flow act as separation points. It is over these regions that the highest suction is experienced. The duct being internally and externally sealed has no influence on the internal pressures. But on the other hand, higher suction over the shaft windows causes the air to flow out of the shaft. As a consequence, flow from the rooms into the corridor and the shaft results. It is this influence of the shaft which reduces the corridor pressures further. It is also seen from Fig 3.10 that because of this reason the corridor pressures for $\alpha = 270^\circ$ are lower than those for $\alpha = 90^\circ$, even though similar outside flow conditions exist for both cases.

The variation of corridor pressures on floors 2 and 4 with the wind incidence are plotted in Figs 3.12 and 3.13 respectively. On floor 4 the pressures are higher than on floor 2. The graph shows that
Fig 3.11: Corridor Pressure ($C_{p_1}$) Variation with Wind Incidence ($\alpha$), Leakage ($b$).
the highest positive pressures in the corridor occur at \( \alpha = 0^\circ \) and that the highest negative pressures at \( \alpha = 270^\circ \).

They change with wind angle in a sinusoidal fashion.

3.1.2.2 Leakage Configuration (b) \( 1.5^* \) \( 1.5 \) \( 1.5 \): Basic pressure distribution (all doors closed).

The influence of the reduction in shaft window leakage is apparent from Figs 3.11, 3.12 and 3.13. For this leakage the influence of the shaft is much reduced which results in the reduction corridor pressures on all floors. The room pressures remain unaffected, hence the corridor pressures are determined by the room pressures. Since the pressure distribution on side R for \( \alpha = 180^\circ \), is the same as side T for \( \alpha = 0^\circ \), then, because of the reduced influence of shaft, the corridor pressures in these two wind directions must be the same. The results shown in Fig 3.11 confirm this conclusion. This figure also shows that the differences between \( \alpha = 135^\circ \) and \( \alpha = 225^\circ \), \( \alpha = 90^\circ \) and \( 270^\circ \) are also reduced: but the corridor pressures for \( \alpha = 45^\circ \) act alone. From the flow symmetry point of view, these pressures must be the same as those for \( \alpha = 135^\circ \) and \( \alpha = 225^\circ \). The comparison of outside pressures for these three cases show (Figs 3.4II, 3.6II and 3.8II) that in the case of \( \alpha = 45^\circ \) the model is not exactly aligned at \( 45^\circ \) to the flow. In fact it seems to be much less than \( 45^\circ \) as there are no negative pressures on side T, and the pressures of side R are very close to those at \( \alpha = 0^\circ \). In this case, since positive pressures are higher, the corridor pressures are also higher, as shown in Fig 3.11. As the wind angle increases
these pressures will decrease, becoming equal to those of
\( \alpha = 225^\circ \) and \( 135^\circ \), but in each case they are not expected to
be exactly the same, due to the slight flow variations.
Fig 3.12: Corridor Pressure ($C_p$) Variation with Wind Incidence ($\alpha$), Floor 2.
Fig 3.13: Corridor Pressure ($C_{p_1}$) Variation with Wind Incidence ($\alpha$), Floor 4.
3.1.3 Internal Shaft Pressures.

From the point of view of smoke control in tall buildings, the relative shaft pressures are very important. With the right wind conditions, the high wind induced shaft pressures can prevent smoke spreading to other floors. If pressures in the shaft or any vertical duct are too low, smoke can fill the shaft and threaten other floors.

As for the room pressures, the shaft pressures are directly influenced by the prevailing wind induced pressures outside the shaft windows. Since these openings are only on to side T, it is the variation of pressures on this wall that determine the magnitude of shaft pressures. The effect of side R is only indirect - through rooms and corridors.

For a given wind, the shaft pressures can only be controlled by changing its leakage characteristics. It is therefore important to see how the variation in outside shaft leakage influences its pressures.

3.1.3.1 Leakage Configuration (a) 1.5 1.5 1.5

Since a shaft is a single volume extending all the way up the building, there is one single value of average pressure at all levels. Because of the nature of pressure distribution on side T, there is a turbulent mixing within the shaft for almost all wind angles, which gives rise to upward and downward flows. This
Fig 3.14: Shaft Pressure ($C_{p_i}$) Variation with Wind Incidence ($\alpha$)
flow is not registered by the pressure measurements as the instrument does not respond to very small pressure changes as encountered in the shaft. The measured values are the average mean pressures.

Since the shaft pressures are equal at all floor levels for any particular wind direction, Fig 3.15 shows the vertical lines representing each direction. This figure is useful in comparing the shaft pressures with the measured corridor pressures shown in Fig 3.10.

Fig 3-14 shows the shaft pressure variation with wind incidence. For the wind directions investigated, the highest positive pressure occurs at zero wind \((\alpha = 0^\circ)\). This is probably not true as it can be seen that for \(\alpha = 315^\circ\) (the measurements for this angle were not possible due to the shortage of time) the wind will blow directly onto the shaft leakage, increasing its (i.e. shaft) pressure. As the angle increases further, the stagnation point reappears on wall T in the region of shaft leakage, causing highest internal pressure in the shaft. There exists a pressure gradient within the shaft (stagnation point being on the 4th floor level) resulting in a flow down the shaft. In that case any smoke releasing into the shaft from floor 4 (assuming that it overcomes the shaft pressure at that level) will be quickly taken down to other floors, threatening people trying to escape.
Fig 3.15: Shaft Pressure ($C_{p1}$) changes with Wind incidence ($\infty$), Leakage ($\alpha$)
Fig 3.14 shows also the results for leakage (b) which are discussed later on.

As the wind direction changes from $\alpha = 0^\circ$ to $45^\circ$, the stagnation point moves towards room 3, but still stays on floor 4. The pressures over shaft windows decrease and the shaft pressure falls very quickly. In comparison, the corridor pressure falls very slowly because the combined effect of rooms 1, 2 and 3 is still the same (the stagnation point merely moves from one room to another, which are connected to the corridor by the same door leakage). For the wind direction change from $\alpha = 0^\circ$ to $45^\circ$ the shaft $C_p\_1$ drops by 0.23, while that of the corridor drops only by 0.07.

At angles greater than $45^\circ$, the corridor pressure also begins to drop rapidly due to the appearance of negative pressures on side T but the shaft pressure becomes negative earlier than the corridor pressure. At $\alpha = 90^\circ$ both the shaft and the corridor pressures are negative but the corridor pressure is still less than the shaft pressure, giving rise to a flow from shaft into corridor. (Flow patterns are discussed later).

From Fig 3.14 it is clear that at about $\alpha = 67^\circ$ the shaft pressures change from positive to negative and they remain negative for all wind directions until some positive pressure begins to appear on side T, and this happens for wind incidence in the region of $\alpha = 315^\circ$. This has very important consequences for the flow pattern. The idea is to keep shaft pressures greater than corridor pressures
as far as possible. For most of the wind directions, the pressures over the shaft remain negative. (Pressures are only positive for $315^\circ < \alpha < 45^\circ$). It is therefore necessary to keep the shaft independent of outside pressure variations by reducing its window leakage as much as possible.

3.1.3.2 Leakage Configuration (b) \[1.5*|1.5|1.5\]

In this case the shaft is only connected to the outside through a small opening on floor 1, equivalent to the main door leakage (when closed). In this way the shaft is almost completely independent of the outside pressures. The shaft pressures are then highly dependent on the corridor pressures. The measured results are shown in Fig 3.14. The comparison of this figure with Figs 3.12 and 3.13 show that the shaft and corridor pressures are in phase, i.e. the increase in one leads to an increase in the other and vice versa. This has the effect of reducing pressure difference across the shaft door. This means that the advantage of higher shaft pressures for $315^\circ < \alpha < 45^\circ$ is not present in this case, but for other wind directions, since the pressure difference is reduced across the shaft door, there will be less amount of air flowing into the shaft. These small pressure differences make the shaft pressurisation problem much easier as the danger of overpressure is reduced.
Fig 3.16: Shaft Pressure ($C_{p_1}$) Changes with Wind Incidence ($\alpha$), Leakage (b).
3.1.4 Basic Flow Patterns

Air flows from high pressure regions to low pressure regions. For smoke control purposes the most critical flow is that across the shaft door. This flow is dependent on the relative shaft and corridor pressures. Figures 3.17 and 3.18 give the pressure differences across doors for each wind direction investigated and for leakage combinations (a) and (b). It is recommended that to stop smoke flow into an escape route, the pressure difference across a door must not exceed 50 N/m². Now if the wind velocity is about 20 m/s, then for the above condition to be satisfied, the \( \Delta C_{p1} \) must not be greater than 0.2. From Fig 3.17 it is clear that this condition is just about satisfied for \( \alpha = 0^\circ \) on floor 2. If fire occurs on this floor, and provided the air flow is normal to side T, smoke will be confined to floor 2. However this is not true for floor 4 where the increased room pressures increase the corridor pressure which results in low pressure difference across the shaft door (\( \Delta C_{p1} = 0.11 \)). To stop smoke entering the shaft, the \( \Delta C_{p1} \) must be raised to 0.2. If this is done by raising the shaft pressure, this will result in increased pressure difference across other shaft doors as well as making them difficult to open by a normal person. If, on the other hand, smoke is allowed to flow into the shaft, it will quickly get into other floors because of the pre-existing flow from the shaft into corridors.

Increase in wind incidence decreases the shaft door pressure differences on all floors. At \( \alpha = 45^\circ \), for example, the \( \Delta C_{p1} \) values
Fig 3.17: Wind Induced Pressure Difference ($\Delta C_{p_1}$) Across Room Doors.
Fig 3.18: Wind Induced Pressure Difference ($\Delta C_p$) Across Room Doors.
for floors 2 and 4 are 0.06 and 0.01, respectively. These values are very much less than the required ($\Delta C_{p_1} = 0.2$) to stop smoke getting into the shaft. Again, shaft pressurisation for fire on floor 4, to maintain required pressure difference, will cause problems on other floors. For this reason lobby pressurisation will be the best.

At a wind incidence higher than $\alpha = 45^\circ$, negative pressures first begin to appear over the shaft region, making the shaft pressure negative or less than the corridor pressure which is still dominated by the positive pressures in rooms 1, 2 and 3. This reverses the flow across the shaft door and air flows into the shaft. This happens for a very small range of wind incidences because as pressures become negative over the whole of wall T, the suction over rooms is much greater than that over the shaft, which causes higher negative pressures in the corridor and the flow across the shaft door is again reversed.

At $\alpha = 90^\circ$, the pressures everywhere within the building are negative and the pressure difference across the shaft door on floor 2 ($\Delta C_{p_1} = 0.19$) is enough to confine smoke to that floor. The flow pattern in this case is not as simple as for the previous two cases in which there was simple inflow and outflow. In this case the only inflow occurs through the shaft door which, according to the measured pressures, is not the same as outflow through the rooms as indicated in Fig 3.17. (See Volume II for full discussion). This means that the measured pressures do not describe the flow
fully. In addition to pressure measurements, smoke tests were carried out to establish the actual flow patterns.

Smoke introduced into the shaft showed that it filled the shaft very quickly. After some time it was noticed that the smoke began to appear in all the corridors and eventually into other rooms with high concentration in rooms of higher negative pressures (highest in rooms 3 and 4; lowest in rooms 1 and 6). Not all the smoke in the shaft was carried into the corridors; most of it escaped through the shaft window holes.

Fig 3.1.4.1 Air flow in the Shaft, $\alpha = 90^\circ$
A close observation of the flow near the shaft windows showed a very complex flow pattern. There was inflow and outflow through the same hole at different times as well as inflow and outflow through different holes.

Smoke was also introduced into the corridor near the shaft door. It quickly filled the corridor as well as rooms 2, 3, 4 and 5, the smoke concentration being very low in rooms 2 and 5. Hardly any smoke was noticed in rooms 1 and 6. No smoke appeared in the shaft. Air flow from the shaft into the corridor was apparent near the shaft door leakage holes, as the smoke there was considerably mixed. All smoke escaped through the room windows. The smoke flow along the corridor towards rooms 3 and 4 was clearly visible, indicating a pressure gradient, but the actual measurements of corridor pressure did not quite show up this gradient.

Smoke tests also showed a very complex flow pattern for individual rooms. The flow was similar to those through the shaft window holes. Most of the air entered and left through these holes and a very small amount entering through the door leakage made no difference to the dominant flow through the windows.

Fig 3142  Air flow in a room, $\theta = 90^\circ$
For room 1, because the corridor pressures are very close to the room pressures, the air entering through the windows also found its way to the corridor but this flow was a very pulsating one and smoke was noticed to enter the corridor in periodic puffs. The same observation was made for room 6. For rooms 2 and 5, the flow into the corridor was much reduced but it still occurred in a periodic fashion. For rooms 3 and 4, no smoke was seen to flow into the corridor.

These tests showed that the flow pattern calculated from the pressure measurements was not accurate. The pressures vary so much that the flow directions across rooms 1, 2, 5 and 6 doors and windows are reversed continuously. More accurate pressure measurements will reveal that the corridor inflow is equal to outflow and this will have to take into account the inflow through rooms 1 and 6 doors. (See Volume II). It must be concluded then that even though there are these inaccuracies in the measurements, any fire on a floor will not cause the smoke to flow into the shaft; most of it will be taken out through the window leakage.

With the further increase in wind incidence, the appearance of positive pressures on side R causes higher corridor pressures than the shaft pressures, resulting in a flow into the shaft. This kind of flow pattern persists for all angles up to and including $\alpha = 270^\circ$. There is a very high rate of flow into the shaft due to very high pressure differences. They are so high that they exceed the maximum
permissible limit, causing the door to be impossible to open. Although there is no danger of smoke spreading to other floors, escape is very difficult.

To overcome such large wind induced pressures for the shaft which has a very large leakage becomes a difficult task as the pressurising fan has not only to maintain a pressure difference of 50 N/m² but also has first to overcome the opposing pressures. As this kind of flow pattern persists for most of the wind direction range, it may not be advantageous to have large shaft leakage.
As discussed earlier, the effect of reduced shaft leakage is that the shaft and corridor pressures become very close to each other, reducing the wind induced pressure difference across the shaft doors. This means that for no wind direction can the wind be relied upon to pressurise the shaft, as even for zero wind incidence the $\Delta C_{p_l}$ across the shaft door is only 0.07 on floor 2 and even less on floor 4.

Apart from the reduced pressure differences, there is no significant change in flow pattern, as shown in Fig 3.18. The critical range of wind directions between $45^\circ \leq \alpha < 90^\circ$ still exists but with small pressure differences.

The major advantage of the low pressure differences is that very small flow rates are required from the fan to pressurize the shaft. The other great advantage is that even if there is no pressurisation system installed in the building, the rate of air flow into the shaft is reduced. If this contains smoke, it takes longer to completely fill up the shaft. In other words, the smoke spread is slowed down, allowing more time for evacuation.
3.1.5 Effect of Internal Door Openings.

In the normal use of a building, the basic flow pattern and pressure differences across doors keep on changing due to the opening and closing of doors on all floors. The degree of change depends very much on the use of the building. It is impossible to investigate the effect of all possible combinations of door openings.

For the present model, three combinations were investigated, repeating measurements on floors 2 and 4. The combinations were:

(i) Shaft door open ( 'S' open)
(ii) Room 6 door open ( '6' open)
(iii) Room 6 + shaft door open ( 'S' + '6' open)

All other doors were kept closed. This was repeated for the two shaft leakage configurations (a) and (b).

The full results and their detailed discussion for each wind incidence is given in Volume II. The important implications are discussed below briefly.

As pointed out and shown by the measurements in Volume II, the room pressures, except for the pressure in the room of the door opening, are insignificantly affected by these door opening combinations.

The effect of the shaft door opening is that it makes the shaft and corridor behave as one single volume with nearly equal pressure.

The pressure difference required to cause flow through the open
shaft door is very small. The shaft and corridor pressures are shown in Figs 3.19, 3.20 and 3.21. These figures show that the influence of door openings is more pronounced in the case of corridor pressures than for the shaft pressures. For zero wind, for example, the maximum pressure change for the shaft is about $\Delta C_{p_i} = 0.13$, whereas in the case of the corridor it is about 0.46 on floor 4 and 0.33 on floor 2. It is these large corridor pressure changes which are responsible for the flow direction change. When the shaft door is opened, the corridor pressure varies in the manner of shaft pressure with wind incidence on both floors 1 and 2 (compare Figs 3.19, 3.20 and 3.21). The corridor pressure drop at $\alpha = 90^\circ$ is less than when the door is closed, but the flow still results from the shaft into the corridor, as shown by the smoke tests. At $\alpha = 180^\circ$, the corridor pressure is dominated by the prevailing negative pressures in the shaft; as a consequence the outflow through rooms 1, 2 and 3 is much reduced which causes most of the air to flow through the shaft door into the shaft. For any smoke control purposes this is to be avoided. Again at $\alpha = 270^\circ$, very low corridor pressures ($C_{p_i} = -0.6$) cause flow into the shaft. The measurements show that in fire situations the opening of the shaft door must be avoided for all wind angles as this makes escape difficult.

The opening of room 6 door is most favourable for all wind angles in which shaft pressure is positive. The negative corridor pressure resulting from opening this door increases the pressure difference
Floor 2
Corridor Pressures:  
+ All Closed  
× 's' Open  
o '6' Open  
△ ('s' + '6') Open

![Graph showing Corridor Pressures (Cp_i) Variation with door Openings]

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Fig 3.19: Corridor Pressures ($Cp_i$) Variation with door Openings Leakage (a), Floor 2.
FLOOR 4 - Corridor Pressures

Fig 3.20: Corridor Pressure ($C_{pi}$) Variation with Door Openings, Leakage (a), Floor 4.

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- + All Closed
- × 'S' Open
- ○ '6' Open
- △ ('S' + '6') Open
Fig 3.21: Shaft Pressure Variation with Door Openings, Leakage (a), Floor 2.
across the shaft door, preventing flow into the shaft. But if this door opening is used in conjunction with shaft pressurisation on any other floor except the fire floor, the increased pressure difference can cause the shaft door to be impossible to open. For $\alpha = 45^\circ$ the same argument applies, but at wind incidence of $\alpha = 90^\circ$ and $270^\circ$ room door opening does not change the pressures significantly. This is apparent from the type of flow pattern that exists for these angles as discussed earlier.

On the other hand for wind angles in which the side $R$ pressure is positive, the opening of room door increases the corridor pressure greatly which, together with the negative shaft pressures, results in very high shaft door pressure differences with a consequent increase in flow rate. On the fire floor more smoke will flow into the shaft but if it is not a fire floor then the pressure difference across the shaft door will increase the maximum limit allowed (e.g. at $\alpha = 180^\circ$ the $\Delta C_p = 0.43$, which is more than the acceptable limit of 0.2).

The shaft and room door openings follow the same pattern as for the shaft door open alone. Once again it causes the shaft to fill with smoke very quickly.

The measurements were also made with these door opening combinations for leakage (b). The results are shown in Figs 3.22, 3.23 and 3.24. These results show that the effect of door openings is similar to that for leakage (a). The corridor pressures are more affected for
all wind directions than the shaft pressures. As figure 3.24 shows, the shaft pressures only change considerably when the doors are opened for $\alpha = 0^\circ$, $45^\circ$, $180^\circ$ and $360^\circ$. For other wind directions, no significant change occurs. For a detailed discussion of each door opening configuration, see Volume II.

A comparison of the shaft pressure changes for the two configurations (a) and (b) (Figs 3.21 and 3.24) shows that for leakage (b) the influence is more felt in the shaft. This is because the shaft pressures for this leakage (b) are determined by the corridor pressures as discussed earlier.

The corridor pressures in contrast to the shaft pressures are affected by the door openings quite considerably. Figs 3.22 and 3.23 show the results. Change in internal pressures is the greatest for $\alpha = 180^\circ$ on floors 2 and 4. It can also be seen from the layout of the rooms that at this wind incidence (i.e. $\alpha = 180^\circ$) the shaft will be directly threatened if shaft and room doors were opened together. Almost all the smoke from a fire in room 6 flows into the shaft. For any leakage configuration, the opening of doors, especially on the fire floor, must be avoided.
3.2 Conclusions.

The measurements of internal pressures have shown that there can be no one solution to the problem of smoke control for tall buildings with outside leakage. The following general conclusions can be made.

1. For wind directions between $315^\circ < \alpha < 45^\circ$, the shaft pressures are high enough to confine smoke to the fire floor for leakage (a). Leakage (b) reduces the shaft pressures considerably and shaft pressurisation is required.

2. At wind incidences $\alpha = 90^\circ$ and $\alpha = 270^\circ$ the flow patterns for this kind of building with only two leaky walls, are very complex. The flow across the shaft door reverses for the two angles.

3. For wind incidences $90^\circ < \alpha < 315^\circ$ leakage (b) will be favourable from the point of view of shaft pressurisation, as this leakage results in small negative pressures in the shaft.

4. Open shaft door on the fire floor endangers all other floors and therefore must be avoided.
Floor 2: Corridor Pressures

Fig 3.22: Corridor Pressure ($C_{p_1}$) Variations with Door Openings, Leakage (b), Floor 2.
Floor 4: Corridor Pressures

Fig 3.23: Corridor Pressure ($C_p_i$) Variations with Door Openings, Leakage ($b$), Floor 4.
Floor 2: Shaft Pressures.

Fig 3.24: Shaft Pressure ($C_{p_i}$) Variations with Door Openings, Leakage (b), Floor 2.
CHAPTER FOUR

THE EFFECT OF A PROBABLE FIRE PRESSURE IN A ROOM ON INTERNAL PRESSURES
Chapter 4

THE EFFECT OF A PROBABLE FIRE PRESSURE IN A ROOM ON INTERNAL PRESSURES.

4.0 Introduction

In previous chapters the discussion has been confined to the flow patterns resulting from outside wind pressures. It has been assumed that the smoke follows the pre-existing flows. But in a real fire situation, the fire itself may change the flow pattern by introducing considerable buoyancy forces. In the vicinity of the fire these forces may be greater than the wind forces. It is, therefore, necessary to make pressure measurements taking into account the effects of fire.

The simulation of fire in a model, such as the one presently used, is not easy. The model is constructed from perspex and it cannot be subjected to high temperatures. Earlier studies on the nature of fire (4.1, 4.2, 4.4) have shown that because of the temperature difference between the fire room and the outside, a pressure difference exists across any opening (e.g. cracks around doors and windows). These measurements show that the pressure difference at the top of a door is unlikely to exceed $7.0 \, \text{N/m}^2$. This differential pressure is responsible for smoke spread into the corridor.
Effect of the fire, then, can be simulated by creating a pressure difference of about 10.0N/m$^2$ across the door. This was done by pumping air into a room to maintain this difference, in still air conditions (i.e. zero outside wind). It must be remembered that this is not exactly equivalent to the full scale fire situation. In a real fire there exists a neutral pressure plane for the doors and windows. Cold air flows into the fire room through the leakage paths below this plane, and hot smoke flows out above the neutral plane. In the present simulation no such plane exists, and air only flows out through the door and window leakages. Another difference is that there is no hot layer in the corridor as is the case for real fires. The simulation of fire pressure this way can give an indication of how pressures in other areas are affected.
In the present model, a room on each floor is provided with a facility for pressurisation (see Figure 4.0.1).

The supply fan was capable of maintaining a pressure difference of up to 10N/m² across the closed fire room door.

For the purposes of present measurements, the supply fan was set at a flow rate that for zero wind the pressure difference across the fire room door was 10.0N/m².
4.1 Discussion of Results

The measurements made for each wind incidence, with simulated fire pressure in room 6 on floors 2 and 4 respectively, are shown in Figures 4.1.1. to 4.7.6. (in Volume II) for both the leakage configurations, (a) and (b). In each case the measurements were also made for different door opening configurations. The results for each wind incidence are discussed in detail in Volume II (Chapter 4).

4.1.1. Leakage Configuration (a)  

4.1.1.1. $\alpha = 0^\circ$

For the case of zero wind incidence, the prevailing negative pressures over the window holes of room 6 help to draw smoke out of the room. The exact amount drawn out depends on the pressure difference developed across the windows by the outside wind and the fire, and on the total leakage area of these windows. If there is enough window leakage area available, and the smoke generated by the fire is not too great, it is likely that under these wind conditions ($\alpha = 0^\circ$) all smoke will escape through the windows. The likelihood of smoke getting into the corridor depends on the prevailing wind induced pressure in the corridor. If this pressure is greater than the combined wind and fire pressure in room 6, the corridor will remain smoke free. If, on the other hand, the combined fire room pressure overcomes the corridor pressure, the amount of smoke flowing into the corridor will depend on the pressure difference across the fire room/door as well as on the total leakage area of the door.
The pressure measurements on floor 2 are shown in Figure 4.1.2 (Volume II). From this figure it can be seen that for all doors closed ("All closed") case, the fire room pressure is slightly higher than the corridor pressure, resulting in a flow into the corridor.

The mass flow rate can be written as

$$M = \sqrt{\frac{\Delta P}{R_r}}$$  \hspace{1cm} (4.1)

where $R_r$ = flow resistance of the opening

$$= \frac{1}{2} \rho \left(C_d A_e\right)^2$$  \hspace{1cm} (See Appendix B)

$C_d$ = flow coefficient of the opening  \hspace{0.5cm} (0.65)

$\rho$ = density of the air flowing

$A_e$ = Area of the opening

$\Delta P$ = pressure difference across the opening.

Equation (4.1) can be re-written in terms of pressure coefficients

$$M = \sqrt{\frac{1}{R} \left(\frac{1}{2} \rho V^2 \Delta C_{p_1}\right)}$$  \hspace{1cm} (4.2)

where $V$ = wind velocity at building height.

or

$$M = R_1 \left(\Delta C_{p_1}\right)^{\frac{1}{2}}$$  \hspace{1cm} (4.3)

where $R_1 = \left(\frac{1}{2} \rho V^2}{R_r}\right)^{\frac{1}{2}}$  \hspace{1cm} (4.4)

Now, the pressure coefficient difference across the fire room door is 0.09

Mass rate of flow (os smoke) into corridor

$$= R_1 (0.09)^{\frac{1}{2}} = 0.3 R_1$$

If there was no wind blowing, the pressure difference responsible for flow into the corridor from room is 10 N/m$^2$. This can be expressed in terms of the dynamic pressure at the building height level, of the previous case. Then $\Delta C_{p_1} = 0.43$ with $\frac{1}{2} \rho V^2 = 23.0$ N/m$^2$. 
\[
\text{Mass rate of flow (of smoke) for no wind conditions}
\]
\[
= R_1 (0.43)^{\frac{1}{2}}
\]
\[
= 0.66 R_1
\]

These calculations show that the mass rate of flow of smoke is nearly halved, when the outside wind is blowing normal to side T at a speed of 6m/s. This is due partly to the positive pressure in the corridor which opposes the flow from room\(\text{6}\), and due partly to the fact that most of the smoke generated is taken out through the windows by the negative pressures on wall R.

Other rooms on any floor are connected to the fire room\(\text{6}\), only indirectly, either by the outside air or by the corridor. The only way that the other room pressures can change is if corridor pressures change dramatically. Because of the small quantities of smoke getting into the corridor, the pressures there remain unaltered. The corridor pressures, with and without the fire pressure in room\(\text{6}\) on floor 2, are shown in Figure 4.14. This figure clearly shows that for \(\alpha = 0^\circ\), the corridor pressure is the same as if there was no fire pressure present in room\(\text{6}\). It is because of this that the room pressures also remain unaltered. The measured room pressures are shown in Figures 4.8 to 4.13.

The shaft is connected to the fire room through the corridor, and if corridor pressures do not change, the shaft pressures also remain unchanged. The measurements shown in Figure 4.14 confirm this conclusion.
Opening the shaft door on fire floor increases the corridor pressure, which reverses the flow direction across the fire room door, and in this case no smoke can get into the corridor. Figure 4.15 shows the shaft and corridor pressure measurements for the shaft door open ("S" open) on floor 2. From this figure it is clear that for $\alpha = 0^\circ$, the corridor pressure increases from $C_p = 0.25$ (All Closed) to 0.27 ("S" open). Such small pressure change does not cause any changes in other rooms (see Figure 4.1.2 II).

The effect of opening room 6 door is to increase dramatically the flow of smoke into the corridor. As a result the corridor pressure changes slightly, but this change is not enough to influence either the shaft or room pressures (see Figure 4.1.2 II). A comparison with the no fire pressure measurements show that the corridor pressure on the fire floor changes considerably, as a result of opening the room 6 door (see Figure 4.16). For zero wind ($\alpha = 0^\circ$) the corridor pressure changes from

$$C_{p_1} = -0.03 \quad \text{Without 'fire'}$$

$$\text{to} \quad C_{p_1} = 0.21 \quad \text{With 'fire'}$$

This increase does not have any direct consequences for the other rooms, as the flow direction across those room doors remain unchanged (with altered pressure differences, Compare Figures 3.3.2 II and 4.1.2 II). But this change has very important consequences for the pressure difference across the shaft door. For $\alpha = 0^\circ$, the shaft pressure is still higher than the corridor pressure, which prevents smoke getting into the shaft. If under certain wind conditions the shaft pressure is not enough to confine smoke on to the fire floor, it must be raised by shaft pressurisation to a value which is higher than the corridor pressure. The wind induced pressure coefficient differences for the shaft door, under two conditions are
For the design of shaft pressurisation system, what is important is the pressure difference value with the fire than without the fire, because they differ quite considerably. It is, therefore, important not to base the design on wind induced pressures alone, but the fire pressure must also be taken into account. This, of course, is only necessary if there is a large probability of the fire room door being left open or it burning down quickly. This problem does not arise if all the doors remain closed as seen from Figure 4.14.

If shaft and room doors are opened at the same time, the corridor and shaft pressures adjust themselves so that they are equal (see Figure 4.17). This figure also shows that the shaft pressure dominates and the final shape of the curve is that of the shaft pressures shown in Figure 4.14. The curves seem to be shifted upwards slightly due to the fire pressure contribution. Opening of these two door, reduces the resistance to smoke flow into the shaft, and creates a greater danger of smoke spreading to other floors.

The results in these figures show that even though the shaft door open on its own prevents smoke flow into the corridor, but the general practice should be to keep all doors closed, at all times, as is recommended.

The corridor pressures for various wind directions at all floor levels are shown in Figure 4.18. Compare this figure with Figure 3.10.
On floor 4, the room\(^1\), \(^2\) and \(^3\) pressures are generally higher than those on floor 2. This is due to the nature of outside pressure distribution on side T, as discussed in the earlier chapter. The corridor pressure on this floor is also higher than on any other floor.

\[ \text{Cp}_i \text{ (corridor)} = 0.23 \quad \text{Floor 2 With 'fire'} \]
\[ \text{Cp}_i \text{ (corridor)} = 0.41 \quad \text{Floor 4 With 'fire'} \]

The relative room, corridor and shaft pressures are shown in Figure 4.1.3 (Volume II). On this floor the wind induced corridor pressure is higher than the combined wind and fire pressure in room\(^6\). As a result no smoke flows into the corridor. The corridor pressure changes only very slightly (from \( \text{Cp}_i = 0.32 \) to \( \text{Cp}_i = 0.4 \)) as a result of the fire pressure in room\(^6\). This change is not enough to influence the pressures in other rooms. This conclusion is confirmed by the measured pressures shown in Figure 4.1.3 II.

Figures 4.8 to 4.13 show the 4th floor room pressures in comparison with the 2nd floor room pressures. In accordance with the outside pressure distribution the 4th floor pressures are higher than those on the second floor. These figures also show that for all wind angles investigated, there are no drastic changes in room pressures as a result of the fire pressure. The changes that occur are in the fire room itself (see figure 4.13). On the 4th floor, for zero wind (\( \alpha = 0^\circ \)), the room\(^6\) pressure jumps from \( \text{Cp}_i = -0.20 \) (no 'fire') to \( \text{Cp}_i = 0.39 \) (with 'fire'), for all doors closed.
Opening of the shaft door ('S' open) has a very negligible effect on the corridor pressure, this is because the shaft and corridor pressures on this floor (4th) are of the same order of magnitude when the door is closed (see Figure 4.1.3 II). The pressures are very similar to these for the no fire case (see Figure 4.20). In this and figures 4.21 and 4.22, the results for $\alpha = 270^\circ$ were lost and are not shown. These three figures show the pressure measurements in the shaft and corridor for different door opening configurations. They show that as on floor 2, room 6 door open produces major changes in corridor pressure (see Figure 4.21) for all wind directions. Even this change is not enough to cause any flow changes across other room doors. Even though the corridor pressure changes from $C_{p_i} = 0.41$ (all closed) to $C_{p_i} = 0.30$ ('6' open), the shaft pressure remain unaltered, and the flow is still from the shaft into corridor.

If the shaft and room 6 doors are opened together, the shaft pressure drops slightly. Since in this case, both the shaft and corridor pressures are lower than the room 6 pressure, it is likely that most of the smoke will find its way into the shaft. Because on other floors there already exists a flow from shaft into the corridors, this door opening configuration can easily cause smoke to spread to other floors. This combination of door openings must be avoided.
4.1.1.2 $\alpha = 45^\circ$

With the increase in wind angle $\alpha$, the outside pressures over the shaft region decrease, and the shaft pressure drops accordingly. Due to the stagnation point disappearing from side T the room(1), (2) and (3) pressures also decrease (see Figures 4.8 to 4.13). As a result of this drop in shaft and corridor pressures, and also due to the fact that room(4), (5) and (6) pressures remain negative, the corridor pressure decreases also (see Figure 4.14).

$$C_{p_i} (\text{Corridor}) = 0.23 \quad \alpha = 0^\circ$$

$$C_{p_i} (\text{Corridor}) = 0.16 \quad \alpha = 45^\circ$$

The shaft pressure, in comparison, drops much more rapidly, as this figure shows. The reason for

$$C_{p_i} (\text{shaft}) = 0.43 \quad \alpha = 0^\circ$$

$$C_{p_i} (\text{shaft}) = 0.17 \quad \alpha = 45^\circ$$

this is that the outside pressures in the shaft region drop considerably more than those on the outside regions of rooms(1), (2) and (3). It is these three rooms that dominate the corridor pressure.

Pressure measurements in rooms(4) and (5) indicate (see Figure 4.2.3 II) that at $\alpha = 45^\circ$, the suction pressure over side R is increased as a result of the change in wind direction. This gives rise to increased pressure difference across room(6) window holes, and lot more of the fire pressurising air (smoke) flows out of these windows. As a consequence the combined 'fire' and wind induced pressure inside room(6) decreases.

$$C_{p_i} (\text{Room(6)}) = 0.32 \quad \alpha = 0^\circ$$

$$C_{p_i} (\text{Room(6)}) = 0.13 \quad \alpha = 45^\circ$$
This decrease requires very small positive corridor pressure to prevent smoke entering the corridor. And it turns out that in this case ($\alpha = 45^\circ$) the corridor pressure ($C_{p1} = 0.16$) is just enough to confine smoke to fire room 6. In this situation, then, no smoke control measures, such as shaft pressurisation, are required provided all doors are kept closed.

The pressure changes in other rooms can occur only if the corridor pressure changes significantly as a result of the fire pressure. Room pressure measurements shown in Figures 4.8 to 4.13 confirm that the room pressures are unaffected. Any small changes apparent from these figures are probably due to the wind turbulence or experimental error.

The opening of shaft door ('S' open, Floor 2) does not have any significant effect on either the shaft or corridor pressures, as shown in Figure 4.15. This is because even when the shaft door is closed, the shaft and corridor pressures are almost equal. The room pressures also remain unchanged (see Figure 4.2.3 II).

No significant changes in pressures occur when the fire room 6 door ('6' open) is opened (see Figure 4.2.3.II). The probable reason for this is that the negative pressures over room 6 windows are so high that they help to draw most of the smoke out, and even when the room 6 door is opened, there is not much smoke left to flow through this increased leakage area. The shaft pressure is still high enough to confine smoke on the fire floor. The shaft and room 6 doors opened together ('S' and '6' open) have the same kind of effect. This way shaft is connected directly to the fire room and this must be avoided. The result for this configuration are given in Figures 4.2.3 II and 4.17.
FLOOR 4

The measurements on floor 4 show that, (Figure 4.2.4 II) due to the higher room pressures, the corridor pressure increases so that it is not only higher than the fire room pressure but also higher than shaft pressure as well (see Figure 4.19). It is because of this that the flow direction across the shaft door is reversed. This has many serious implications. If under certain conditions, the fire pressure is such that it is able to overcome the corridor pressure, smoke flowing into the corridor will find its way into the shaft helped by the higher corridor pressure. Once it gets into the shaft, it is taken to other floors by the already existing flow from shaft to corridor. Under such circumstances shaft pressurisation will be required, to stop smoke flow from 4th floor, at the same time not resulting in excess pressure on other floors.

As the shaft and corridor pressures do not differ very much, the opening of shaft door (‘S’ open) has very little effect. The flow pattern remains almost unchanged (see Figure 4.2.4 II). As fire room and the corridor pressures are very nearly equal, it is necessary to increase the shaft/corridor pressure to ensure that smoke is confined to the fire room. The shaft and corridor pressures, with and without the fire pressure in room(6) are shown in Figure 4.20. It shows no significant change.

Again because the corridor and room(6) pressures are of the same order of magnitude, no drastic change occurs when room(6) door is opened (‘6’ open). Room pressures also remain unaffected (see Figure 4.2.4 II). Similarly as this figure shows, no changes occur when shaft and room(6) doors are opened together (‘S’ and ‘6’ open).
Although for this particular wind direction door opening combinations do not produce any significant effects, on either floors 2 or 4, but it is useful to keep them closed all the time.

4.1.1.3 $\alpha = 90^\circ$

FLOOR 2

As the wind angle increases further, the negative pressure region over side T also increases, until at $\alpha = 90^\circ$, both the sides (T and R) are subjected to very high negative pressures. The outside pressures are discussed in Chapter 3 in detail. When there is no fire pressure in room(6), the negative pressure in this room is higher than that in the corridor, and air flows into room(6) from the corridor (see Figure 3.5.2 II). But a fire pressure in room(6) increases the pressure, and negative pressure outside the windows are unable to draw out all the air (smoke) supplied to room(6). The result is that large quantities of air (smoke) flow into the corridor (see Figure 4.3.2). This causes a slight increase in the corridor pressure (Figure 4.14) but is not enough to reverse flow across the shaft door. The shaft, therefore, remains smoke free, and no need for smoke control measures (such as shaft pressurisation) arises, in this case. The large quantity of smoke ($M = 0.53R_1$) that enters the corridor, is sucked out through other rooms which are at high negative pressures. The internal room pressures are dominated by the prevailing outside wind pressures therefore extra flow resulting into the corridor from fire room, has a negligible effect on the room pressures. This conclusion is substantiated by the measured results shown in Figures 4.8 to 4.13. It must be said here that the measurement of mean pressures do not fully describe the internal flow pattern.
For this particular wind direction, flow through all the leakage paths is of fluctuating nature. For full discussion see Chapter 3 Volume II.

As soon as the shaft door ('S' open) is opened the shaft and corridor become one volume, with one average pressure. As a result the corridor pressure increases slightly and the shaft pressure decreases (see Figure 4.3.2). Because of this increase in corridor pressure, the smoke flow from room 6 decreases. Opening of shaft door virtually eliminates any resistance to smoke flow into the shaft, and this smoke can spread easily to other floors as well. In this case shaft pressurisation will be necessary to keep shaft free of smoke. No significant changes in other room pressures occur.

When room door 6 is opened the door leakage area becomes much higher than the total window leakage area, which results in an increased flow rate into the corridor. The corridor pressure rises, with a consequent decrease in pressure difference across the shaft door.

\[ \Delta C_{p_1} \text{ (shaft door)} = 0.17 \quad \text{'All Closed'} \]
\[ \Delta C_{p_1} \text{ (shaft door)} = 0.05 \quad \text{'6' open}. \]

Compare Figures 4.14 and 4.16.

Even though the flow into the corridor is taken out through other rooms, any growth in fire giving rise to higher corridor pressure can endanger the shaft and bring about the need for shaft pressurisation. As seen from Figure 4.3.2 II other room pressures remain unchanged.
The opening of shaft and room doors together ('S' and '6' open) brings about equalisation of the shaft and corridor pressures (see Figure 4.3.2 II), which is higher than the room pressure. From these pressure measurements it is clear that, perhaps, no smoke gets into the corridor/shaft, but any growth in fire can easily alter that situation, and the shaft will be threatened directly. These doors, therefore, must be kept closed. The room pressure changes are very small, and do not alter the flow direction across the doors.

FLOOR 4

On this floor the negative outside pressures are higher than those on floor 2 and as a result the internal negative pressures are also higher (compare Figures 4.3.2 II and 4.3.3 II).

\[
\begin{align*}
C_{pi} \quad \text{(Corridor)} &= -0.32 \quad \text{Floor 2} \\
C_{pi} \quad \text{(Corridor)} &= -0.40 \quad \text{Floor 4}
\end{align*}
\]

If is this higher negative pressure that results in an increased flow rate of smoke from room into the corridor.

\[
\begin{align*}
M &= 0.53 \ R_1 \quad \text{Floor 2} \\
M &= 0.61 \ R_1 \quad \text{Floor 4}
\end{align*}
\]

This increased flow rate does not present any danger to the shaft, as the pressure difference across shaft door is also increased.

\[
\begin{align*}
\Delta C_{pi} \quad \text{(shaft door)} &= 0.17 \quad \text{Floor 2} \\
\Delta C_{pi} \quad \text{(shaft door)} &= 0.23 \quad \text{Floor 4}
\end{align*}
\]

Figures 4.8 to 4.13 show that the room pressure changes as a result of the fire pressure in room are negligible.
In this case, even though there is a large amount of smoke resulting into the corridor, no shaft pressurisation is required as all of this smoke is drawn out through other rooms, which are subjected to higher negative pressures.

Opening of shaft door ('S' open) results in an increase in the corridor pressure which reduced the flow rate of smoke into the corridor. Because of the reduced resistance to flow into the shaft, smoke can easily flow into the shaft and form there on to the other floors. This door must, therefore be kept closed.

When room(6) door is opened, flow of smoke into the corridor increases dramatically, and the room(6) pressure tends toward the corridor pressure. The increased flow rate raises the corridor pressure, and the pressure difference across shaft door decreases.

\[ \Delta C_{p1} (\text{shaft door}) = 0.23 \quad \text{'All Closed'} \]
\[ \Delta C_{p1} (\text{shaft door}) = 0.05 \quad \text{'6' open}. \]

In this case shaft pressurisation will be required to confine smoke to the fire floor. Most of the smoke flows out through other rooms.

The shaft and room(6) doors opened together ('S' and '6' open) make it easier for the smoke to flow into the shaft. If no pressurisation is present, these doors must be kept closed.

The results for all these door opennings are summarised in Figures 4.19 to 4.22. Apart from the increased flow rates, the general flow pattern is the same as on floor 2.
4.1.1.4 $\alpha = 135^\circ$

FLOOR 2

As positive pressures begin to appear on side R, with the increase of wind incidence, the pressures in rooms 4, 5 and 6 begin to increase. Whereas for $\alpha = 135^\circ$, the room 4 and 5 pressures stay the same as for no fire case (Figures 4.11 and 4.12) room 6 pressure combined with the fire pressure becomes very high. The fire pressure of 10N/m$^2$ when expressed in terms of pressure coefficient becomes

$$C_{p_{\text{fire}}} (\text{Room 6}) = 0.41$$

From Figure 3.4.2 II the wind induced pressure in room 6 is

$$C_{p_{\text{w}}} = 0.22$$

The sum of fire and wind pressures is

$$C_{p_{\text{fire and wind}}} = C_{p_{\text{fire}}} + C_{p_{\text{w}}} = 0.41 + 0.22 = 0.63$$

This as shown in Figure 4.4.3 II is very nearly equal to the measured pressure in room 6 ($C_{p_{\text{w}}} = 0.61$). Compared with $\alpha = 0^\circ$, and $45^\circ$, the internal flow pattern is reversed, with inflow into the corridor occurring through rooms 4, 5 and 6, and outflow through the shaft door and rooms 1, 2 and 3. The corridor pressure assumes negative value being dominated by the negative pressures in room 1, 2 and 3 and the shaft. Most of the flow generated by fire in room 6, flows into the corridor, and in fact about 60% of the total inflow occurs through room 5 door (Figure 4.4.3 II 'All Closed'). Because of the very high negative pressures in the shaft, smoke also finds its way into the shaft. In fact about 25% of the total outflow, flows through the shaft door.
As on other floors, the wind induced flow is from corridor into the shaft, there is no danger of this smoke in the shaft getting on to other floors. But since shaft is the only escape route, it must be kept smoke free, and shaft pressurisation is required. The fan system used for shaft pressurisation must generate enough pressure so that it is equal to $\Delta C_{p(shaft)} = 0.25$. At the same time, it must ensure that shaft doors on other floor do not exceed the permissible limit of 50N/m$^2$.

A comparison of Figures 3.6.2 II and 4.4.3 II show that the fire pressure in room® has a negligible effect on the other room pressures.

The opening of shaft door ('S' open) is very serious in this case as it not only increases the rate of flow into corridor, it also results in a decrease in outflow through rooms 1, 2 and 3 (see Figure 4.4.3 II). The figure shows that the corridor pressure is lowered so much that the flow across room 3 door is reversed. The smoke flow into the corridor increases from $M = 0.82 R_1$ (All Closed) to $M = 0.94 R_1$ ('S' open) and only 0.2 $R_1$ of this flows out through rooms 1 and 2, while the rest flows into the shaft. The shaft pressurisation system must develop very high pressure in the shaft to keep it free of smoke. In fact since shaft and corridor behave as 'one volume' the pressurisation system will only be effective if it overcomes the fire room door pressure ($\Delta C_{p_1(6)} = 0.89$). The relative shaft and corridor pressures are shown in Figure 4.15, which compares the 'with' and 'without fire' pressure cases.
Fire room door opening ('6' open) presents less serious problems compared with the shaft door open. Opening of this door increases the corridor pressure considerably as smoke fills the corridor.

\[ Cp_i \text{ (Corridor)} = -0.06 \quad 'All Closed' \]
\[ Cp_i \text{ (Corridor)} = 0.35 \quad '6' \text{ open}. \]

This results in an increased outflow through rooms 1, 2 and 3 and the shaft. The flow through the shaft door is higher than when all door are closed, and much lower than when the shaft door is opened.

In this case, the shaft pressure must be raised so that it overcomes the pressure difference \( \Delta Cp_i = 0.63 \) (see Figure 4.4.3 II).

The relative shaft and corridor pressures are shown in Figure 4.16.

Negative pressure in the fire room shows that when shaft and fire room doors are opened at the same time ('S' and '6' open) almost all the smoke is drawn into the shaft directly. This can smoke log the shaft in a very short time making escape impossible. Any shaft pressurisation system must work at a very high rate to confine smoke on to fire floor. For this wind incidence it is important to avoid opening these doors.

FLOOR 4

On floor 4, the wind induced room pressures are higher than those on floor 2 which results in an increased smoke flow rate into the corridor.

\[ M = 0.82 R_1 \quad \text{ (Floor 2)} \]
\[ M = 0.87 R_1 \quad \text{ (Floor 4)} \]

'All Closed'

Higher corridor pressure increases the pressure difference across shaft door

\[ \Delta Cp_i \text{ (Shaft door)} = 0.25 \quad \text{Floor 2} \]
\[ \Delta Cp_i \text{ (Shaft door)} = 0.35 \quad \text{Floor 4} \]
which means that the shaft pressurisation system will have to work at a higher rate. The room pressures remain unaltered as shown in Figures 4.8 to 4.13. Relative shaft and corridor pressures on this floor are shown in Figure 4.19.

When the shaft door is opened ('S' open), the corridor pressure drops dramatically to equal that in the shaft.

\[
\begin{align*}
C_{P_i} \text{ (Corridor)} &= 0.05 \quad \text{All Closed} \\
C_{P_i} \text{ (Corridor)} &= -0.24 \quad \text{ 'S' open.}
\end{align*}
\]

This drop in the corridor pressure increases the smoke flow rate which flows directly into the shaft. Flow through rooms 1, 2 and 3 is also reduced, and in fact for room 3, the pressure there is equal to the corridor pressure, indicating no flow (see Figure 4.4.4 II).

The shaft pressurisation must develop a pressure difference across the fire room door which is equal to \( \Delta C_{P_i} = 1.08 \)

With the opening of room 6 door, the corridor pressure is increased so that it is equal to the pressure in room 6. As a result flow through rooms 1, 2 and 3 is also increased. The shaft pressurisation system, in this case, has to overcome a pressure difference of \( \Delta C_{P_i} = 0.81 \). Other room pressures remain unchanged.

As for floor 2, all door openings must be avoided, especially shaft and room 6 door opening at the same time ('S' and '6' open). In this case all the smoke finds its way into the shaft, making escape from other floors impossible.
4.1.1.4 \( \alpha = 180^\circ \)

FLOOR 2

The highest wind pressure in room 6 is created when outside wind blows normal to side R in such a way that the stagnation point is over the windows of room 6 on floor 4. At this wind incidence, room 6 on floor 2 also experiences the higher positive pressure compared with other rooms on this floor.

On floor 2, the sum of wind and fire induced pressure is the same as measured in room 6 shown in Figure 4.5.3 II.

\[
C_{p_i} \text{(due to Fire)} = 0.41
\]

\[
C_{p_i} \text{(Wind alone)} = 0.59 \quad \text{(see Figure 3.7.2)}
\]

\[
C_{p_i} \text{(Fire room)} = 0.41 + 0.59 = 1.00
\]

The measured value is = 0.96. This is well within the experimental error. Compared with the previous incidence \( \alpha = 135^\circ \) the smoke flow into the corridor is not much higher.

\[
M = 0.82 \quad R_1 \quad \alpha = 135^\circ
\]

\[
M = 0.93 \quad R_1 \quad \alpha = 180^\circ
\]

This is due to the fact that the outside pressures over the room 6 windows are higher for this wind incidence than for \( \alpha = 135^\circ \). In fact, the combined fire and wind pressure in room 6, is much higher than the outside pressure over the windows of this room, and as a result smoke also flows out through these windows (see Figure 3.7 II). Same is also true for \( \alpha = 135^\circ \). Due to the decreased suction over side T, the shaft pressure is higher than for \( \alpha = 135^\circ \). Compare Figures 4.4.3 II and 4.5.3 II.

\[
C_{p_i} \text{(shaft)} = -0.31 \quad \alpha = 135^\circ
\]

\[
C_{p_i} \text{(shaft)} = -0.15 \quad \alpha = 180^\circ
\]
It is this increase which keeps the shaft door pressure difference the same ($\Delta C_{p_1} = 0.25$), even though the corridor pressure is higher for $\alpha = 180^\circ$. Here no extra flow into the shaft results due to the change in wind incidence. This means that for any wind direction between $135^\circ < \alpha < 180^\circ$, no change in pressurisation system will be required. The room pressures are shown in Figures 4.8 to 4.13, which show no significant changes due to fire pressure.

The opening of shaft door ('S' open) connects the corridor directly to the outside wall $T$, which is subjected to negative pressures. As a result the corridor pressure decreases to equal shaft pressure. This decrease in corridor pressure increases the rate of flow of smoke, which also finds its way into the shaft through the open door. Because the flow through rooms $1, 2$ and $3$ decreases, most of the smoke generated by fire flows into the shaft. It also flows out through room $6$ windows; outside pressures being smaller than inside room $6$ pressure. To stop smoke entering the shaft, its pressure, as well as that of the corridor must be raised, so that the pressure difference across the fire room $6$ ($\Delta C_{p_1}$ (fire)) is $1.05$. It is because of this reason that the shaft door must be kept closed as in that case, the shaft pressurisation has only to overcome $\Delta C_{p_1} = 0.25$.

Even though the flow rate into the shaft is increased due to the opening of room $6$ door, but the problem is not as serious as opening the shaft door. In this case, a pressure difference of $\Delta C_{p_1}$ (shaft door) $= 0.78$ must be maintained to confine smoke to the fire floor. Other room pressures remain unchanged as shown in Figure 4.5.3 II. The relative shaft and corridor pressures are shown in Figure 4.16.
Opening of shaft and room 6 doors ('S' and '6' open) must be avoided, as in this case all the smoke generated by fire gets into the shaft. Negative shaft and corridor pressures also lower the fire room pressure, which means no smoke can escape through room 6 windows. These doors must be kept closed.

FLOOR 4

On floor 4, due to the higher room pressures, the fire room pressure increases to a very high value.

\[ C_{p_i} \text{ (fire room)} = 0.96 \quad \text{Floor 2} \]
\[ C_{p_i} \text{ (fire room)} = 1.19 \quad \text{Floor 4} \]

The rate of smoke flow into the corridor also increases, which results in higher corridor pressure. Due to the negative pressure in the shaft, flow across the shaft door is also increased (see Figure 4.5.4 II). In this case the shaft pressurisation system must work at a rate so as to overcome the increased pressure difference across shaft door

\[ \Delta C_{p_i} \text{ (shaft door)} = 0.25 \quad \text{Floor 2} \]
\[ \Delta C_{p_i} \text{ (shaft door)} = 0.38 \quad \text{Floor 4} \]

The room pressures shown in Figures 4.8 to 4.13, are not changed.

When the shaft door is opened ('S' open) the pressure difference across the fire room door increases due to the drop in corridor pressure, sending more smoke into the shaft. Smoke also flows out of the fire room windows. The pressurisation system in this case must overcome the pressure difference across fire room door

\[ \Delta C_{p_i} \text{ (fire room door)} = 1.28 \]
Once again the changes in corridor pressures do not have any significant effect on other room pressures. The shaft and corridor pressures for this case are shown in Figure 4.20.

The corridor pressure increases dramatically when the fire room door is opened. As a result of this increase, the smoke flow rate through the shaft door also increases. The pressurisation system must overcome this higher pressure in order to confine smoke to the fire floor. But at the same time it is necessary to ensure that the maximum allowed pressure difference (50N/m^2) is not exceeded on other floors. This is always the danger when shaft pressurisation is used for smoke control. As figure 4.5.4 II shows the room pressures do not change significantly. The corridor and shaft pressures are shown in Figure 4.21.

As on floor 2, the opening of shaft and room doors at the same time must be avoided, as in this case all the smoke finds its way into the shaft. The pressures are shown in Figures 4.5.4 II and 4.22.

These results show that for this wind incidence, as well as for the previous one, any door openings must be avoided. And that the shaft pressurisation system must be very carefully designed not to create problems of over-pressure on floors other than the fire floor.
4.1.1.6 $\alpha = 225^\circ$

FLOOR 2

As the stagnation point on wall R moves towards the duct (D) due to increase in wind angle, the positive pressures in rooms 4, 5 and 6 decrease. On side T, on the other hand, the suction pressure increases due to the large vortices present in the wake. The situation is very much similar to that for $\alpha = 135^\circ$, only the rooms change places with respect to the pressure contours. The corridor pressure drops and becomes negative as shown in Figure 4.14. The pressure outside room 6 is still positive, but less than the fire room pressure, which makes smoke flow out of the windows (see Figure 4.6.3 II). The amount of smoke flow into the corridor is the same as for $\alpha = 180^\circ$, because even though the positive pressures on side R are small for $\alpha = 225^\circ$, the negative corridor pressure compensates for that decrease. Very little smoke gets into the shaft, because most of it that flows into the corridor, is taken out through rooms 1, 2 and 3, due to the high negative pressures there. The shaft door pressure differences for the two wind direction are (compare Figures 4.5.3 II and 4.6.3 II).

$$\Delta C_{p_1} \text{ (shaft door)} = 0.28 \quad \alpha = 180^\circ$$

$$\Delta C_{p_1} \text{ (shaft door)} = 0.06 \quad \alpha = 225^\circ$$

This decrease is very helpful from the smoke control point of view, as the shaft pressurisation system, in this case, has to overcome, very small opposing pressure, to stop smoke getting into the shaft. The room pressures are shown in Figures 4.8 to 4.13, which show no change due to the fire pressure in room 6.
A dramatic increase of flow into the shaft occurs when the shaft door is opened ('S' open). The corridor in this case is directly connected to the outside wall T, and its pressure drops from $C_{p_1} = -0.12$ to $C_{p_1} = -0.25$ (see Figure 4.6.3). As a result the smoke flow from room(6) into the corridor increases due to the increase in pressure difference across room(6) door. This drop in the corridor pressure decreases the flow rate through rooms(1, 2) and(3), and consequently smoke can only go out through the shaft. The shaft pressurisation system in this case has to overcome the pressure difference across room(6) door to keep it smoke free. The door therefore, must be kept closed. The shaft and corridor pressures are shown in Figure 4.15. No change in other room pressures occur as Figures 4.8 to 4.13 show.

Opening of room(6) door must also be avoided, as it increases the flow rate into the shaft, because of the increased corridor pressure (see Figure 4.6.3 II). In this case the shaft pressurisation system has to overcome a pressure difference of $\Delta C_{p_1} = 0.60$.

As in the case of other wind incidences, shaft and room(6) doors opened together is most dangerous, as almost all the smoke gets into the shaft. Any pressurisation system that tries to keep back smoke from the shaft, will certainly create over pressures on other floors. These results confirm that, as for other wind directions, all doors must be kept closed for this direction too.
FLOOR 4

On this floor, once again, the positive room pressures are much higher than those on floor 2. See Figure 4.6.4 II. The shaft and corridor pressures are shown in Figure 4.19.

The combined wind induced and fire pressure in room 6 is still higher than the outside pressure, and as a result smoke flows out through the windows. Compared with the floor 2, the corridor pressure on this floor is positive.

\[ C_{p_i} \text{ (Corridor) } = -0.12 \text{ Floor 2} \]
\[ C_{p_i} \text{ (Corridor) } = 0.03 \text{ Floor 4} \]

A comparison of Figures 3.8.3 II and 4.6.4 II (without 'fire' and with 'fire') shows that the further increase in corridor pressure is brought about by the flow of smoke into the corridor. But when the steady state conditions are reached, the pressure difference across the fire room door is the same on floors 2 and 4 (compare figures 4.6.3 II and 4.6.4 II). Higher corridor pressure increases the flow rate through the shaft door.

\[ \Delta C_{p_i} \text{ (shaft door) } = 0.06 \text{ Floor 2} \]
\[ \Delta C_{p_i} \text{ (shaft door) } = 0.33 \text{ Floor 4} \]

This increase is caused by the higher corridor pressure and the lower shaft pressure. The shaft pressurisation is required, which must overcome the pressure difference of \( \Delta C_{p_i} = 0.33 \) across the shaft door. Other room pressures remain unaffected by the changes in corridor pressures.
As on floor 2, opening of shaft door ('S' open) results in a drop in corridor pressure, which increases the pressure difference across room \(6\) door, with a consequent increased smoke flow into the corridor.

Since the shaft and corridor behave as 'one volume', the pressurisation system must be capable of maintaining a pressure difference of \(\Delta C_{p_i} (\text{fire room} 6\text{ door}) = 1.09\), to confine smoke to the fire room.

This way the system will almost certainly create over pressures across shaft doors on other floors. This shaft door, therefore must be kept closed.

A dramatic increase in corridor pressure occurs when room \(6\) door is opened ('6' open). This increase results in higher pressure differences across other room doors. Since pressures in rooms \(4\) and \(5\) are small (see Figure 4.6.4 II) the flow direction across these rooms is reversed, and their pressures are also altered. Room \(5\) pressure increases to equal the corridor pressure, hence no flow across room \(5\) door.

\[
\begin{align*}
C_{p_i} (\text{Room} 3) &= 0.38 \quad \text{'All Closed'} \\
C_{p_i} (\text{Room} 5) &= 0.50 \quad \text{'6' open}.
\end{align*}
\]

Room \(4\) pressure, on the other hand, although increased, but is still less than the corridor pressure, and a flow from corridor pressure, and a flow from corridor into this room results.

\[
\begin{align*}
C_{p_i} (\text{Room} 4) &= 0.24 \quad \text{'All Closed'} \\
C_{p_i} (\text{Room} 5) &= 0.33 \quad \text{'6' open}.
\end{align*}
\]

This increased outflow through all the rooms is not enough to draw all the smoke out of the corridor, and quite a lot of it flows into the shaft, helped by the high pressure difference.
Since the flow into shaft is less for the 'All Closed' case, this door must be kept closed.

When the shaft and fire room doors are opened together, room then becomes directly connected to the outside wall through the shaft and corridor. If there was no fire pressure in room, the pressure in shaft, corridor and room will be same. But in this case, room pressure is higher due to the fire. As a result smoke flows directly into the shaft. These door openings must therefore be avoided. The shaft and corridor pressures are shown in Figure 4.22.

4.1.1.7 $\alpha = 270^\circ$

FLOOR 2

The external pressure distribution for this wind incidence is a mirror image of that at $\alpha = 90^\circ$. In this case highest negative pressures appear over the windows of the shaft, and this has very important consequences for the internal flow pattern. The relative room, shaft and corridor pressure measurements are shown in Figure 4.7.2 II. It shows that for the 'all doors closed' case, the corridor pressure is much higher than the shaft pressure, with a flow

\[
\begin{align*}
C_{p_1} \text{ (shaft)} &= -0.70 \\
C_{p_1} \text{ (Corridor)} &= -0.35
\end{align*}
\]

resulting into the shaft. For room since there are very high negative pressures over the windows of this room, most of the smoke is drawn out of these windows. Because the corridor pressure is lower than the combined fire and wind pressure in room, some of the smoke also flows into the corridor.
For rooms 1, 2 and 5 the flow is from the corridor, as these rooms experience very high negative pressures. But in the case of rooms 3 and 4, the flow results into the corridor. The smoke that flows into the corridor from room 6 is taken into the shaft by the existing pressure difference across the shaft door ($\Delta C p_1 = 0.35$, Figure 4.7.2 II). Although the flow of smoke into the corridor is not much compared with some of the other wind directions (e.g. $\alpha = 180^\circ, 135^\circ, 225^\circ$), but to keep the shaft effectively smoke free, shaft pressurisation is required, which is capable of overcoming the shaft door pressure difference of $\Delta C p_1 = 0.35$.

When the shaft door is opened, the corridor pressure decreases, as the corridor becomes directly connected to the outside wall T. This decrease in pressure increases the smoke flow into the corridor ($\Delta C p_1$ (fire room door) = 0.22) which can easily find its way into the shaft. In this case the shaft pressurisation system must work so as to oppose the pressure difference created across the fire room door. As a result of the decrease in corridor pressure, the flow direction across rooms 2 and 5 doors is reserved. The pressures in other rooms go through very small changes. See Figures 4.8 to 4.13.

As soon as room 6 door is opened ('6' open), the flow of smoke into the corridor increases dramatically, and as a result the corridor pressure increases compared with the previous door opening case (see Figure 4.7.2 II). There exists a considerable pressure difference across the shaft door, which can push smoke into the shaft. Shaft pressurisation is required to counteract this pressure difference.
The room pressures are very little affected by the change in corridor pressure. The flow pattern is the same as for 'All Closed' case. The relative shaft and corridor pressures are shown in Figure 4.16. This figure shows that the shaft pressure are less effected by the fire pressure in room 6. The corridor pressure, on the other hand, experiences large changes.

The pressure changes in the shaft and corridor, due to the opening of shaft and room 6 doors together ('S' and '6' open) are shown in Figure 4.17. The room pressures are shown in Figure 4.7.2 II. Because the shaft is subjected to very high negative pressures, smoke from the fire room is directly sucked into the shaft. This particular configuration must be avoided. Under these conditions shaft pressurisation is essential to confine smoke to the fire room. Very large negative pressure outside room 6 window helps to draw most of the smoke out.

FLOOR 4

The room, corridor and shaft pressure measurements on this floor are shown in Figure 4.7.3 II and Figures 4.19 - 4.23.

Because the rooms are subjected to very high negative pressures on this floor, the measurements show that almost all the fire pressurising air (smoke) is drawn out through the room 6 windows. The shaft and corridors on this floor remain smoke free (see Figure 4.7.3 II, 'All Closed'). Even though there is a tendency for the air to flow into the shaft, no shaft pressurisation is needed. Figure 4.19 shows that the shaft pressure is unaffected by the fire pressure, and that only very small changes occure in the corridor pressure.
This is mainly due to the fact that most of the smoke escapes through the room® windows.

As soon as the shaft door is opened ('S' open), the drop in corridor pressure creates favourable pressure difference across the room® for the smoke to flow into the corridor. Some of this smoke finds its way into the shaft. A shaft pressurisation is required to counteract the pressure difference ($\Delta Cp_1 = 0.16$) across the fire room door. The room pressures remain unaffected.

The opening of room® door has the same consequences as on floor 2, and a shaft pressurisation system is required to counteract a pressure difference of $\Delta Cp_1$ (shaft) = 0.36 (see figure 4.7.3 II and Figure 4.21). Figure 4.21 shows that as before the corridor pressures are much affected by the fire pressure.

The opening of shaft and room® doors together must be avoided, as the shaft can become smoke logged in a very short time.
4.1.2 Leakage Configuration (b) | 1.5* | 1.5 | 1.5

As discussed in chapter 3, the effect of reducing the shaft leakage is to make the shaft pressures dependent on the corridor pressures. This reduces the shaft door pressure difference considerably, making it easier for the smoke to flow into the shaft. But if a shaft pressurisation is used for smoke control purposes, reduced pressures difference would mean no danger of overpressurisation. A detailed discussion of internal pressures is given in chapter 4 Volume II. The shaft and corridor pressure measurements are shown in figs 4.24-4.34 on floors 2 and 4 for all the internal door opening configuration investigated. The present discussion is confined to the shaft door pressure difference.

4.1.2.1 All internal doors closed (all closed):

The results for all wind angles on floor 2 are shown in fig 4.21. A comparison of these results with those of fig 4.14 shows that the shaft pressures are similar to the corridor pressures for leakage (b) than for (a). This means that the flow direction across the shaft door can easily be altered by the small changes in shaft or the corridor pressures.

For zero wind angle ($\alpha=0^\circ$) when there is no fire pressure in room 6, the higher shaft pressure causes the air to flow into the corridor, but the amount flowing is very small because of the small pressure difference ($\Delta p_1=0.08$). But as soon as a fire pressure
is introduced in room (6), the corridor pressure increases which reverses the flow direction across the shaft door, with no air flowing into the shaft from the corridor ($\Delta C_p = 0.01$). In a real fire situation this flow could be the smoke, and shaft pressurisation will be required to confine smoke to the corridor. On floor 4, the flow rate into the shaft is much higher ($\Delta C_p = 0.05$) because of the high wind induced pressures at that level (fig 4.29).

As the wind direction changes, the internal pressures change also. At wind incidence $\alpha = 45^\circ$, the shaft and corridor pressures at the floor 2 level, are very nearly equal. Very small amounts of smoke get into the shaft, but shaft pressurisation required if fire grows. On floor 4 (fig 4.29) flow into the shaft is higher due to the high pressure difference across the shaft door.

A very complicated flow pattern exists at wind incidence of $\alpha = 90^\circ$ (see chapter 3). Both the leaky walls (T and R) are subjected to very high negative pressures. As fig 4.24 shows the corridor negative pressure is higher than the shaft negative pressure, even with the fire pressure in room (6) on floor 2. This results in a flow of air from shaft into the corridor, keeping shaft free of smoke. Accordingly no shaft pressurisation is needed in this case. But since the pressure difference responsible for this flow is small, any further growth in fire may require shaft pressurisation. On floor 4 (fig 4.29) the wind induced negative pressures are higher than on floor 2 which results in an increased flow rate into the corridor. Again no shaft pressurisation is required unless the fire grows.
At wind incidences higher than $\alpha=90^\circ$, positive wind induced pressures start to appear on side R. This reduces the flow of smoke through the room windows and most of it finds its way into the corridor.

The pressure measurements for $\alpha=135^\circ$ (fig. 4.24) on floor 2 show that both the shaft and corridor pressures are negative but the shaft pressure is slightly lower than the corridor pressure. As a result smoke flows into the shaft. The amount of flow is small due to the small pressure difference ($\Delta P = 0.06$). The shaft pressure must be raised so as to keep it completely smoke free. The corridor pressure on floor 4 becomes positive while that of the shaft remains negative. This increased pressure difference increases the flow of smoke into the shaft ($\Delta P = 0.15$, fig. 4.29), which shaft pressurisation must counteract.

As the wind angle continues to increase further, the positive wind induced pressure outside room windows also increases. On side T, on the other hand, the negative pressure is decreased. As a result the wind induced corridor pressure becomes positive and opposes the flow of air from room. As the shaft pressure is dependent on the corridor pressures on all floors, it too becomes positive. The result of this is that the pressure difference across the shaft door, responsible for the flow of smoke into the shaft, remains virtually unchanged (see fig. 4.24, $\alpha=135^\circ$ and $180^\circ$). The same is true for the pressures on floor 4 (fig. 4.29). But the pressure difference responsible for the flow into the shaft is much higher.
Figure 4.24 shows that both the shaft and corridor pressures start to drop as the wind angle is increased. At wind incidence $\alpha=225^\circ$ they become negative with flow still into the shaft caused by approximately the same pressure difference, as for $\alpha=180^\circ$, $135^\circ$. But on floor 4 (fig 4.29), because of the high outside positive pressures, the corridor pressure remains positive whereas the shaft pressure drops to negative values. Again the pressure difference across the shaft door does not change very much from the previous wind angles.

These measurements for $135^\circ < \alpha \leq 225^\circ$ show that, although the shaft and corridor pressures change a great deal with the change in outside wind direction but the pressure difference across the shaft door remains the same. Therefore no changes in the shaft pressurisation system will be required for this range of wind angles.

When the external wind direction changes to $\alpha=270^\circ$, the situation is very much similar to that for $\alpha=90^\circ$, in that both sides T and R are subjected to very high negative pressures. As a result most of the smoke from the fire room is sucked out of the windows. The shaft in this case is subjected to very high negative pressure which is higher than the negative pressures in corridors on floor 2 or 4 (fig 4.24 and 4.29). As a result air is pulled into the shaft from each floor corridor. If on the fire floor corridor is smoke logged, it will flow into the shaft due to this favourable pressure difference. Hence shaft pressurisation is required which is contrary to the case of $\alpha=90^\circ$. 
From these measurements, it is clear that even with the fire pressure in room 6 the outside wind direction $0^\circ \leq \phi \leq 90^\circ$, there is a tendency for the air to flow from the shaft on to the corridors. In these cases then even if there is no shaft pressureisation present the shaft will not be threatened by smoke. Even if smoke does flow into the shaft, its concentration is very low.

For wind directions $90^\circ \leq \phi \leq 270^\circ$, the flow across the shaft door is reversed, and the shaft pressurisation becomes essential to keep it free of smoke. These conclusions apply only if all doors are kept closed at all time. The effects of internal door openings were also investigated.

4.1.2.2 Shaft Door open on the 'fire' floor (s' open)

As the shaft and corridor pressures are very nearly equal when the door is closed, the opening of the door does not alter pressures significantly. Compare figs 4.24 and 4.25 for floor 2 and figs 4.29 and 4.30 for floor 4 for both $\phi = 0^\circ$ and $45^\circ$. The opening of the shaft door reduces, considerably, the resistance to flow either way. If the flow rate from the fire room into the corridor increases, due to the increased size of the fire, it can endanger shaft direction as no resistance is offered to the flow of smoke. From the measurements shown in figs 4.1.5 II and 4.2.7 II, it is clear that in the present case very small amounts of smoke flows into the corridor, and not all of it flows into the shaft. Some is
true for the measurements on floor 4 for $\alpha=0^\circ$ and $45^\circ$ (see figs 4.1.6 II and 4.2.8 II).

A wind incidence of $\alpha=90^\circ$, the shaft and corridor pressures are again close to each other, which means that the flow pattern remains unchanged by the opening of the shaft door, as figs 4.25 and 4.30 show.

For wind angles higher than $\alpha=90^\circ$, the situation begins to change considerably. The measurements for $\alpha=135^\circ$ show that when the shaft door is closed, the shaft pressure is much lower than the corridor pressure which results in large flow rate into the shaft. As soon as the door is opened, the leakage area through which this flow can occur increases dramatically and the pressure difference drops. The resulting decrease in the corridor pressure increases the rate of flow of smoke (air) from the fire room. And this flows directly into the shaft (see fig 4.4.6 II). Same is true for floor 4 (fig 4.4.7 II).

For wind incidences $\alpha=180^\circ$ and $\alpha=225^\circ$, the results (figs 4.5.7 II and fig 4.6.6 II for floor 2 and figs 4.5.8 II and fig 4.6.7 II for floor 4) show that the smoke flows directly into the shaft. In all these cases shaft pressurisation is required, and the pressure must be raised to such a value so that it is higher than the fire room pressure. But if the shaft door is kept closed, the shaft pressurisation has only to overcome the corridor pressure.
Same is true for $\alpha=270^\circ$ on the results shown in figs 4.7.5 II and 4.7.6 II indicate.

4.1.2.3 Fire room (6) door open ('6' open):

When room (6) door is opened the rate of flow of smoke into the corridor increases dramatically because of the decreased resistance to flow. The shaft and corridor pressure measurements on floor 2 are shown in fig 4.26. It shows that the shaft pressures for all wind angles remain virtually unchanged by the fire pressure. Due to the opening of this door the corridor becomes directly connected to the fire room and undergoes very large pressure changes.

For wind angle $\alpha=0^\circ$ and $45^\circ$ (fig 4.26) the shaft and corridor pressures are very nearly equal, and there is a possibility that some smoke finds its way into the shaft. The pressure difference responsible for this flow is very small (fig 4.26). Same is true for floor 4 (see fig 4.31.

At wind incidence $\alpha=90^\circ$, the corridor pressure both on floors 2 and 4 (figs 4.26 and 4.31) becomes higher than the shaft pressure and the flow direction across the shaft door is reversed. For the wind direction, then shaft pressurisation is required.

The effect of opening this door is much more serious for wind angles higher than $\alpha=90^\circ$. The increased flow rate into the corridor increases its pressure. As the shaft pressure remain unchanged, the pressure difference across the shaft door increases which results in an increased flow into the shaft. This pressure difference is the
highest for $\alpha = 180^\circ$ (see figs 4.26 and 4.31). For this range of wind angles ($135^\circ \leq \alpha \leq 225^\circ$) shaft pressurisation is necessary.

Because of the very high flow rate through the window leakage at $\alpha = 270^\circ$, the effect of opening the fire room door is very small. The pressure difference developed across the shaft door is not very high and as a result the rate of flow of smoke into the shaft is also very small compared with the previous angles (see figs 4.26 and 4.31). In this case the shaft pressurisation has to overcome very small corridor pressures.

4.1.2.4. Shaft and Room doors open ('s'+'6' open).

The fire room and the shaft are connected directly when these doors are opened. The resistance to the flow of smoke into the shaft becomes very small, which means that a small pressure difference can cause very large flow rates.

For wind angles $\alpha = 0^\circ$ and $45^\circ$ the fire room pressure is much higher than the corridor or shaft pressure (see figs 4.1.5II and 4.2.7 II) which means that the rate of smoke flow is much higher than any of the previous cases. This kind of door opening configuration must be avoided. The shaft pressurisation must develop a pressure higher than the fire room pressure in the pressure in the shaft and corridor to confine smoke to the fire room.
At $\alpha=90^\circ$, the corridor and shaft pressure is higher than the fire room pressure which helps to confine smoke to the fire room (fig 4.3.5 II). Same is also true for floor 4 (fig 4.3.6 II). The shaft and corridor pressures are also shown in fig 4.27 and 4.32. These figures show that for all wind angles, the shaft and corridor pressures are the same.

The rise in shaft and corridor pressures for $\alpha=135^\circ$, $180^\circ$ and $225^\circ$ is caused by the flow of smoke into these areas from the fire room through the open doors. On floor 4 the flow rate is much higher because of the high positive pressures on side R. For these wind angles the shaft pressurisation must develop very high pressures in the shaft and corridor to keep these areas free of smoke. This might result in over pressures on other floors, making it difficult to open doors for escape. It is from this point of view that this kind of door opening combination must be avoided.

At $\alpha=270^\circ$, the shaft and corridor pressure is higher than the fire room pressure indicating that most of the smoke is taken out of the fire room windows (see fig 4.7.5 II). In this case no pressurisation will be required.
4.1.3. Conclusions:

From the pressure measurements with a 'fire' pressure in room 6, the following conclusions may be made.

(i) The 'fire' pressure when combined with the wind induced pressure have a considerable effect on the pressure difference across the shaft door. The design of any shaft pressurisation system must take this into account.

(ii) For positive wind induced pressures on the shaft windows, higher shaft leakage requires no shaft pressurisation.

(iii) For other wind angles shaft pressurisation is required with small shaft leakage.


Fig 4.8: Room pressure ($C_{p_1}$) variation with wind incidence ($\alpha$)
Fig 4.9: Room pressure ($C_{p1}$) variation with wind incidence ($\alpha$)
Fig 4.10: Room pressure ($C_{p_1}$) variation with wind incidence ($\alpha$).
Fig 4.11: Room pressure ($C_{p_i}$) variation with wind incidence ($\alpha$).
Fig 4.12: Room pressure ($C_{p_1}$) variation with wind incidence ($\alpha$).
Fig 4.13: Room pressure ($C_{p_i}$) variation with wind incidence ($\alpha$).
Shaft and Corridor $C_{p_i}$, 'Fire' Floor 2.

'All Closed'.

Fig 4.14: Changes in Shaft and Corridor Pressures due to Door Openings and 'Fire'.
Shaft and Corridor $C_{p_i}$, 'Fire' Floor 2.
'S' Open, Floor 2.

Fig 4.15: Changes in shaft and corridor pressures due to door openings and 'fire'.

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Shaft and Corridor $C_{p_1}$, 'Fire' Floor 2.

'6' Open, Floor 2.

Fig 4.16: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_p$, 'Fire' Floor 2.
('S' + '6' open) Floor 2.

Fig 4.17: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_{p_1}$, 'Fire' Floor 4. 'All Closed'.

Fig 4.19: Changes in shaft and corridor pressures due to door openings and 'fire'.

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Fig 4.20: Changes in shaft and corridor pressures due to door openings and 'fire'.
Fig 4.21: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_{p_1}$, 'Fire' Floor 4.

('S' + '6') Open, Floor 4.

Fig 4.22: Changes in shaft and corridor pressure due to door openings and 'fire'.
Fig 4.24: Changes in shaft and corridor pressures due to door openings and 'fire'.

Shaft and Corridor $C_p$, 'Fire' Floor 2.

'All Closed'.

$T\ D\ R$

$1.5\ 1.5\ 1.5$

$+$ With 'Fire'

$+$ Without 'Fire'

$Sh.$

$Cor.$
Shaft and Corridor $C_p$, 'Fire' Floor 2.
'S' Open, Floor 2.

Fig 4.25: Changes in shaft and corridor pressures due to door openings and 'fire'. 
Shaft and Corridor $C_{p1}$, 'Fire' Floor 2.
'6' Open, Floor 2.

Fig 4.26: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_p$, 'Fire' Floor 2.

('S' + '6') Open, Floor 2.

Fig 4.27: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_{p_{1}}$, 'Fire' Floor 4.
'All Closed'.

Fig 4.29: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_p$, 'Fire' Floor 4.
'S' Open, Floor 4.

Fig 4.30: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_p$, 'Fire' Floor 4.
'6' Open, Floor 4.

Fig 4.31: Changes in shaft and corridor pressures due to door openings and 'fire'.
Shaft and Corridor $C_{p_l}$, 'Fire' Floor 4

('S' + '6') Open, Floor 4.

Fig 4.32: Changes in shaft and corridor pressures due to door openings and 'fire'.
Fig 4.28 Corridor pressure variation with $\alpha$, Leakage (b), Fire room (6) Floor 4
CHAPTER FIVE

MEASUREMENTS OF FULL SCALE INTERNAL AND EXTERNAL WIND INDUCED PRESSURES ON THE DARWIN BUILDING.
5.0 Introduction

Tall buildings present special problems from the smoke control point of view in fire situations. Because of their height (30m) the use of firemen's ladders in any kind of rescue from the outside becomes impossible. In such circumstances, the building stair shafts are the only principal means of escape and these must be kept clear of smoke.

Shaft or lobby pressurisation has been suggested for confining smoke to the fire floor. This involves supplying outside fresh air to the areas to be kept clear of smoke (such as shafts and perhaps corridors), in order to achieve excess pressure in these areas. This method, although theoretically sound, presents many practical problems, one of them being the limit to which an excess pressure can be imposed on a door so that it can be opened by a normal person in the building.

Apart from that, before such a system is installed in a building, it is essential to know under what conditions it will be required to perform. The system will not perform exactly as it is required if the shaft leakage is changed for some reason, because it may not be designed to cope with that changed leakage. But if the system is working, assuming one or two doors to be open and in a fire situation these doors are closed, it might generate unacceptable excess pressures, trapping people because they are unable to open the doors.
Other difficulties arise due to the changing outside wind conditions. If the building is completely sealed to isolate it from the effects of outside environments, any pressurisation system in this case will not work as the pressurisation air cannot flow to the outside. This is what is generally known as the "Concrete Balloon" effect.

On the other hand, leaky buildings present their own problems. A building is essentially a closed space designed to maintain different conditions from those prevailing outside, the most important of these conditions being the temperature. In winter conditions the temperature is higher than that outside and lower in summer conditions. Because of this difference in temperature, the consequent pressure difference sets up a flow pattern into and out of the building. This is usually known as the "Stack Effect" which depends very much on the size of the building, its leakage characteristics and temperature difference. This effect causes a wide range of pressure variation in the shaft which usually extends from top to bottom of the building.

Outside wind is another very important factor responsible for very high pressures over the building surfaces which vary quite considerably round the periphery, setting up air flow through the building interior and giving rise to pressure variation within the building. This, together with the stack effect, can generate quite high pressure differences across the interior doors. The pressure differences across the shaft doors are very important for shaft pressurisation. In many buildings these vertical shafts have their window openings to one of the walls and are therefore directly influenced by the outside
wind. The pressurising fan must be adjusted to take account of these pre-existing pressures otherwise one of two conditions can result:

(a) The fan is not generating enough pressure to prevent smoke from entering the shaft.

(b) The shaft pressure becomes so high that it makes door opening impossible.

From these considerations, then, the measurement of inside as well as outside pressures in real buildings under all possible wind conditions is essential. If smoke control measures are to be built into a building before it is constructed, some method of calculation or model tests are required.

To devise any mathematical calculation tool, or to test a model in the wind tunnel, full scale measurements on existing buildings are the starting point. According to Davenport (5.10) the objectives of such measurements are two-fold:

(1) To give vital clues for successful theories

(2) These theories cannot be claimed to be successful until verified by observation.

Literature surveys show that vast amounts of data have been collected over a number of decades for the pressure distribution over building surfaces caused by wind. Hardly any publications exist dealing with the effect of outside wind on internal pressures. Malinkowski (5.9) in his paper has briefly indicated some mechanisms
of flow by which air can enter a building. He discusses the importance of these pressures but does not suggest that he or anybody else in the field has done such measurements.

5.0.1 The Problems of Full-Scale Measurements.

In building aerodynamics, full scale measurements present considerable difficulties. They are due partly to the fact that wind is a very complex fluid and besides the statistical studies, not much is known about the real nature of atmospheric wind and turbulence. Some of the other difficulties are attributable to the size of buildings involved. The most common difficulties are:-

(i) All buildings have their own unique structural properties and surroundings, and the full-scale measurements are a reflection of these properties.

(ii) Any test programme is costly and time consuming because of the size of buildings involved. This imposes limits on instrumentation.

(iii) Unpredictability of wind (short duration, undesired gusts, etc) leave the experiments incomplete.

(iv) Building of special instruments is required.

Ideally, the instantaneous measurement of internal and external pressures, together with the knowledge of outside wind structure impinging on the building at the same time, is required. This ideal situation is almost impossible to achieve due to the lack of proper instrumentation of buildings. Under these circumstances,
it becomes necessary to compromise by taking pressure readings at discrete points. This can be done by fitting wind pressure gauges at a number of convenient locations round the periphery of the building. To obtain instantaneous measurements of pressure at these points, it is necessary to have these gauges working independently, recording pressure variations on a chart recorder to be analysed later in conjunction with similar results from other gauges. In this way the pressure variations on all the wall surfaces can be correlated with the measured or estimated outside wind profile. Using a limited number of these instruments, Newberry made pressure measurements on a number of buildings and the results are reported in references (5.12, 5.13, 5.14, 5.15). Such a method of independently working gauges presents great practical difficulties. For very large buildings the number of gauges required will be quite large and this may not be economically feasible.

The other method frequently employed for such measurements is to use one central pressure measuring instrument and connect these measuring points on the building through a multi-channel scanner by long plastic tubes. The measuring points are simply small holes (a few millimetres in diameter) drilled into the construction (in this case, windows) at convenient points on chosen floors. The plastic tubes are fitted into these holes so that they do not protrude out of the window glass. Care must be taken that these holes are not near any surface discontinuities giving rise to local very large pressure variations.
This method requires a very long length of tubing, depending on the height of building and the number of points at which pressure measurements are to be taken.

If the full scale results are to be compared with those of wind tunnel studies, the establishment of a reference pressure is necessary. Pressure at a point can be measured in absolute terms giving the sum of atmospheric and wind induced pressures. It is possible that when the wind induced pressure measurement is made, the atmospheric pressure also changes. Normally the range of wind induced pressures is about ± 500 N/m², and it is very rarely that this value is exceeded. At the same time, the atmospheric pressure can change by as much as 10,000 N/m². When that happens the contribution of wind will be difficult to assess. It is therefore convenient to express all pressure measurements relative to atmospheric pressures. All wind induced pressures then will either be above or below the atmospheric pressure. If the independently working pressure gauges are used to measure the pressure, then it is required that they be opened at the back to the atmosphere. However, due to the varying pressures within a building, the instrument will be measuring the outside wind induced pressure relative to the then prevailing room pressure. Due to the varying internal room pressures, the outside measurements cannot be related to each other. For this reason it is necessary to have a common reference pressure for all gauges.

For the purpose of the present measurements, no such gauges were
available. Instead, the pressure tapping points were connected
to the micromanometer by long plastic tubes, as described earlier,
and the measurements taken in turn. Because the atmospheric
pressure changes with height, it is common practice to use reference
pressure as the ground level atmospheric pressure. This kind of
instrumentation has its own disadvantages.

The obvious drawback is that the measuring point is joined to the
manometer by a very long plastic tube which runs up and down the
building through the vertical shaft and is subjected to varying
temperatures. This results in an error in the measurement.

For very high buildings some method of connecting these values
is required. Due to the small height of the present building,
no corrections were made. Since the emphasis was more on the
pressure differences across internal leakage paths, the choice of
reference point did not matter.

The other problem encountered in these exercises was the
inconvenience to the building users. Because the internal
pressures were also measured for different internal door opening
configurations, complete control of the building was required, which
was only possible at night time. All measurements were therefore
made in the evenings after 7.00 pm. Another problem was with the
switching off of the building ventilation system. The building
is normally used by the Departments of Microbiology, Forestry and
Natural Resources, and the experiments under controlled conditions
go on all the time. For this reason, the ventilation system was
switched off for a very limited time (maximum 3 hours per night). As each set of readings took about an hour, only three sets at the most were possible per night.

After the measurements, the tubes were left lying in the shaft and outside the designated rooms, for ease of setting up everything the next time. After a few weeks it was found that some of the tubes were blocked by water, due to condensation. As a result, the entire procedure was scrapped and some other method had to be devised.

The subsequent measurements were made by taking a very long tube and connecting it to the point of measurement when the reading was taken. That meant there was one person going from floor to floor and from room to room with this tube and connecting it to the appropriate points, while the other person recorded the reading and noted the position of the measuring point. The problem of communication between the two persons was solved by using two portable 2-way short wave radios. This method proved to be less tedious and gave quite good results, even though it took a longer time.

The biggest draw back of both these methods was that each set of measurements took no less than 45 minutes and over this interval of time the wind conditions can change quite considerably. Some of the measurements show this quite clearly. There is no guarantee that the wind speed and direction will be the same for
measurements on floors 2 and 8. Even on a single floor, due to the time lag in the measurement of one room pressure and the next, the wind pressure may have changed so that for one floor the measurements are due to a set of wind conditions (speed and direction, but under the circumstances these assumptions were inevitable. Considering all these problems, the results obtained were sufficiently reliable.

Assuming then that the wind conditions remained unchanged, at least over the time interval during which the measurements were made, the next problem was the correlation of these results with the outside wind. This is necessary for comparison with other results from model studies and full scale measurements on other geometrically similar buildings. For this a knowledge of the wind speed incident on the building is required. Ideally what is required is an anemometer placed at a considerable distance away from the building in the direction of flow at roof level, so that it is outside the building influence and all the pressure readings referenced to the dynamic pressure, as indicated by this anemometer. A distribution of such anemometers will be required to cater for possible wind directions. Unfortunately this is impracticable. The next best solution is to mount an anemometer on the roof on a mast so that it is outside the influence of the building. Here one thing must be remembered and that is that since the wind speed and turbulence vary with height, the anemometer must not be too remote from the roof.
5.0.2 The Building and its Surroundings

The building used for the purpose of full scale measurements forms a part of the Edinburgh University's King's Buildings complex at a site outside the city's built up areas. It is the only tall building in the area and can be considered to be free from influences of other buildings.

The Darwin Building is a square plan-section (29m x 29m) building which is approximately 45 metres high. It consists of ten floors with ground floor, in level with the ground on the north face (main entrance) and the floor below this is in level with the ground on the other three sides. The north and east walls are facing towards the main city while other two walls (west and south) are exposed to the open countryside. It is from this direction that strong winds blow on to the building most of the time. The pressure measurements have shown that the north wall is always subjected to negative pressures. Most of the time, west and south walls are subjected to positive pressures. It has not been possible to measure the wind profile at this site but it is assumed that the power law profile exponent is the same for woodland areas (0.30) because of the small hills nearby.

The building itself consists of one main stair shaft and four lift shafts, extending all the way up to the top floor. All these shafts are inside the building and are not exposed to the outside except at the roof level, where there is a door (usually kept
locked) leading from the shaft to the roof. The lift shafts are well protected from the outside. Two of the main lift shafts which are most commonly used are situated next to the stair shaft, while the other two are on the other side of the building and only used by staff for special purposes.

There is one emergency staircase outside the building on the east wall connecting every floor and it is protected from the outside weather conditions. The main entrance is at the ground level on the north wall.

The layout on each floor varies from floor to floor. The room sizes vary from very small offices to very large laboratories forming a complete side of the building as one of the walls of the room. The temperatures also differ from room to room quite considerably as some rooms are refrigerated while others are kept at very high temperatures for experimental purposes. Many offices are built within the large laboratories and are not connected to the corridor directly. The full details of the building are given in Appendix B.
5.1 Discussion of Results

The internal and external pressure measurements on the building were carried out over a period of several months under varying outside wind conditions (such as wind direction and speed). In almost all the sets of measurements, "stack effect" was also present in addition to the wind. Fortunately, out of all these sets of results, there is one set in which stack effect dominates (nearly zero wind), see Fig 5.2a, Stack Effect, and Tables 5.7, 5.7a and 5.7b, and in the other, wind effect dominates (internal and external temperatures equal) see Fig 5.2b Wind Effect $\alpha = 252^\circ$ and Tables 5.8, 5.8a and 5.8b.

As pointed out earlier, the pressure measurement results are only averages over a period of time and it has been assumed that the same wind direction and speed persists at least for the time during which measurements were taken (about one hour). All measurements were done at night time.

Fig 5.0: Definition of Wind Angle($\alpha$) with respect to the Darwin Building.
For the purpose of these measurements, the wind angle, $\alpha$, is defined as the angle between wind direction and normal to the north wall of the building.

Four rooms on floors 2, 4, 6 and 8 were chosen for internal and external pressure measurements. In this way, each room gave a measurement of outside pressure on each of the floor walls. All the pressure measurements were referred to the atmospheric pressure at ground level.

An anemometer was installed on a mast (height 4.0m) so that it was outside the building influence, to measure the wind speed at roof level. The dynamic pressure, $q$, was calculated using this wind speed. The outside pressure measurements were expressed in terms of this dynamic pressure.

The dynamic pressure, $q$, is given by

$$ q = \frac{1}{2} \rho V_H^2 $$

where

- $\rho$ = outside air density,
- $V_H$ = wind speed at building height.

The pressure coefficient is then defined as

$$ C_{p_o} = \frac{p_o}{q} $$

where $p_o$ = outside pressure relative to the atmospheric pressure, and similarly

$$ C_{p_i} = \frac{p_i}{q} $$
Where $p_i = \text{internal pressure relative to the atmospheric pressure.}$

Average internal and external temperature measurements were also made.

5.1.1 Stack Effect

Out of all the sets of internal and external pressure measurements on the Darwin Building under different environmental conditions, one set gives the measure of stack effect. When the measurements were taken the anemometer at the roof did not register any outside wind speed and under these conditions, the internal and external temperatures were:

\[
\begin{align*}
T_{\text{in}} &= 23^\circ \text{C} \\
T_{\text{out}} &= 15^\circ \text{C}
\end{align*}
\]

The pressure measurements on all four floors are shown in Table 5.7. As there was no outside wind blowing, these pressures are purely due to the stack effect. Since the internal temperature is higher than the external temperature, air rushes into the building through the leakage paths on lower floors and leaves through the leakage paths on upper floors. It is this potential inflow and outflow that gives rise to very small outside pressures which decrease with height.

This is why on floors 2 and 4 (Table 5.7) there are positive pressures on all four walls. These pressures decrease with height as the inflow is decreased; the table shows this quite clearly.
On the floors above the neutral pressure plane (i.e. the height at which the internal and external pressure is equal, in the present case this happens between 6 and 7 floors) the outside pressure changes but it does not have to be negative as the measurements on floor 8 show (Table 5.7).

![Diagram of neutral pressure plane and small positive pressures](image)

Fig 5.2.1: Stack Effect Giving Rise to Small Outside Positive Pressures on Lower Floors.

The measured internal room pressures are shown in Table 5.7a. From this table it is clear that they too decrease with height and that according to the room pressures the neutral pressure plane is also between floors 6 and 7.

The shaft and corridor pressures are shown in Table 5.7b, and the pressure differences across the shaft doors are plotted in Fig
5.2d. This figure shows that the flow direction across the shaft door varies from floor to floor and that, except for the ground floor (G), the shaft and corridor pressures can be considered to be very nearly equal. Neglecting the floor 2 measurements, it seems that the neutral pressure plane is between floors 5 and 6, which is very close to what other measurements (room and outside) show. From these measurements it can be concluded that at a temperature difference of 8°C the stack effect in the building does not produce any significantly high pressure differences across the shaft doors, provided of course all the shaft doors are closed.

5.1.2 Wind Effect Alone

In Table 5.8 are shown the outside pressure measurements for wind alone. In this case the internal and external temperatures were nearly the same and the contribution of stack effect to the internal pressures was negligible.

The outside pressure measurements show that on the west wall (W) all pressures are positive and increase with height up to floor 6 and above that floor they start to decrease. North (N) and south (S) walls are subjected to negative pressures. The table shows that the negative pressures on the north wall (N) are higher than those on the south wall, indicating that the size of the vortices coming off the north-west corner is much bigger than those coming off the south-east corner. This suggests that the wind direction
is more towards the south wall \(6\). From the empirical relationship between \(C_{p_0}\) and \(\alpha\), used in the computer program (see chapter 6), the wind direction is calculated to be about \(\alpha \approx 252^\circ\). It must be realised that this is only an average value as the wind direction changes quite a lot.

The measured internal room pressures are shown in Table 5.8a from which it is evident that they are all negative and small in magnitude. The latter fact suggests that the building window leakage is so small that outside wind has relatively little effect on the internal pressures. These windows are almost evenly distributed over the building surfaces, and from the distribution of outside wind induced pressures it is clear that more windows are subjected to negative pressures than to positive. As a result, negative pressure dominates inside the building, which is confirmed by the measurements shown in Table 5.8a.

The internal shaft and corridor pressures are shown in Table 5.8b and the pressure difference across the shaft doors is plotted in Fig 5.2h. This figure shows that on all floors (except for floor 6) air flows from the shaft into the corridor (\(+\Delta P\) - Flow into corridor; \(-\Delta P\) Flow into shaft). This is because most of the building is subjected to high outside negative pressures and as a result air is drawn out of the building. On the lower ground floor (LG) the shaft is connected to the outside wall W (wind is nearly normal to this wall) through two doors. It is possible that quite a lot of air flows into the shaft through these doors and from the shaft it flows on to other floors.
Apart from the above two sets of measurements, in all the others both the stack and wind effects were present at the same time.

Table 5.1 shows the outside pressure measurements along with the wind velocity at roof level; internal and external temperatures. Considering the fluctuating nature of outside wind speed and direction, as well as the problem of instrumentation, the results for outside pressure measurements are remarkably good. On the east wall (E) the positive pressure coefficient varies from 1.1 on floor 2 to 0.76 on floor 8. This is contrary to what might be expected from the knowledge of the outside wind velocity profile, in which the speed increases with height. Accordingly the pressure coefficient $C_p$ must also increase from lower to upper floors. The probable reason for the discrepancy shown in Table 5.1 may be that the higher positive value on the second floor is caused by the secondary flows. The results on other floors are considerably better. From the wind tunnel measurements on models, it is known that when air flows normal to a wall the stagnation point occurs at about four-fifths the height of the building (see Chapter 3). In the case of the Darwin Building this height is reached at the sixth floor level. The outside pressure must be highest at this floor level and on floors 4 and 8 it must be less. The measurements shown in Table 5.1 confirm this.
For the south wall, the $C_p$ values are positive, except on floor 8 where it is negative. If this value is ignored (it may be negative due to an experimental error) then it can be said that the wind is blowing directly onto south wall 6) giving rise to positive pressures there. This is possible for wind incidence range of $135^\circ \leq \alpha \leq 225^\circ$. However, these positive values on floors 2, 4 and 6, present another problem in that these pressure coefficients decrease with height $C_p$ (floor 2) = 0.57, $C_p$ (floor 6) = 0.32) As before, this is contrary to what is expected from the outside wind profile but despite this, the fact remains that three of the four measurements on the south wall indicate positive pressures. At this stage not much can be said about the direction of the wind. Pressure measurements on other walls must also be examined for further clues.

The pressure measurements on the west wall (W) show (Table 5.1) that on floors 4, 6 and 8 the $C_p$ values are negative and that they also increase with height. This is what is expected if the whole of the west wall (W) is in the wake region. The pressure on floor 2 is positive but very small, which, under certain flow conditions in the wake at heights near the ground, can happen. Since other values are sensible, the measurement on floor 2 can be ignored. So it is clear that wall W is in the wake region and according to this, wind is probably blowing from the south-easterly direction, but this cannot be confirmed without examining the pressure distribution on the north wall (N).
The pressures on the north wall (N) are all negative (see Table 5.1) and the negative values increase with height. This shows that this wall too is in the wake region. A comparison of the negative pressures on walls N and W shows that the north wall (N) is subjected to higher negative pressures and this means that the size of the vortices coming off the north-east corner is bigger than those coming off the south-west corner. Also, the positive pressures on wall E are higher than those on wall S. According to this then, the wind incidence must be very nearly equal to \( \alpha = 135^\circ \). From the empirical formula used for computer analysis, the wind direction has been calculated to be about \( \alpha = 118^\circ \).

**Internal Pressures**

The internal room, corridor and shaft pressures are shown in Tables 5.1a and 5.1b for \( \alpha = 118^\circ \).

The room pressures shown in Table 5.1a suggest that the effect of outside wind is very small. On floor 2 all values are positive (i.e. higher than the atmospheric pressure on ground floor) and on floors 4, 6 and 8 these values are negative (i.e. lower than the atmospheric pressure on ground floor). Even though the north (N) and west (W) walls on floor 2 are subjected to negative outside pressures, the rooms with windows on to these walls still experience positive pressures. This suggests that the building is very well sealed. If that is the case, how do these internal pressures arise? Since these pressures are very small, the
possible explanation can be found in the internal temperature distribution. Even though the internal average temperature measured was as shown in the table, there were slight variations between the shaft, corridor and room pressures. Generally the shaft temperature is lower than that of the room and that of the corridor is between these two limits. On the lower floors, since there is a tendency for the air to flow from the shaft into the corridor region, the room and corridor temperature difference causes it to flow into the rooms. Since the building is not perfectly sealed, the internal flow combines with the very small amount of flow that occurs through the window leakages to give the resultant pressure distribution on a floor. In the present case the wind is blowing from the south-easterly direction, with the result that rooms 201 and 204 experience higher internal pressures compared with those of rooms 210 and 212. The conclusion is that the internal flow is dominant.

**Wind Incidence \( \alpha = 105^\circ \)**

Another set of outside pressure measurements which give the same wind direction are shown in table 5.2. Due to the difficulties associated with the availability of the building, these measurements were possible only on the sixth floor level.

From Table 5.2 it can be seen that the highest positive pressures occur on south (S) and east (E) walls, with the east wall pressure being higher than that on the south wall. The other two walls
(N and W) are subjected to negative pressures. From those values it is clear that the wind must be blowing from the south-easterly direction and the wind incidence is $\alpha = 105^\circ$.

The wind speed at the roof level is twice that for the previous case (Table 5.1) but the internal and external temperatures are about the same.

The internal room pressures on floor 6 are shown in Table 5.2a. These values are all negative and indicate that, as before, the internal pressures are very little influenced by the outside pressures. The relative shaft and corridor pressures at each floor level are shown in Table 5.2b and the pressure differences across the shaft doors are plotted in Fig 5.2c. This figure shows that the neutral pressure plane is between floors 5 and 6.

Wind Incidence $\alpha = 180^\circ$

Table 5.3 lists another set of measurements for a different wind direction. In this case the measurements were made on all chosen floors (2, 4, 6 and 8). These values show that at floor 2 level the outside pressures are positive on all walls: this can only happen under pure stack effect conditions, as seen earlier. Even then, very high temperature differences are required to produce such high pressures. The possibility of pure stack effect can be discounted as the roof level anemometer recorded wind speeds up to 10 m/s. It is likely that positive pressures on some walls on floor 2 are caused by local disturbance.
All measurements on floor 4 were not possible due to some administrative difficulties. The table shows that on floor 6, east (E), west (W) and north (N) walls are subjected to negative pressures. It is only the south wall (S) on this floor that experiences positive pressures. This kind of pressure distribution is only possible if the wind blows directly on to the south (S) wall. If this is the case, the stagnation point must be on the south wall (S) and that the measuring position 604° is not near that point (the positive $C_p$ value is too small $C_p = 0.48$). From this and from the relative magnitude of pressures on walls E and W it can be said that the position of the stagnation point is near the south-east corner. This must mean that the wind must be blowing from the south-easterly direction in such a way that negative pressures on the east wall (E) just begin to appear because the position 602° is very near the north-east corner of the building and the negative pressure value there is quite small.

The measurements on floor 8 show that the pressures on walls E, W and N are very highly negative. These walls can only be subjected to such high negative pressures if the wind direction is normal to the south (S) wall. Unfortunately no measurement on this wall was possible on floor 8. It can only be assumed that the pressure there is positive. If that is the case, then the measurements on floors 6 and 8 suggest that the wind direction is southerly and perhaps the average wind incidence is slightly less than $180^\circ (\alpha < 180^\circ)$. 
Under these conditions, the measured internal room pressures are shown in Table 5.3a. This table shows that, as before, the internal pressures are very little influenced by the outside wind. The table indicates that the room pressures decrease with height.

The shaft and corridor pressures are shown in Table 5.3b and the resulting pressure differences across the shaft doors are plotted in Fig 5.2e. From this figure it is clear that on lower floors there is a flow into the shaft, while on upper floors the direction is reversed. This is typical of the pure stack effect flow. In this case the neutral pressure plane lies between floors 6 and 7. These values indicate that the building has negligibly small outside leakage. Such a building can have considerable problems from the smoke control point of view. Any shaft pressurisation system will not work as there will be no, or virtually little, outflow ("concrete balloon" effect). Under such circumstances supply as well as exhaust fans are needed.

**Wind Incidence $\alpha = 225^\circ$**

In Table 5.4 are shown the outside pressure measurements on floor 6, which indicate the wind direction to be south-westerly. The south (S) and west (W) walls are subjected to almost equal positive pressures. From the position of the respective measuring points (6040, 6180) on the walls, the wind incidence can be estimated to be about $\alpha = 225^\circ$. In that case the north and east walls (N and E) will be in the wake region and experience negative pressures.
This is confirmed by the measurements shown in Table 5.4. The outside temperature is higher than in the previous sets of measurements, making stack effect contribution smaller.

The internal room pressures are shown in Table 5.4a. Comparison of these with the previous case (Tables 5.3a and 5.4a) show that they are similar and from this it can be concluded that, as before, the internal pressures are dominated by the stack effect.

The relative shaft and corridor pressures are shown in Tables 5.4b and Fig 5.2g. The figure shows that in accordance with the small temperature difference between the inside and outside of the building, the stack effect is also small compared with the previous wind incidence. The neutral plane in this case is clearly at the fifth floor level. Again, for this wind direction the effect of outside pressures on the internal pressures is negligibly small.

**Wind Incidence $\alpha = 230^\circ$**

The same measurements repeated on the same night are shown in Tables 5.5, 5.5a and 5.5b. The outside pressure coefficients $C_p$ indicate that, as before, the south and west walls are subjected to almost equal positive pressures but the north wall (N) differs from the previous case considerably. This time the north wall measurement indicates a positive pressure. Since the value of this positive pressure is small, the likely cause may be due to the secondary flows resulting at the time the measurement was taken. If that is the case, the wind is most likely to be blowing from the
south-westerly direction. Also, since pressure on the north wall (N) is higher than in the previous case, the wind direction is also higher: it works out to be about \( \alpha = 230^\circ \).

The internal room pressures are shown in Table 5.5a which, as before, indicate that they are very little influenced by the external pressures.

The shaft and corridor pressures on all floors are shown in Table 5.5b and the pressure differences across the shaft doors are plotted in Fig 5.2f. From this figure it is clear that the neutral pressure plane has shifted slightly downwards compared with the previous case (compare Figs 5.2f and 5.2g). This figure also shows that inflow into the shaft has increased due to the pressure differences. It is in fact because of this that the neutral plane has shifted. The pressure changes are not due to the stack effect as the internal and external temperatures remain the same as before. The changes therefore must be attributed to the changes in outside wind direction. The data for the outside pressure distribution is not sufficient to explain the drop in shaft pressures.

Wind Incidence \( \alpha = 270^\circ \)

A set of measurements shown in Table 5.6 indicate that the pressure on the west wall is very high and positive. It increases with height up to floor 6 and starts to decrease again towards the roof. The highest pressure occurs on floor 6. The south wall is
subjected to very high negative pressures which vary with the height. Except for the value on floor 4, the pressures on the north wall are also negative and the highest negative occurs on the 6th floor level. Very small positive pressures occur on the east wall (E) on floors 4 and 8, while the 6th floor value is negative. From all these measurements, it is clear that wall (W) is subjected to very high positive pressures and the pressures on the north and south walls are negative. Accordingly it can be concluded that the outside wind blows normal to the west wall, i.e. $\alpha \approx 270^\circ$.

The internal room pressures are shown in Table 5.6a. These values again show that the effect of outside pressures on internal room pressures is very small.

The shaft and corridor pressures are listed in Table 5.6b and the pressure differences across the shaft doors are shown in Fig 5.2b. The figure shows that the position of the neutral pressure plane is between floors 5 and 6. A comparison of the shaft pressures with those for $\alpha = 225^\circ, 230^\circ$, shows that the internal shaft and corridor pressures are higher in this case (compare Tables 5.4b, 5.5b and 5.6b). This is most probably due to the distribution of outside window leakage around the building. As before, the measurements show that the outside wind has very little effect on the internal pressures.
5.1.4 The Effect of Internal Shaft Door Openings

If shaft pressurisation is to be used as a method for control of smoke in tall buildings, it is important to investigate the effect of a combination of door openings on the shaft and corridor pressures. This is necessary to establish the modified flow pattern. The opening of one or more shaft doors on some floors can result in a drop in the shaft pressure, giving rise to a reversal of flow across the shaft doors on other floors. As a result, smoke can easily enter the shaft from the fire floor, making escape difficult. The pressurisation system must be designed in such a way as to ensure a smoke free shaft, even if some of the doors are left open. To do this it is necessary to know the response of shaft pressures to the opening of doors on different floors.

Along with the internal and external pressure measurements on the Darwin Building, the effect of door openings on shaft pressures was investigated also. Because of the problems associated with the availability of building, a very limited number of such measurements was possible. Even this was achieved at the expense of cutting down the number of external and internal measurements. The results for three wind directions are presented here.

Wind Incidence $\alpha = 105^\circ$

For this wind direction the internal and external pressures are discussed in the previous section when all shaft doors are closed.
The shaft and corridor pressures resulting from the opening of floors 4 and 6 shaft doors separately are shown in Tables 5.2c and 5.2d. The pressure differences across the shaft doors are plotted in Fig 5.1a. This figure shows that when the fourth floor shaft door is opened the pressure difference across other shaft doors decreases with no significant change in the flow pattern. The increase in flow rate into the shaft is compensated for by the slight downward shift of the neutral pressure plane so as to increase the outflow by the same amount.

When all the shaft doors are closed the pressure measurements show that the neutral plane is very close to the 6th floor level. Therefore, the opening of the 6th floor shaft door does not produce any noticeable shift in the neutral pressure plane. Fig 5.1a shows this quite clearly.

These results show that if the open doors are near the neutral plane, the flow pattern across the shaft doors does not change significantly.

Wind Incidence $\alpha = 230^\circ$

A combination of doors were opened for the case when the outside wind direction was $\alpha = 230^\circ$. Under these conditions the neutral pressure plane lies between floors 3 and 4 (all doors closed) as shown in Fig 5.1b.

If doors on the ground floor (G) and the 1st floor (1) are opened together, the flow rate through these doors into the shaft increases
dramatically. This increased flow of air can only flow out of
the shaft through other shaft doors and as a result the pressure
difference across these doors increases. This causes the neutral
plane to shift downwards to the open doors. As Fig 5.1b shows,
the new position of the neutral plane is between floors 1 and 2.
As expected, the highest pressure differences occur on floors 7
and 8, these being further away from the neutral plane.

When floor 7 and 8 doors are opened together, the situation changes
quite considerably as the figure (5.1b) shows. In this case the
rate of flow of air into the corridor (floors 7 and 8 being above
the neutral plane) increases due to the increased leakage. The
neutral plane then moves towards floors 6 and 7, increasing the
pressure difference across other floor doors which are below this
plane, so as to equal inflow and outflow. The maximum pressure
difference occurs on the 1st floor ($\Delta P = -8.0 \, \text{N/m}^2$).

The opening of floors 6, 7 and 8 shaft doors has the same effect
as Fig 5.1b shows quite clearly: the neutral pressure plane in
this case is on floor 6. Such a combination of door openings
again creates a maximum pressure difference on the 1st floor
($\Delta P = -8.6 \, \text{N/m}^2$).

These results show that the opening of shaft doors has a
considerable effect on the pressure differences across shaft
doors.
Wind Incidence $\alpha = 225^\circ$

For this particular wind direction, the pressure differences across closed shaft doors are quite small, as shown in Fig 5.1c. The neutral plane in this case is on floor 5.

Because the pressures in the shaft and corridors are very nearly equal, the opening of the 2nd floor shaft door does not effect the position of the neutral plane, but when shaft doors on floors 2 and 4 are opened together, the neutral pressure plane moves down to 4th floor, increasing the pressure differences on other floors so that inflow into the shaft is equal to outflow.

Since the 8th floor is above the neutral plane, opening the shaft door on this floor increases the air flow into the corridor. As a result of this increase, the shaft pressure falls to increase the pressure difference and flow rate on floors below the neutral plane, which is between floors 6 and 7. The measured results are shown in Fig 5.1c.

Opening the doors on floors 4 and 6 has a similar effect. In this case the neutral plane is at floor 5 level.
5.2 Conclusions

From the internal and external pressure measurements on the Darwin Building, the following conclusions can be made:

1. The window leakages are so small that the external wind induced pressure distribution has very little effect on the internal pressures.

2. 'Stack Effect' and 'Wind Effect', when acting alone, produce very small pressure differences across shaft doors.

3. The opening of a shaft door has a considerable effect on the flow pattern across the shaft doors. The distance of the open door or doors from the neutral pressure plane determines the amount by which shaft pressures change.


5.5 W.A. Dalgliesh, "Comparison of model/full-scale wind pressures on a high-rise building". National Research Council of Canada, Division of Building Research, Research Paper No 661.
5.6 N.M. Standen, W.A. Dalgliesh and R.J. Temlin, "A wind tunnel and full-scale study of turbulent wind pressures on a tall building". NRCC, Division of Building Research, Research Paper No 585.


5.11 N. Isyumor and A.G. Davenport, "Comparison of full scale and wind tunnel wind speed measurement in the


Fig 5.1: Variation of Shaft door Pressure Difference with Door Openings. $\alpha = 225^\circ$. (Darwin Building).
Fig 5.2: Pressure Difference across Shaft Doors in the Darwin Building.
Figure 5.2: Pressure Difference across Shaft doors in the Darwin Building.
Pressure Tappings on the Darwin Building.
Table 5.1: Pressure measurements on Darwin Building, $\alpha = 118^\circ$

Date: 7/12/77  Time: 8.00 PM

Average Outside Temperature = 4°C
Average Inside Temperature = 20°C

(a)

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<th>$P_o$ [N/m²]</th>
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<th>$C_{P_o}$</th>
<th>$P_i$ [N/m²]</th>
<th>$C_{P_i}$</th>
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Stair Shaft and Corridor pressures

(b)

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<th>$P_s$ [N/m²]</th>
<th>$P_c$ [N/m²]</th>
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### Table 5.2: Pressure measurements on Darwin Building, $\alpha=105^\circ$

**Date:** 13/2/79  
**Time:** 7.30 PM  
**Outside Temperature:** 6°C, **Inside Temperature:** 20°C

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<th>$P_c$ (N/m$^2$)</th>
<th>$C_{PL}$</th>
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(b) Stair Shaft and Corridor Pressures (All Doors Closed)

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<th>Level</th>
<th>$P_0$ (N/m$^2$)</th>
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(c) Stair Shaft and Corridor Pressures (Floor 4 Shaft door OPEN)

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<th>Level</th>
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<th>$P_c$ (N/m$^2$)</th>
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(d) Stair Shaft and Corridor pressures (Floor 6 Shaft door OPEN)

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<th>$P_c$ (N/m$^2$)</th>
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Table 5.3: Pressure measurements on Darwin Building, $\alpha = 180^\circ$

Date: Time: 9.00 PM
Average Outside Temperature = 5°C
Average Inside Temperature = 20°C

(a) Room

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<th>$C_{p0}$</th>
<th>$P_1$ (N/m²)</th>
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(b) Stair Shaft and Corridor pressures (All doors Closed)

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<th>$P_C$ (N/m²)</th>
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Table 5.4: Pressure measurements on Darwin Building, $\alpha = 225^\circ$

Date: 20/2/79  
Time: 10.00 PM

Average Outside Temperature = 10°C
Average Inside Temperature = 22°C

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(b) Star Shaft and Corridor pressures (All doors CLOSED)

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(c) Stair Shaft and Corridor pressures (Floor2 shaft door OPEN)

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(d) Shaft and Corridor pressures (Floor 2+4 shaft doors OPEN)

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(e) Stair Shaft and Corridor pressures (Floor 8 Shaft door OPEN)

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(f) Stair shaft and Corridor pressures (Floors 4+6 shaft doors OPEN)

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<th>( P_c (\text{N/m}^2) )</th>
<th>( \Delta P = P_s - P_c )</th>
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Table 5.5: Pressure measurements on Darwin Building, $\alpha = 230^\circ$

Date: 20/3/79/  
Time: 7.30 PM

Average Outside Temperature = 8$^\circ$ C  
Average Inside Temperature = 20$^\circ$ C

<table>
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<th>$C_{P0}$</th>
<th>$P_i$ (N/m$^2$)</th>
<th>$C_{DI}$</th>
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(b) Stair shaft and Corridor pressures (All doors CLOSED)

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<th>$P_c$ (N/m$^2$)</th>
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(c) Stair shaft and Corridor pressures (G+1 shaft doors OPEN)

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(d) Stair shaft and Corridor pressures (Floors 7+8 shaft doors OPEN)

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(e) Stair shaft and Corridor pressures (Floors 6+7+8 shaft doors OPEN)

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Table 5.6: Pressure measurements on Darwin Building, $\alpha=270^\circ$

Date: 12/2/77  Time: 8.30 PM
Average Outside Temperature = 11°C
Average Inside Temperature = 21°C

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<th>$P_i$ (N/m²)</th>
<th>$C_{pi}$</th>
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(b) Stair shaft and Corridor pressures (All shaft doors CLOSED)

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<th>$P_0$ (N/m²)</th>
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</table>
Table 5.7: Pressure measurements on Darwin Building, (Stack Effect)

Date: 20/10/77  Time: 10.00 PM
Average Outside Temperature = 15°C
Average Inside Temperature = 23°C

(a)

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<th>$P_i (N/m^2)$</th>
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<td>2.0</td>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>N817</td>
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<td>-</td>
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(b) Stair shaft and Corridor pressures (All shaft doors CLOSED)

<table>
<thead>
<tr>
<th>Level</th>
<th>$P_S (N/m^2)$</th>
<th>$P_C (N/m^2)$</th>
<th>$\Delta P = P_S - P_C$</th>
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</thead>
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<td>1.8</td>
</tr>
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<td>4</td>
<td>0.5</td>
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<td>1.0</td>
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<tr>
<td>8</td>
<td>2.0</td>
<td>0.2</td>
<td>1.8</td>
</tr>
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</table>
Table 5.8: Pressure Measurements on Darwin Building, \( \alpha = 252^\circ \)

Date: 29/9/77  
Time: 9.55 PM

Average Outside Temperature = 20\(^\circ\)C  
Average Inside Temperature = 22\(^\circ\)C

(a)

<table>
<thead>
<tr>
<th>Room</th>
<th>( P_o (N/m^2) )</th>
<th>( \frac{1}{2} \rho V_i^2 )</th>
<th>( C_{pi} )</th>
<th>( P_i (N/m^2) )</th>
<th>( C_{pi} )</th>
</tr>
</thead>
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<tr>
<td>E201</td>
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<td>357.2</td>
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<tr>
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</table>

(b) Shaft and Corridor pressures (All shaft doors CLOSED)

<table>
<thead>
<tr>
<th>Level</th>
<th>( P_s (N/m^2) )</th>
<th>( P_c (N/m^2) )</th>
<th>( \Delta P = P_s - P_c )</th>
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</tr>
<tr>
<td>2</td>
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<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
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<td>2.7</td>
</tr>
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<td>-1.2</td>
<td>-0.8</td>
</tr>
<tr>
<td>8</td>
<td>?</td>
<td>-3.0</td>
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</table>
CHAPTER SIX

COMPUTER ANALYSIS OF INTERNAL PRESSURE DISTRIBUTION IN THE WIND TUNNEL MODEL (32-CELL) AND THE DARWIN BUILDING.
Chapter 6

COMPUTER ANALYSIS OF INTERNAL PRESSURE DISTRIBUTION IN THE WIND TUNNEL MODEL (32-CELL) AND THE DARWIN BUILDING.

6.0 Introduction:
In recent years, due to the increasing size and complexity of tall buildings, it has become necessary to incorporate the smoke control methods in the design of such buildings. The need has arisen from a number of fires in this type of buildings in which deaths occurred at remote areas from the seat of the fire, due to the spread of smoke and toxic gases.

The smoke control methods rely on creating pressure differences across leakage parts, so as to confine smoke to the fire areas. In such methods two factors are important:

(i) The pressure in the escape routes must be raised to such a value that it keeps the smoke out.
(ii) This pressure must not be such that it makes door opening difficult.

Before any of the smoke control devices are installed in a building, a knowledge of the pressure distribution, caused by such factors as outside wind or stack effect, is necessary. Hence for design purposes a calculation method is required, which can readily provide information about the internal pressure distribution, in a building of known leakage characteristics, under all possible outside wind conditions.
A number of computer programs dealing with this kind of problem are being used in many countries. All these programs are basically similar and employ the same physical laws for calculation procedure. The programs described by Barrett and Locklin [6,2], Fothergill [6,3] and Shannon [6.6] use the generalised orifice flow equation, which relates mass flow rate to the pressure difference across a given flow path. All the compartments in a building are inter-connected by these flow paths, and the resulting airflow net work is then solved by alternative technique. From the knowledge of flow rate and airflow patterns the smoke concentration in any part of the building is calculated. The Barrett and Locklin program enables them to examine the effect of:

(i) Fire
(ii) Smoke holes at the top of shafts
(iii) Effects of altering ventilation or exhaust fan operation during fires.
(iv) Effects of rupturing windows.

These programs make very important simplifying assumptions which limit their use.

(a) The fire is a low energy fire and has reached a steady state.
(b) Smoke from the fire floor is carried to other areas of the building by pre-existing flows.
(c) Diffusion in a compartment is instantaneous. For full details see references.
The computer program used in the present analysis (6.7) is very much similar to the one described by Wakamatsu [6.1]. For full details of this program see Appendix B.

In the present analysis, since there is no fire or stack effect simulated in the wind tunnel model, only the effects of outside winds are considered. Before discussing the results, it is important to examine the simplifying assumptions made with respect to the outside pressure distribution.

The computer program assumes that, for a given wind direction, the pressure over the surface of a wall is uniform. It is assumed to be a function of wind direction only

The typical values of pressure coefficients $C_p$ are given as (based on empirical results)

$$C_p = \begin{cases} 
0.75 & 0^\circ < |\alpha| \leq 30^\circ \\
-0.021 \alpha + 1.38 & 30^\circ < |\alpha| \leq 80^\circ \\
-0.5 & |\alpha| > 90^\circ 
\end{cases}$$

where $\alpha$ is the angle between wind direction and the normal to the wall.

As a result of this assumption considerable errors are introduced in the calculations.

The model measurements, described in chapter 2, 3 and 4, show that
for wind direction normal to a wall \((\alpha=0^\circ)\), the outside pressure coefficient varies from \(C_p = 0.25\), at small heights from the ground level to \(C_p = 1.0\) at the stagnation point. This means that if a uniform value of \(C_p = 0.75\) is assumed a considerable error (between 25\% to 50\%) is introduced into the calculations. The computer program is therefore, not expected to generate realistic results.

As there is no stack effect present in the wind tunnel model, no flow results from one floor to another. All floors, in this case, can be considered to be independent of each other. Under these conditions the computer program can be used to perform calculations for each floor assuming a different value of \(C_p\) for the floor. In the case of the 32-cell model, the calculations were performed for floors 2 and 4. Even this technique fails when there is a considerable lateral variation of pressure on outside walls.

Fire in the computer program is simulated by assigning a very high temperature to one of the rooms (e.g. 1000°C). For the calculation of wind induced pressures, the effect of fire was minimized by assigning fire temperature to be a few degrees above the room temperature. The fire room was chosen so that it was furthest away from the floor on which calculations were performed.
6.1 Discussion of Results for the wind tunnel Model:

As described earlier, the computer program assumes a uniform value for the outside pressure coefficient ($C_{p_o}$) on a wall for any particular wind incidence. Since all internal leakages are the same (all doors closed) and for one value of outside leakage ratio ($R_L$) the pressure differences calculated across room doors under these conditions, will be the same. This is far from the truth, as the wind tunnel measurements show (see chapter 2 and 3).

To overcome this difficulty, the computer calculations were performed for each floor separately, assuming the outside pressure coefficient ($C_{p_o}$) to be uniform for that floor, but different from that on other floors. The calculations were repeated for two wind incidences, $\alpha=0^\circ$ and $\alpha=45^\circ$.

6.1 Wind Incidence, $\alpha=0^\circ$

6.1.1.1 Floor 2

From the outside pressure distribution on wall T (fig 2.2) for zero wind incidence, it is clear that over the region of the shaft, the average outside pressure coefficient is about $C_{p_o}=0.60$. The variation with height is much less over this region than over the rooms. The figure also shows that over the region of floor 2 the average value of $C_{p_o}$ is about 0.60. If then according to this, a uniform value of $C_{p_o}=0.60$ is assumed for the Computer calculations, the measured shaft door pressure difference must
be very close to that calculated. Here it must be remembered that the above assumption also introduces considerable errors in the calculation of internal pressures, hence accurate prediction is not expected.

The outside pressure distribution on side R does not present any problems, as it is fairly uniform over the surface (see fig 2.2). The average value on side R is $C_{p_0} = -0.15$.

Using these average values, calculation for floor 2 were performed for various external leakage ratios ($R_L$). The results for the pressure difference across the shaft door are shown in fig 6.1d. It shows an excellent agreement with the measured values. The figure shows the calculated results for two values of outside pressure coefficients ($C_{p_0} = 0.5$, $C_{p_0} = 0.6$). There results confirm that, at least, for the shaft, the pressure difference across the shaft door is independent of leakage ration $R_L$.

For the region outside room (1) on floor 2 the $C_{p_0}$ varies from 0.6 to 0.75. And the average value over that region is, then, about 0.67. This is higher than the average for the floor, used in the calculations. On this basis room (1) calculations are expected to differ considerably from the measurements. The results for the pressure difference across room (1) door are plotted in fig 6.1a, which show, that the computer calculations underestimate the results, as expected.
The outside pressure distribution over the region of room\textsuperscript{2} is similar to that over room\textsuperscript{1}. See fig 2.2. The pressure differences across this room door are plotted in fig 6.1b. From this figure it is clear that, as for room\textsuperscript{1}, the calculations underestimates the pressure differences, which are clearly shown to be independent of leakage ratio, $R_L$.

For room\textsuperscript{3} the outside pressure drops by a considerable amount. The pressure coefficient varies from $C_{p_0} = 0.3$ to $C_{p_0} = 0.5$, and the average over the region is about 0.4 (see fig 2.2). This is a lot less than the average considered over the floor. In this case then the computer results over-estimate the pressure difference across room\textsuperscript{3} door. The results are shown in fig 6.1c.

Rooms\textsuperscript{4}, \textsuperscript{5} and \textsuperscript{6} have their window openings on the side H, which is subjected to uniform negative pressures. The pressures in these rooms are then dominated by the outside pressures on side R. On this side then, as fig 2.2. shows, the variation in outside pressure from one room to another on floor 2 is negligible. It is, therefore expected that the computer productions are going to be very close to the measured values. The results for all these three rooms are shown in fig 6.1e. The figure shows that both the $C_{p_0}(T)$ values give good results. The average outside pressure coefficient on side R being $C_{p_0}(R) = 0.15$
These results for floor 2 show clearly that the prediction of internal wind induced pressures is only possible if outside pressures distribution can be described accurately. Even the assumption of an average pressure on a floor introduces considerable errors. The assumption of uniform outside pressure is not correct.

6.1.1.2 Floor 4

Over the region of floor 4, the lateral variation of outside pressure, $C_p$ (fig 2.2) is quite considerable. The stagnation point occurs on this floor in the region outside of room 1. It is in this region that the outside pressure is the highest, with an average $C_p=1.0$. Now, if the floor is considered as a whole, then the average pressure coefficient is $C_p=0.75$. The computer calculations were performed for a range of $C_p$ values up to $C_p=1.0$. The results for two of them ($C_p=0.7$, $C_p=0.8$) are shown in figs 6.2a, b, c, d and e for various rooms. Due to the large lateral variations of outside pressures on this floor compared with those on floor 2, the errors in computer calculations are going to be larger.

Considering the shaft region, then, the average outside pressure coefficient is $C_p=0.60$. On the 4th floor level this value is about 0.70. The computer calculations along with the measured results are shown in fig 6.2d. It is clear from this figure that the computer calculations over estimate the pressure difference. The reason for the low measured pressure difference is due to the fact that even though the shaft pressure is the same on all
floors, the corridor pressure on floor 4 is increased. Hence the difference between the calculated and measured values is larger.

Because of the very high pressure outside room\(^1\), the pressure difference across this room door is also very high. The calculated and measured results are shown in fig 6.2a. From these results it is clear that an average pressure considered over the floor under estimates the pressure difference.

Now moving to the region outside room\(^2\) the pressure drops slightly, and the value for the average pressure coefficient is \(C_p^00.90\). This is much higher than the floor average of 0.75. The calculated results for \(C_p^00.7\) and 0.8 are shown, together with the experimental results, in fig 6.2b. Once again the measured results are much higher than those predicted.

For room 3, the average outside pressure is about \(C_p^00.70\). This is very close to the average for the floor. But the computer program is still not expected to give good results, because the influence of very high pressures in room\(^1\) and\(^2\) or the corridor pressure is not taken into account. The results are shown in fig 6.2c. These results are evidently better than those for rooms\(^1\) and\(^2\). This is because, the pressure in a room is dominated by the outside pressures. The corridor pressure has a comparatively small effect.
These results for floor 4 confirm the conclusions arrived at from the discussion of floor 2 results.

The results for rooms 4, 5, and 6 are summarized in fig 6.2e. A comparison of these with the results for rooms 1, 2, and 3 shows that the computer predictions are much better in this case. This is because of the relatively uniform nature of pressure distribution on side R.

The internal pressure differences across room doors are independent of the leakage ratio, $R_L$.

6.1.2 Wind Incidence, $\alpha=45^\circ$

As the original program assumes uniform pressure distribution over the wall surfaces, the change in wind direction is represented by a different value of that uniform distribution. Otherwise the calculation procedure remains the same from this point of view, the computer is not aware of the change in wind direction, but only performs the calculations for a different set of $C_p$ values.

As the outside pressure distribution changes with the change in wind direction, the internal pressures also change. The outside pressure distribution for $\alpha=45^\circ$ is considerably different from that for $\alpha=0^\circ$ (see chapter 2 and fig 2.10). From the figure it is clear that for side R, the pressure still remains uniform. But for side T the pressure varies (as for $\alpha=0^\circ$) from point to
point on the surface. The average value for the whole surface is about \( C_p(T) = 0.45 \). As the pressure coefficient varies quite considerably over the surface, the assumption of an average value will not generate accurate results for the internal pressures as seen from the analysis of \( \alpha = 0^\circ \). The computer calculations are therefore performed for floors 2 and 4 separately using different \( C_p \) values.

6.1.2.1. Floor 2

From fig 2.10, it is clear that the outside pressure distribution is still uniform and that the pressure coefficient is \( C_p = -0.20 \). On side T, on the other hand, the pressure coefficient varies considerably. On floor 2 the \( C_p \) varies from 0.30 to 0.50. And for this particular floor the average value is about \( C_p = 0.40 \). A number of computer calculations were made for a range of \( C_p(T) \) values. The results for only two of such values (\( C_p(T) = 0.5 \), \( C_p(T) = 0.4 \)) are presented in figs 6.3a, b, c, d, and e.

Because the shaft region is subjected to very low outside pressures, the pressure difference across the shaft door drops considerably compared with that for \( \alpha = 0^\circ \). The computer calculations fig 6.3d over-estimate this value.

The average pressure coefficient outside room 1 is about \( C_p = 0.35 \), i.e. very nearly equal to the average for the floor. The calculated results, for the pressure difference across room 1 door, are shown in fig 6.3a along with the measurements. The figure
shows that the calculation for $C_p(T) = 0.40$, $C_p(R) = -20$, give very good results.

The outside pressure measurements (fig 2.10) show that in the region outside of room(2), the average pressure coefficient is about $C_p = 0.40$. A comparison of computer calculations with the measurements are shown in fig 6.2b. The figure shows that, although the pressure coefficient is the same, the calculation underestimates the results. Figure 6.2c shows that the results for room(3). Once again the predicted pressure differences are very much less than those measured.

A possible explanation for this may be that because in the calculation procedure, all three rooms are subjected to outside $C_p = 0.40$. But the measurements show that room(1) and the shaft regions experience much lower pressure (i.e. $C_p < 0.30$). These pressures lower the corridor pressure, which increases the pressure difference across room(2) and(3) doors.

In the computer calculations, on the other hand, it is assumed that the outside wind induced pressure is $C_p = 0.40$, for floor 2. This result is a higher value of the corridor pressure, which decreases the pressure difference across rooms(2) and(3) doors. That is why the computer predictions shown in figs 6.2b and 6.2c are much lower than the measured pressure differences.

The difficulty can only be overcome, if some way of representing
the exact outside pressure distribution can be found.

The calculations show that the internal pressure differences are independent of outside leakage ratio $R_L$.

The pressure differences across rooms 4, 5 and 6 doors are shown in figs 6.2e, 6.2f and 6.2g. These results show that, because of the uniform pressure distribution on side R, the computer prediction are very close to the measured results. Average $C_{p_0}(T)=0.40$ gives very good results.

6.1.2.2. Floor 4

The variation of outside pressures on this floor (side T) is very similar to that on floor 2. The highest pressures are in the region of room 3 and lowest in the shaft region (see fig 2.10). On side R there is no marked variation, and the negative pressure is the same as on floor 2 ($C_{p_0}(R)=-0.20$). Because of the higher pressures on side T, the internal pressures on this floor are also expected to be higher than those on floor 2.

The pressure coefficient on this floor varies from $C_{p_0}=0.30$ (outside shaft) to $C_{p_0}=.80$ (outside room 3). In view of this, taking an average value can introduce considerable errors in the calculations. From the measurements, the average pressure coefficient for floor 4 is about $C_{p_0}(T)=0.50$. 
Computer calculations were made using a range of outside \( \text{C}_p(T) \) values, and the results for two of them (\( \text{C}_p(T) = 0.4, \text{C}_p(T) = 0.5 \)) are shown in figs 6.4a - 6.4h.

The measured average \( \text{C}_p(T) \) over the shaft region (\( \text{C}_p(T) = 0.3 \)) is much less than the average for the floor (\( \text{C}_p(T) = 0.5 \)). The computer calculations, therefore, give much higher results for the pressure difference across the shaft door. See fig 6.3d. In this case the measured low values are not due to the high corridor pressure, but are more due to the very low shaft pressure. In fact the measurement of corridor pressures show (fig 2.12) that they are approximately the same on floors 2 and 4. Since outside pressure distribution over the shaft region does not change very much with height, the pressure difference across the shaft door on floor 2 and 4 is the same (compare Figs 6.3d and 6.4d).

The average pressure coefficient outside room(1) is only very slightly higher than the same room on floor 2. For this reason the measured pressure difference across the door is also higher than on floor 2 (compare figs 6.3a and 6.4a). These figures also show that the computer prediction are very close to the measurements.

The measured and calculated pressure differences across room(2) and 3 doors are shown in figs 6.4b and c. In these the computer predictions are very low. The reason is that the average value of \( \text{C}_p(T) \) assumed for the calculation is very much less than the values obtained from the experimental measurements. For better calculations it is necessary to represent the outside pressure distribution more
The results for room 4, 5 and 6 are much better (see figs 6.4f, g and h because of the uniform pressure distribution on side R.

These results also show that, the internal pressure differences are independent of the outside leakage ration, \( R_L \).

6.1.3. Wind Incidence, \( \alpha = 90^\circ \)

For this particular wind direction both the leaky walls (T and R) are subjected to very high negative pressures, which vary from point to point on the wall surfaces (see fig 2.18). Theoretically both these walls must have identical pressure distribution, because of the symmetry of outside flow. The figure shows that the small differences are due to the misalignment of the model to the flow, i.e. the wind direction is not exactly at 90\(^\circ\).

The general feature of the pressure distribution is that, ignoring the vertical variation for the moment, there is a very high suction pressure at the leading edges of these walls (T and R) and that this suction decreases downwind. In other words, room 3 and 4 are subjected to very high negative pressures while the shaft and the duct regions experience smaller negative pressures.
This means that as for previous wind directions, the pressures in all rooms vary from floor to floor. On a floor the pressure differences result from.

(i) Assymetry of the pressure distribution of sides T and R
(ii) Pressure variation down wind.

If the pressure distribution on the two leaky sides (T and R) was exactly similar, then the internal pressures of rooms

3 and 4
2 and 5
1 and 6

will be the same but distinct.
If, on the other hand, there was no variation downwind (i.e. uniform pressure distribution on both T and R) there will be no internal pressure differences i.e. (uniform internal pressure).

The computer program relies on assuming a uniform pressure on any wall surface. The consequence of this for the present wind direction (α=90°) is that the computer calculation generate zero pressure differences across all internal doors (or flow paths).

The same problem arises even if floors are considered separately, as before.

Some results for the pressure differences can be obtained by subjecting the walls to varying uniform negative pressures. These results then cannot be compared with the measurements, as the computer will generate a flow from wall of low negative pressure to the high negative pressure.

Fig 6.1.3.2: Equal pressures on sides T and R, giving zero internal pressure differences
Fig 6.1.3.3: Different uniform pressures on side R and T giving rise to internal flow pattern of the type for $\alpha = 45^\circ$.

From these considerations, the computer program fails for $\alpha = 90^\circ$. Only an exact representation of the outside pressure distribution can result in accurate prediction.

6.2 Discussion of Results for the Darwin Building:

The computer analysis of a full scale building is a complex task as it requires a detailed knowledge of the building leakage characteristics. In real buildings, flows also occur through the wall constructions as well as through the cracks around doors and windows. For these flows different relationships between the main flow rate and the pressure difference, hold. To write a computer program taking all these flow paths into account will be impossible. The problem is simplified by ignoring the flow through the walls, which is very small compared with that through the door and window cracks. For real buildings, even the estimation or measurement of cracks around doors and windows is not so easy. In the wind
tunnel model no such problems exist, as the leakage hole dimensions are known accurately.

It was with this assumption that the computer analysis of the Darwin Building was carried out. Cracks sizes around doors and windows were measured approximately by going round the building. Location of rooms and their sizes were also measured and used in the calculation. The form of the input data is shown in Appendix B.

The difficulties in measuring the full scale pressures (discussed in Chapter 5) leaves the computer analysis incomplete. Although the results for the shaft pressure measurements and calculations are encouraging no definite conclusions can be drawn. The present very brief analysis only points out some of the difficulties and suggest possible topics for future work.

Quite a number of other calculations were performed by varying the building leakage characteristics (such as door and window crack sizes, wind speed and direction, varying stack effect). These results are not presented here, as the measured results are not available for comparison.

Because the full scale measurements were made over a period of a few months, the results for various outside wind conditions were recorded. Out of these are set forms the pure Stack
Effect and the other Wind Effect.

6.2.1. Stack Effect:

The measurements were made on the evening of 29 October 1977, when the outside and inside temperatures were:

\[ T_{\text{out}} = 15^\circ C \]
\[ T_{\text{in}} = 30^\circ C \]

For the computer calculation, the following crack widths (CW) were assumed.

- Outside door, \((CW) = 0.031 \text{ inches}\)
- Inside door, \((CW) = 0.011 \text{ inches}\)
- Window, \((CW) = 0.005 \text{ inches}\)
- Roof shaft door, \((CW) = 0.011 \text{ inches}\)

Under these conditions, the calculated and measured pressure differences across the shaft doors were as given in the following table

Table 6.2.1.1: Shaft door pressure difference \((P_{\text{cor}} - P_{\text{sh}})\)

<table>
<thead>
<tr>
<th>Level</th>
<th>(\Delta P_{\text{cal}} [\text{N/m}^2])</th>
<th>(\Delta P_{\text{meas}} [\text{N/m}^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>3.8</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>-1.8</td>
</tr>
<tr>
<td>4</td>
<td>-0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>-2.1</td>
<td>-0.3</td>
</tr>
<tr>
<td>8</td>
<td>-4.5</td>
<td>-2.0</td>
</tr>
</tbody>
</table>
The program was run for various other combinations of leakages, the above results seem to the closest to those measured. At first sight, the results do not look at all comparable. But in view of the problems in both calculation and measurements, it must be concluded they are encouraging. First in the calculation procedure, the exact leakage characteristics of the building are unknown. At the time of measurement it is almost impossible to ensure that all the doors and windows are closed. The assumption of uniform outside pressures on walls in the computer program is not correct.

In the case of measurements, the pressures fluctuate so much that, it is very difficult to decide on a mean value, and the most important factor is that the time over which the measurement is taken, to decide on the mean, is very short. This introduces a considerable error, sometimes even up to about +50%. With these difficulties in mind, the above results are very good in so far as they follow the same pattern. Best results can be obtained by minimising the errors in calculation and in measurements.

Wind and Stack Effect Combined:

The outside pressure measurements made on 29 September 1979 were used to calculate the internal pressures. The wind direction is shown in the diagram on the next page-
Wind direction was estimated to be W18°S, from the outside pressure measurements.

The mean wind speed was 61.6 ft/s.

The average pressure coefficients used in the calculation were:

\[ \begin{align*}
C_{p0}(W) &= 0.85 \\
C_{p0}(S) &= -0.12 \\
C_{p0}(E) &= -0.10 \\
C_{p0}(N) &= -0.28
\end{align*} \]

With the lower ground floor shaft door open and the roof shaft door crack width=0.010 in. the calculated results are shown below in Table 6.2.2.
Table 6.2.2.: Shaft door pressure difference (P_{\text{cor}} - P_{\text{sh}})

<table>
<thead>
<tr>
<th>Level</th>
<th>$\Delta P_{\text{cal}}$ [N/m$^2$]</th>
<th>$\Delta P_{\text{meas}}$ [N/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>-1.95</td>
<td>-2.4</td>
</tr>
<tr>
<td>2</td>
<td>-1.64</td>
<td>-1.8</td>
</tr>
<tr>
<td>4</td>
<td>-1.63</td>
<td>-2.7</td>
</tr>
<tr>
<td>6</td>
<td>-1.60</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>-1.65</td>
<td>23.4</td>
</tr>
</tbody>
</table>

In the above table the measured result for floor 8 level can be ignored as it is most probably due to experimental error. During the measurements, some of the measuring tubes were found to be water logged due to condensation. For other floors, the results seem to be quite good. Although the exact figures are questionable, but the calculated values do follow the same pattern as the measured values. In both cases the pressure differences are negative.

The results for the room door pressure differences were not so good. The main reason for that was that the room windows are directly exposed to the outside pressures, and to predict the room pressure, exact knowledge of the outside pressure at the window portion is required. Unless this is done, no sensible results are possible.

Quite a number of other computer runs were made, and they all showed the similar trend. It will, therefore, not be useful to present and discuss all of them here.
Conclusion:

The general conclusions from this analysis can be summarised:

1. Some mathematical expression from the outside pressure distribution is required, with wind direction as a parameter.

2. The error in calculation is minimised considerably if average outside pressure is considered on each floor.

3. The full scale leakage characteristic of building must be known more accurately.

4. Error in the full scale pressure measurements must be minimized for good comparison.
References and Bibliography


6.7 Appleton, I.C. "A model of Smoke movement in Tall Buildings"

6.8 Koyi Iizuka, Akio Kodaira and Tsukasa Takada. "Linear Analysis of Smoke Movement in Buildings on Fire"
CAPARATIVE STUDIES OF SOME AERODYNAMIC ASPECTS OF SMOKE CONTROL IN TALL BUILDINGS.

by B S Kandola.

Addendum to Volume I

Applies to page 280 et seq

Captions to various diagrams were omitted and the following schedule clarifies the situation.

<table>
<thead>
<tr>
<th>Page</th>
<th>Fig No.</th>
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</thead>
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<tr>
<td>280</td>
<td>Fig. 6.1(a) and (d)</td>
</tr>
<tr>
<td>281</td>
<td>Fig. 6.1(b) and (c)</td>
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<tr>
<td>282</td>
<td>Fig. 6.1(e)</td>
</tr>
<tr>
<td>283-285</td>
<td>Figs. 6.2(a) - 6.2(e)</td>
</tr>
<tr>
<td>286-289</td>
<td>Figs. 6.3(a) - 6.3(g)</td>
</tr>
<tr>
<td>290-293</td>
<td>Figs. 6.4(a) - 6.4(h)</td>
</tr>
</tbody>
</table>

Caption for each set of figures should read:

Variation of internal door pressure difference ($\Delta Cp_1$) and $R_L$. 
Fig. 6.1: Variation of internal door pressure difference ($\Delta C_{pi}$) with $R_L$
Room 3
Floor 2
$\alpha = 0^\circ$

Theoretical
- $C_{p_O}(T) = 0.50$, $C_{p_O}(R) = -0.15$
- $C_{p_O}(T) = 0.60$, $C_{p_O}(R) = -0.15$

Experimental

Floor 2
$\alpha = 0^\circ$

Theoretical
- $C_{p_O}(T) = 0.50$, $C_{p_O}(R) = -0.15$
- $C_{p_O}(T) = 0.60$, $C_{p_O}(R) = -0.15$

Experimental
Rooms 4, 5, 6

\[ \Delta C_{p_i} \]

-0.5  -0.4  -0.3  -0.2  -0.1

Experimental

Theoretical

\[ C_{p_0}(T) = 0.50, \quad C_{p_0}(R) = -0.15 \]

\[ C_{p_0}(T) = 0.60, \quad C_{p_0}(R) = -0.15 \]

Floor 2

\( \infty = 0^\circ \)

(e)

\[ R_L \]
**Room (c)**

- **Floor 4**
- **Theoretical**
  - $C_{P_{o}}(T) = 0.70, C_{P_{o}}(R) = -0.15$
  - $C_{P_{o}}(T) = 0.80, C_{P_{o}}(R) = -0.15$

**Shaft**

- **Floor 4**
- **Theoretical**
  - $C_{P_{o}}(T) = 0.70, C_{P_{o}}(R) = -0.15$
  - $C_{P_{o}}(T) = 0.80, C_{P_{o}}(R) = -0.15$
Rooms \(4, 5, 6\)

\[\Delta C_{p_i}\]

-0.6
-0.5
-0.4
-0.3
-0.2

Floor 4

Theoretical

- Experimental

- Theoretical

\[C_{p0}(T) = 0.70, C_{p0}(R) = -0.15\]

\[C_{p0}(T) = 0.80, C_{p0}(R) = -0.15\]
**Diagram (a):**

- **Room (1):**
  - Experimental
  - Theoretical
  - $\alpha = 45^\circ$
  - $C_{pO}(T) = 0.40$, $C_{pO}(R) = -0.20$
  - $C_{pO}(T) = 0.50$, $C_{pO}(R) = -0.20$

- **Diagram (b):**

- **Room (2):**
  - Experimental
  - Theoretical
  - $\alpha = 45^\circ$
  - $C_{pO}(T) = 0.40$, $C_{pO}(R) = -0.20$
  - $C_{pO}(T) = 0.50$, $C_{pO}(R) = -0.20$
**Room 3**

\[ \Delta C_{p_i} \]

Floor 2
\[ \alpha = 45^\circ \]

- **Experimental**
- **Theoretical**
  - \( C_{p_0}(T) = 0.40, C_{p_0}(R) = -0.20 \)
  - \( C_{p_0}(T) = 0.50, C_{p_0}(R) = -0.20 \)

**Shaft**

\[ \Delta C_{p_i} \]

Floor 2
\[ \alpha = 45^\circ \]

- **Experimental**
- **Theoretical**
  - \( C_{p_0}(T) = 0.40, C_{p_0}(R) = -0.20 \)
  - \( C_{p_0}(T) = 0.50, C_{p_0}(R) = -0.20 \)
Room 4

Floor 2

$\alpha = 45^\circ$

Experimental

Theoretical

$C_{p_{O}}(T) = 0.40, C_{p_{O}}(R) = -0.20$

$C_{p_{O}}(T) = 0.50, C_{p_{O}}(R) = -0.20$

$\Delta C_{p_{i}}$

(f)

Room 5

Floor 2

$\alpha = 45^\circ$

Experimental

Theoretical

$C_{p_{O}}(T) = 0.40, C_{p_{O}}(R) = -0.20$

$C_{p_{O}}(T) = 0.50, C_{p_{O}}(R) = -0.20$

$\Delta C_{p_{i}}$
Floor 2
\[\alpha = 45^\circ\]

Experimental

\[C_{p_0}(T) = 0.40, C_{p_0}(R) = -0.20\]

Theoretical

\[C_{p_0}(T) = 0.50, C_{p_0}(R) = -0.20\]
Floor 4
$\alpha = 45^\circ$

**Room 1**

<table>
<thead>
<tr>
<th>$R_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>4.0</td>
</tr>
</tbody>
</table>

$\Delta C_{p_i}$

- Experimental
- Theoretical

$C_{p_o}(T) = 0.40$, $C_{p_o}(R) = -0.20$

$C_{p_o}(T) = 0.50$, $C_{p_o}(R) = -0.20$

(b)
Experimental

Theoretical

\[ \begin{aligned}
C_{pO}(T) &= 0.40, \quad C_{pO}(R) = -0.20 \\
C_{pO}(T) &= 0.50, \quad C_{pO}(R) = -0.20
\end{aligned} \]
Room 4

Floor 4

$\alpha = 45^\circ$

$C_{p0}(T) = 0.40, C_{p0}(R) = -0.20$

$C_{p0}(T) = 0.50, C_{p0}(R) = -0.20$

Room 5

Floor 4

$\alpha = 45^\circ$

$C_{p0}(T) = 0.40, C_{p0}(R) = -0.20$

$C_{p0}(T) = 0.50, C_{p0}(R) = -0.20$
Floor 4

$\alpha = 45^\circ$

Room 6

Experimental
Theoretical

$C_{p_0}(T) = 0.40, C_{p_0}(R) = -0.20$

$C_{p_0}(T) = 0.50, C_{p_0}(R) = -0.20$
CHAPTER SEVEN

GENERAL CONCLUSIONS AND
RECOMMENDATIONS FOR FUTURE WORK
Chapter 7

General Conclusions and Recommendation for Future Work.

As seen from the work described in this thesis that a lot more experimental work needs to be done before the phenomenon of internal flows within large buildings can be understood. The model and full scale measurements and the computer analysis have their own unique problems: In the wind tunnel model study there is the problem of similarity of flow through the various leakage paths (the Reynolds Number problem); in the full scale buildings, apart from the difficult problems associated with the actual measurement of pressures (internal and external), there is an almost insurmountable task of knowing their leakage characteristics, which form the basis of computer calculations.

Apart from these problems, the simulation of a fire both in the wind tunnel model and in the computer model needs to be improved. The measurements made in the present case point to what extent a fire can influence the pressures in the neighbouring areas. A possible theoretical approach to this problem is briefly discussed later.

From the present study the implications for smoke control methods can be summarised.
7.1 Shaft Pressurisation:

The wind tunnel model pressure measurements show that in buildings which rely on natural ventilation, the design of a shaft pressurisation system must take into account the pressure distribution arising from Stack and Wind effects. This is particularly true where the main stair shaft is directly exposed to the outside environment.

The problem can be divided into two outside flow requirements:

(i) When the wall with shaft wind openings is subjected to positive outside wind induced pressures.

(ii) When the same wall is subjected to negative outside wind induced pressures.

In case (i) the higher shaft leakage will produce very high positive pressures in the shaft confining smoke to the fire floor. To apply this to real buildings a probabilistic analysis of prevailing wind and fire occurrence is required. If, for example the outside wind blows in such a way as to produce conditions (i), for most of the time over a one year period, then for high shaft leakage no shaft pressurisation will be required if the probability of the fire occurrence is also high. For remainder of the period when the outside wind is not expected to produce positive shaft pressures, fire prevention measures can be taken within the building. If, on the other hand, the probability of fire occurrence is very high, then the
the shaft pressurisation system can be installed by completely isolating the shaft from the outside environment.

It may be that for a building in a particular location, the probability of outside wind is such that for most of the time over a year conditions (ii) result. When that happens shaft pressurisation is necessary at minimum outside shaft leakage to keep it free of smoke.

The probability of fire location within the building can also be an important factor in deciding on the use of a smoke control system. If a room, with its window openings to the wall which has the highest probability of being subjected to negative wind pressures, has the highest probability of fire occurrence, then this fire will present less danger from the smoke spread point of view. If the probability is high for the positive outside pressures to occur, then the appropriate smoke control measures can be taken.

It is clear from this that a probabilistic analysis of fire occurrence as well as of outside wind is required for the smoke control problem. Along with this on estimation of smoke production is also required.

If the smoke control measures are to be incorporated in the design of a building, a wind tunnel model study as well as the computer analysis of internal pressure distribution is essential.
To do this with confidence, the improvements in the model simulation and the computer program used presently, are required.

7.2 Wind Tunnel Model Simulation:

More useful information can be obtained from the pressure measurement on the existing 32-cell model.

(i) The results described in chapter 2 show that for 0.5% of the door leakage, the internal pressures are independent of leakage ratio $R_L$. This cannot be expected to be true for very high door leakages. Further measurements with higher door leakage values can be made to see at what values this relationship breaks down.

(ii) Internal pressure measurements similar to those described in chapter 3 and 4 must be repeated for other window leakage values.

(iii) For wind angles $\leq 90^\circ$ and $270^\circ$ smoke visualisation as well as detailed pressure measurements are necessary to establish the exact flow patterns.

(iv) Apart from these wind tunnel tests, the stack effect in the model can also be measured by subjecting it to different temperature environments.
7.3 Modifications to the computer Program.

The computer analysis of the internal pressure distribution in the wind tunnel model has shown that the accuracy of calculations are highly dependent on the outside pressures. Ideally what is required is the value of outside pressure at each leakage hole for the prediction of internal pressure distribution for a given wind direction. This can be done without difficulty for a very small number of leakage holes, but for large buildings where windows are distributed all over the building surface, it becomes very tedious. To simplify the calculation procedure, a very important assumption is made in the existing computer program. It has been assumed that for any one particular wind direction, the wind induced pressure distribution over any wall surface is uniform. This, as the measurements have shown is not true. To minimize the error in calculations resulting from this assumption, some way of describing the outside pressure distribution is required.

For any wind direction, the mean pressure over a surface varies considerably from point to point. The measurements discussed in chapter 2 and 3 show that a simple mathematical relationship between wind angle, position of a point and the pressure is impossible. There are three possibilities of overcoming the problem.

(i) The building can be divided into a number of arbitrary vertical strips (e.g. one entire floor can be considered as a strip) and a uniform pressure value
assumed over this strip. This will reduce the error considerably. But the pressure measurements show that the lateral pressure variation is also significant.

(ii) This problem of lateral variation can be overcome if a large computer storage space is available. The outside pressure coefficient values can be stored for small elements of a wall, which are identified by non-dimensional co-ordinates, for a range of wind angles over which the average pressure for the element does not change significantly. When calculation is performed by the computer on a leakage path, it first identifies the element in which this path is contained and then retrieves the appropriate pressure coefficient values. Obviously, this kind of method relies on the availability of a large computer as well as on the precise measurement of pressures in the wind tunnel, of various shapes of buildings.

(iii) The third possibility is to derive a mathematical expression which gives $C_p$ values in terms of wind angles and the position on the building surface. This is possible if it is considered that the pressure contours continue from one wall to another. Taking stagnation point as the origin, the pressure contours can be considered to originate from this point in concentric circles. An object shape (a building) can be defined which moves into these circles and these
circles being flexible deform into contour shapes, depending on the position of the stagnation point (i.e. wind direction).

Apart from these, there is the problem of representing a fire in the computer model. In the present version fire is simulated by assigning a very high temperature to a room, which sets up a neutral pressure plane for the door, with cold air flowing in through the gap at the bottom of the door and hot smoke flowing into the corridor through the top gap. This hot smoke forms a hot layer under the corridor ceiling in which the temperature decays exponentially towards the stair shaft. This model is not representative of a real fire situation in which the temperature within the fire room varies considerably and that the hot layer in the corridor grows with time.

This can be improved by dividing the fire room and the corridor into elements (the size of which depends on the degree of accuracy required) and solving the mass, momentum and energy equations for each element subject to specified boundary conditions.

7.4 Fire in Enclosures:

Any theoretical analysis of flows resulting from a fire in an enclosure is a formidable task, because of the complexity of the basic 'fire phenomenon'. A step forward is to consider a fire in the open. Such a fire forms vertical plume of hot gases, which rise due to buoyancy and the surrounding cold air is entrained
into the plume. The problem of entrainment and fire spread has been studied both experimentally and theoretically (7.1, 7.2, 7.3, 7.7). In the theoretical approach of Yih (7.15), which was used by Thomas et al (7.7) as the basis for roof venting calculations, the fire is assumed to be a point source of heat of constant heat output. In real situations this assumption does not hold due to the growth of fire.

A small fire in an enclosure behaves like that in the open (7.4), but as it becomes larges the internal flow pattern changes dramatically. The hot layer forming under the ceiling grows and fills the room, in which the plume theory breaks down. A very simplified analysis of a plume in a confined region is presented by Baines et al (7.18). In this approach the concept of entrainment is used in the solution of mass, momentum and energy equations (7.17).

Another improved theoretical approach to the problem is presented by Torrance and Rockett (7.9). In this analysis apart from using the Boussinesq approximation, it is assumed that the flow is incompressible and axisymmetric. This assumption enables the mass, momentum and energy equations to be solved by defining vorticity and stream function.

In compressible flows resulting from real fires, these assumptions do not hold. A numerical method to the solution of this problem has been developed by Ku et al. (7.11, 7.12). This analysis present the solution to mass, momentum and energy equations for 2D flow with no Boussinesq approximation and without the use of
vorticity or stream function. Because of this the model is capable of dealing with the flows in which large density variations occur. The effect of door and window leakages as well as the radiation from the walls can be taken into account.

The computational region is divided into a number of rectangular cells (number depending on the degree of accuracy required). The governing equations in integral form are then written for each cell, and are solved subject to appropriate boundary conditions.

For a two dimensional flow these equations are:

For a two dimensional flow these equations are:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \quad \ldots 7.1
\]

\[
\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho u^2) + \frac{\partial}{\partial y}(\rho uv) = \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \quad \ldots 7.2
\]

\[
\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho v^2) = \frac{\partial p}{\partial y} - \rho g + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \quad \ldots 7.3
\]

\[
\frac{\partial}{\partial t}(\rho C_p T) + \frac{\partial}{\partial x}(\rho C_p u T) + \frac{\partial}{\partial y}(\rho C_p v T) = \frac{\partial q_x}{\partial x} \frac{\partial q_y}{\partial y} + q_{R}'' \quad \ldots 7.4
\]

The term \( q_{R}'' \) represents a volumetric heat source or sink.

The pressure temperature and density are related by an equation of state

\[
P = \rho R g T \quad \ldots 7.5
\]

where \( R g \) = gas constant
The initial density and pressure distribution satisfies the hydrostatic equilibrium equation.

\[ \frac{\partial p_e}{\partial y} - \rho_e g = 0 \]  \hspace{1cm} \ldots 7.6

where \( p_e(y) \) and \( \rho_e(y) \) are the static equilibrium pressure and density distribution for some prescribed temperature.

For laminar motion the molecular transport equation gives the stress and heat flux terms.

\[ \tau_{xx} = 2\mu_{\text{eff}} \frac{\partial u}{\partial x} \]  \hspace{1cm} \ldots 7.7

\[ \tau_{xy} = \mu_{\text{eff}} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \]  \hspace{1cm} \ldots 7.8

\[ \tau_{yy} = 2\mu_{\text{eff}} \frac{\partial v}{\partial y} \]  \hspace{1cm} \ldots 7.9

\[ q_x = -k_{\text{eff}} \frac{\partial T}{\partial x} \]  \hspace{1cm} \ldots 7.10

\[ q_y = -k_{\text{eff}} \frac{\partial T}{\partial y} \]  \hspace{1cm} \ldots 7.11

where \( \mu_{\text{eff}} \) = effective viscosity

\( k_{\text{eff}} \) = effective thermal conductivity

full details see Ref (7.11)

Boundary Conditions:

Some boundary conditions are necessary for the solution to these equations.
The governing equations are elliptic in the spatial variables. The boundary conditions must be satisfied over the entire boundary of the computation region.

No-slip condition on the solid boundary is employed. For the thermal boundary condition, temperature and heat flux are prescribed.

The results obtained for the temperature and velocity profiles for a combination of door and corridor, show very good agreement with the measured results.

This particular model for the fire room can be incorporated into the present SCICON computer program, in the form of a subroutine.

7.5 From the brief discussion it follows that modification to the computer program are possible which can give better predictions of internal flows.

Once the computer and wind tunnel model results correlate with minimum percentage error, a wind tunnel model of a real building can be made and tested. Improved full scale pressure measurements can be carried out to perfect the wind tunnel modeling technique and to validate the computer program.


7.14 Bullen, M.L. The ventilation required to permit growth of a room fire. BRE current paper CP 41/78.


