Code of practice for

Design of buildings : ventilation principles and designing for natural ventilation

(formerly CP 3 : Chapter 1 (C))

Code de bonne pratique pour la conception des bâtiments :
Principes de ventilation et études de ventilation naturelle

Richtlinie für Baukonstruktionen :
Belüftungsgrundsätze und Konstruktion für natürliche Belüftung

British Standards Institution Gr 7

Contents

This code of practice represents a standard of good practice and therefore takes the form of recommendations. Compliance with it does not confer immunity from relevant statutory and legal requirements.

Foreword

This code of practice is a revision of CP 3 : Chapter I(C): 1950 which it supersedes. It takes account of the research on ventilation which has taken place since the original code was first published.

The design of mechanical ventilation systems is dealt with in BS 5720.

This revision gives recommendations for the supply of outside air and also covers briefly the processes by which these recommendations may be put into practice.

Requirements regarding the ventilation of buildings are controlled by the following Building Regulations.

(a) The Building Regulations 1976, applicable in England and Wales except London as covered by (b);

(b) The London Building Acts (Amendment) Act 1939;

(c) The Building Standards (Scotland) (Consolidation) Regulations, 1971;

(d) The Building Regulations (NI) 1977;

(e) The Code of Practice for Buildings of Excess Height and/or Additional Cubical Extent requiring approval under Section 20 of the London Building Acts (Amendment) Act 1939, applicable to Inner London.

Where the expression 'comply with the relevant Building Regulations' is used, it means compliance with the above regulations or any revisions currently in force.

Further requirements relating to the ventilation of buildings are contained in the following regulations:

(f) Offices, Shops and Railway Premises Act, 1963;

(g) Factories Act, 1961;

(h) Health and Safety at Work etc. Act, 1974.

Advisory documents covering ventilation practice are issued in the form of building notes by the Department of Health and Social Security and the Department of Education for those types of buildings for which they have responsibility. Advice is also given in the Greater London Council's Code of Practice for means of escape in case of fire.

Appendix F is a bibliography and references to publications listed in it are shown thus: reference [15].

British Standard Code of practice for

Design of buildings : ventilation principles and designing for natural ventilation

Section one. General

1. Scope

This British Standard code deals with ventilation of buildings for human occupation.

In section two, the main reasons for the provision of ventilation are outlined and, where possible, recommended quantitative air flow rates are given. It is shown that these form the basis for air supply recommendations for different types of buildings and rooms characterized by usage. The basis for the choice between natural and mechanical ventilation is given.

Section three gives guidance upon the design of natural ventilation systems.

The design of mechanical ventilation systems is dealt with in BS 5720.

2. References

The titles of the standards publications referred to in this code are listed on the inside back cover.

3. Definitions

For the purpose of this code the definitions given in BS 5643 apply; other terms are defined as follows.

3.1 absolute temperature. Temperature measured with respect to absolute zero.

3.2 discharge coefficient. A coefficient which relates the volume flow rate through an orifice to its area and the applied pressure difference.

3.3 equivalent area. The area of a sharp-edged orifice through which air would pass at the same volume flow rate, under an identical applied pressure difference, as the opening under consideration.

3.4 gust ratio. The ratio of the maximum gust lasting three seconds in one hour to the mean wind speed over the same period, measured at an effective height of 10 m.

3.5 input rating. The heat available for liberation by combustion within an appliance, based upon the gross calorific value of the fuel.

3.6 kerosene. A petroleum oil fuel suitable for appliances with small vaporizing and atomizing burners; classified as class C in BS 2869.

3.7 open-flued appliance. An appliance designed to be connected to an open flue system; its combustion air being drawn from the room or internal space within which it is installed.

3.8 premium grade kerosene. Kerosene suitable for flueless space heaters, complying with the requirements of the specification for class C1 petroleum oil fuels in BS 2869.

3.9 reference static pressure. The static pressure in the free wind, away from any interference with the flow.

3.10 static pressure. The pressure which would be recorded by a pressure gauge moving with the flow (i.e. static relative to the fluid).

3.11 threshold limit value-time weighted average (TLV-TWA). The time weighted average concentration for a normal working day, or 40 h working week, to which nearly all workers may be repeatedly exposed day after day without adverse effect.

3.12 threshold limit value-short term exposure limit (TLV-STEL). The maximum concentration to which workers can be exposed for a period of up to 15 min continuously without suffering from (a) intolerable irritation, (b) chronic or irreversible tissue change, or (c) narcosis of sufficient degree to increase accident proneness, impair self-rescue, or materially to reduce work efficiency, provided that no more than four excursions per day are permitted, with at least 60 min between exposure periods, and provided that the daily TLV-TWA is not also exceeded.

3.13 wake. The region of disturbed flow which persists some distance downstream of a building or similar structure exposed to the wind.

4. Necessity for ventilation

The provision of permanent and/or controllable draught-free ventilation is necessary for all buildings. Designers should take all factors into consideration in determining the ventilation rate necessary for a particular project.

5. Notation

For the purposes of this code the following notation applies. Commonly used abbreviations for units of measurement are not listed.

A	Equivalent area of an opening
$A_1, A_2, A_3, A_4, A_b, A_w$	Equivalent area of specific openings denoted in the text
a	Exponent relating wind speed to height
C_d	Discharge coefficient for an opening
C_p	Surface pressure coefficient
c	Concentration of contaminant in air by volume
c_e	Concentration of contaminant in outside air
c_0	Concentration of contaminant at time $t = 0$

c_E	Equilibrium value of contaminant concentration
g	Acceleration due to gravity
H_1	Vertical distance between the centres of two openings in a wall
H_2	Vertical distance between top and bottom edges of a rectangular opening in a wall
h	Vertical distance between ground and the eaves or parapet
J	Function relating ventilation rate through an open window to the angle of opening, ϕ
K	Factor relating wind speed to height
k	Window leakage factor
L	Length of a crack
l	Length of a building
M	Metabolic rate
n	Exponent relating flow rate through crack to applied pressure difference
p	Surface pressure
$\bar{p}$	Mean surface pressure
p_0	Static pressure in undisturbed wind
Q	Volume flow rate of air
q	Input volume flow rate of contaminant
R	Air change rate
t	time
U	Thermal transmittance
u	Wind speed
u_m	Wind speed at 10 m, exceeded for a given proportion of time
u_r	Reference wind speed
V	Room volume
w	Width of building
z	Height
α	Angle made by wind relative to building
Δ	Difference between two values of the same quantity, e.g. $\Delta C_{\bar{p}}$
ϵ	Area ratio
θ	Absolute temperature
θ_e	Absolute temperature of outside air
θ_i	Absolute temperature of inside air
$\bar{\theta}$	Average of inside and outside temperature
ρ	Air density
ϕ	Angle made by an open window with the plane containing the wall of a building

Section two. General principles of ventilation

6. Basic data

6.1 General. A supply of outside air is required for one or more of the following purposes:

(a) human respiration;

(b) dilution and removal of odours, tobacco smoke, toxic and flammable gases and other contaminants;

(c) control of internal humidity;

(d) provision of air for fuel burning appliances;

(e) control of thermal comfort;

(f) clearance of smoke resulting from a fire.

In 6.2 to 6.7 the need for ventilation is explained and quantitative guidance given on how these needs should be met in general.

6.2 Composition of outside air. In ordinary engineering practice fresh air means air from outside. The usually accepted composition of dry air is 20.94 % O_2, 0.03 % CO_2, 79.03 % N_2 and inert gases. The CO_2 content can be less than 0.03 % in country areas, and higher in built-up areas where it is a product of respiration and fuel combustion, perhaps nearer 0.04 %. In addition, air contains particulate matter and consideration should be given to the need for filtering. It also contains water vapour such that in winter it is about 80 % to 95 % saturated on average in Britain and in summer 55 % to 75 %.

6.3 Human respiration. The body requires oxygen for the production of energy at a rate approximately proportional to metabolic rate. This in turn is proportional to body surface area and to activity level. Metabolic rates are listed in references* [1] and [2] for a wide range of activities.

As an indication of the required flow rates†, table 1 gives values for general activity levels for an adult male. The corresponding rate for adult females can be taken as 75 % of that for adult males for the same activity.

Expired air contains 4.4 % by volume or (V/V) of CO_2 and if, as is usually the case, it mixes within the space into which the fresh air for respiration is being introduced, a gradual increase in CO_2 level will result. The threshold limit value for CO_2 is 0.5 % by volume and the flow rates necessary to accomplish this are also given in table 1.

Table 1. Outside air requirements for respiration

Activity (adult male)	Metabolic rate, M	Requirements for respiration; O_2 concentration of 16.3 % in expired air	Requirements to maintain room CO_2 at 0.5 % assuming 0.04 % CO_2 in fresh air*
	W	litres/s	litres/s
Seated quietly	100	0.1	0.8
Light work	160 to 320	0.2 to 0.3	1.3 to 2.6
Moderate work	320 to 480	0.3 to 3.5	2.6 to 3.9
Heavy work	480 to 650	0.5 to 0.7	0.3 to 0.5
Very heavy work	650 to 800	0.7 to 0.9	5.3 to 6.4

*The rate of production of CO_2 in terms of metabolic rate M is $40 \times 10^{-6} M$ litres/s where M is in watts.

6.4 Dilution and removal of contaminants

6.4.1 *General.* Provided that good mixing takes place within the ventilated space, the supply rate of outside air necessary to limit the concentration of contaminant should be determined using equation (7) in appendix A. In many

*References are listed in appendix F.

†The required flow rate of air, Q, is related to the metabolic rate, M, by the following expression:
$Q = 0.001M$ litres/s where M is the metabolic rate (in watts).

situations, in particular, industrial works, laboratories and commercial kitchens, contaminants should be extracted mechanically as near to the source as possible. Other methods of counteracting contaminants by masking or adsorption and absorption may be considered. It should be noted that when air passes from one space to another in a building, the ventilation rate for each room will depend upon the total requirement of all the interconnecting spaces (see example in appendix A).

6.4.2 *Limiting concentration of contaminants.* The threshold limit value (TLV) is the level of concentration used by the Health and Safety Executive to define maximum concentration levels of contaminants in the work place. Values for many substances have been listed (see references [3] and [4]). They apply to airborne concentrations, and fit and healthy people at work for a 7 h or 8 h day and a 40 h working week. The TLV can be modified to cover shorter and longer periods. The TLV normally quoted is a time weighted average (TLV-TWA), and for some contaminants short term exposure limit (TLV-STEL) concentrations are given (see reference [3]) for exposure periods of 15 min.

For exposure times longer than 40 h in a week it seems reasonable that limits should be lower than the TLV-TWA especially for the general population which includes old, young and unfit people. Very little information is available but in the review (see reference [5]) data for continuous exposure to carbon monoxide in submarines and spacecraft indicate maximum concentrations of one fifth of the TLV-TWA.

When two or more contaminants are present their effects should be considered together if they act on the same parts of the body (see references [3] and [4]).

6.4.3 *Density difference.* It should be noted that some gases and vapours differ considerably in density from air and may form layers which will not mix readily with the outside air. This may give rise to regions of dangerously high concentration despite a theoretically sufficient ventilation rate (see reference [6]).

6.4.4 *Odour.* The odours which emanate from the human body may create a disagreeable environment. The degree of nuisance, based on subjective judgement, has been shown (see reference [7]) to depend both upon the outside air supply rate per person and the density of occupation of the space concerned. Figure 1 gives the air supply rate per person to reduce odour nuisance to a moderate level for sedentary adults, as a function of occupation density. The particular problem of the removal of lavatory odours is discussed in reference [8].

6.4.5 *Tobacco smoke.* Apart from carbon monoxide production the smoking of tobacco can produce an undesirable odour, particularly to non-smokers, and because of certain of its constituents, in particular acrolein, can produce irritation to the eyes and nasal passages. Research has shown that the removal of tobacco smoke odour requires higher air flow rates than for the removal of associated irritants, and use is made of the results of this research in the derivation of fresh air requirements for areas where smoking occurs.

Current knowledge (see reference [5]) indicates a considerable variation in recommended flow rates. In the absence of more definitive information, a value of 20 m^3 per cigarette smoked appears to be a reasonable compromise. To translate this into an air supply rate requires a knowledge of the number of smokers present and the rate of smoking. The average smoker consumes 1.3 cigarettes per hour: this requires a fresh air rate of 26 m^3/h or 7 litres/s per smoker. An allowance can be made for the fact that only a proportion of the adult population smokes, when determining the design ventilation rate of spaces which are relatively heavily

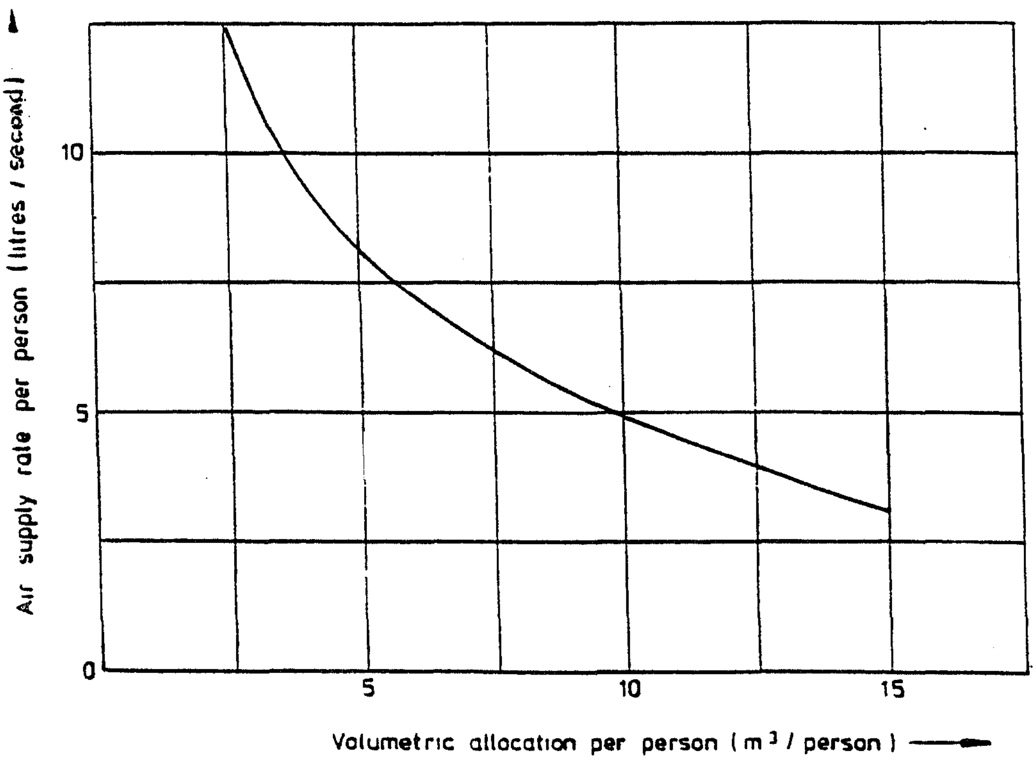


Figure 1. Air supply rate for odour removal

populated, e.g. open-plan offices, which may have a lower required flow rate per person than cellular offices (see reference [5]). It also follows that if the smoking rate is expected to be more than 1.3 cigarettes per smoker per hour, appropriate corrections will need to be made.

6.5 Control of internal humidity. The relative humidity (r.h.) of air is approximately equal to the ratio of the moisture content of the air to the moisture content of saturated air at the same temperature. Low relative humidities can give rise to respiratory discomfort and nuisance from electrostatic effects. High relative humidities incur the risk of condensation and mould growth on surfaces whose temperatures fall below the dewpoint temperature of the air. The reader should refer to BS 5250 which deals with factors affecting condensation and mould growth in dwellings, including the thermal properties of the structure, the temperature and humidity of the outside air and the heat and moisture input. The contribution made by ventilation is to lower the moisture content of the internal air by dilution with outside air which normally has a lower moisture content. For any required moisture level the flow rate will depend upon the moisture level in the outside air, and the rate of moisture input from such sources as respiration, cooking, washing and flueless combustion of certain fuels. Tables 2(a) and 2(b) give some guidance on the likely moisture input rates and, given the temperature and relative humidity of outside air, which for design purposes should be taken as 90 %, given flow rates should be obtained using equation (7) in appendix A. It should be noted that in newly constructed buildings large quantities of moisture are released from the fabric as the building dries out. Consideration should be given during this period to the question of whether additional ventilation should be provided (see reference [9]).

Table 2. Typical moisture emission rates

(a) Rates fixed by the nature of the process	Moisture emission rate
*Occupation *:*	
sleeping adult	0.04 kg/h
active adult	0.05 kg/h
Flueless combustion:	
natural gas	0.16 kg/h per kW
premium grade kerosene	0.10 kg/h per kW
liquefied petroleum gas	0.13 kg/h per kW
(b) Rates estimated*, but subject to variation due to occupants' lifestyle	
Cooking†	3.0 kg/day
Bathing, dishwashing; etc.	1.0 kg/day
Clothes washing	0.5 kg/day
Clothes drying†	5.0 kg/day

*From table 2 of BS 5250 : 1975

†From the process only and excluding fuel by-products.

For the particular case of steady state heat transfer, appendix B gives a simple method using a nomograph (see figure 2) for estimating the ventilation rates necessary to reduce the risk of surface condensation occurring.

6.6 Provision of air for fuel burning appliances

6.6.1 *General provisions.* An air supply to a fuel burning appliance is required for one or more of the following purposes:

(a) to supply primary and secondary air for combustion;

(b) to limit the concentration of combustion products within the space to an acceptable level (this is normally taken to be 0.5 % CO_2);

(c) to prevent overheating of the appliance and its surroundings.

6.6.2 *Primary and secondary air.* The supply rate necessary to provide air for typical open-flued domestic fuel-burning appliances, both for combustion and for adequate operation of the flue, is about 0.8 litres/s to 1.1 litres/s per kW output of the appliance according to the appliance efficiency. (For gas appliances see BS 5440 : Part 2. For oil-burning appliances see BS 5410 : Parts 1 and 2.)

6.6.3 *Control of concentration of combustion products.* This applies to flueless combustion appliances where the products of combustion pass into the room or space containing the appliance. Flueless appliances are categorized as:

(a) continuous, such as kerosene or gas space heaters;

(b) intermittent, such as gas water heaters and cookers.

The criterion most usually applied in assessing the ventilation rate is the need to maintain the concentration of carbon dioxide below 0.5 %. For continuously operating appliances this leads to the specification of an air supply rate derived from equation (7) in appendix A and a knowledge of the constitution of the products of combustion. Table 3 shows the required flow rates for kerosene, liquefied petroleum gas and natural gas.

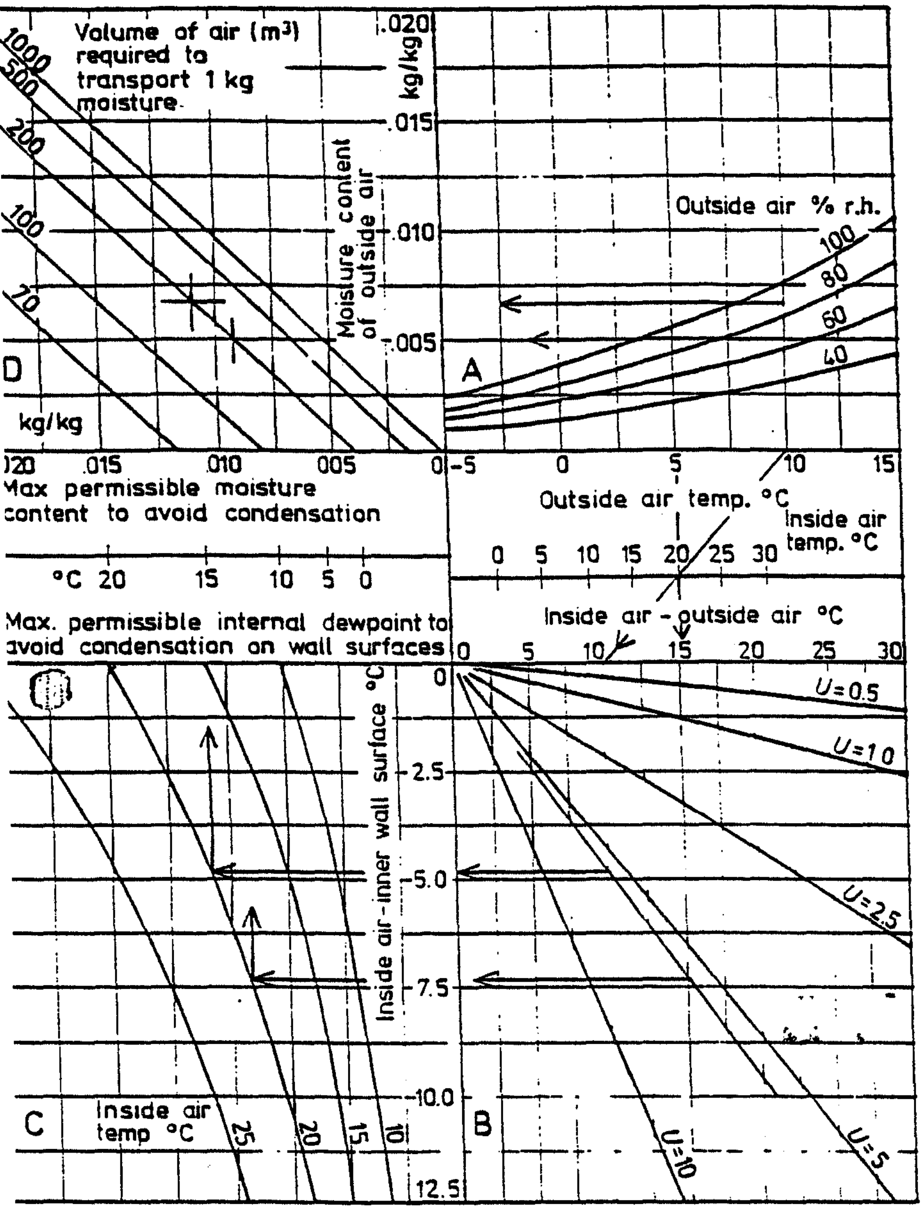
NOTE. For kerosene, another criterion should be applied, which is the need to maintain the concentration of sulphur dioxide below a recommended level. The value for air supply rate based on this criterion is also given for a fuel containing 0.06 % sulphur and with a limiting sulphur dioxide concentration of 5.0 p.p.m. (the TLV) and 1.0 p.p.m. (for continuous exposure of the general population).

For gas appliances which are likely to be operated intermittently for limited periods of time, a lower outside air supply rate is permissible since it is only necessary to ensure that the level of carbon dioxide concentration does not exceed 0.5 % during the period of operation of the appliance. Manufactured gas and natural gas produce 0.027 litres/s of carbon dioxide per kW heat input. Thus, equation (6) in appendix A should be used in order to determine the required ventilation rate, given the length of the period of operation of the appliance. It will be noted that room volume is required for this calculation. For a given heat output the ventilation requirement will increase with decreasing room volume.

NOTE. Direct fired air heaters are subject to special restrictions. Details can be obtained from the local gas authority.

6.6.4 *Appliances in confined spaces.* Consideration should be given to the provision of an air supply to heating appliances in confined spaces, to prevent overheating of such appliances and of their surrounding enclosures.

For further guidance reference should be made to BS 5410 : Parts 1 and 2, and to BS 5440 : Part 2 and references [10] and [11].



IOTE. The method of use of this nomograph is explained in appendix B. The two examples shown elate to appendix C.

igure 2. Ventilation required to reduce the risk of surface condensation occurring on the inner wall urface for various wall *U*-values and ambient air conditions (Reproduced from reference [27] by ermission of the Institution of Gas Engineers)

Table 3. Air supply rates required for flueless appliances

Fuel	Basis	Air supply rate
		litres/s per kW*
Natural gas	CO_2 <0.5 %	5.4
Liquefied petroleum gas	CO_2 <0.5 %	6.6
Premium grade kerosene	CO_2 <0.5 %	6.8
Premium grade kerosene	SO_2 <5.0 p.p.m.	1.8 †
Premium grade kerosene	SO_2 <1.0 p.p.m.	9.0 †

*Input rating of the appliance.
†These figures are based upon the maximum level of sulphur, of 0.06 % allowed by BS 2869. In many cases sulphur levels will be lower than this, in which case the required air supply rates may be reduced in proportion, e.g. for 0.04 % the rates would be 1.2 litres/s per kW and 6.0 litres/s per kW respectively.

6.7 Control of thermal comfort. Temperatures achieved in buildings depend upon the solar heat gain, the heat deliberately supplied, the heat generated by the occupants or processes within the building, the type of construction and the ventilation rate. Methods exist for relating the ventilation rates and corresponding temperatures.

6.8 Clearance of smoke resulting from an accidental fire. A fire can generate large quantities of combustion products, namely hot gases carrying smoke particles and containing toxic or noxious and irritant products (usually referred to as 'smoke').

In the event of a fire within a building, ventilation by natural or mechanical means can be used to limit the spread of these products which could otherwise hinder or prevent escape and thus endanger the lives of the occupants, and restrict or prevent effective rescue and fire fighting by the fire brigade.

For certain kinds of building, provision should be made for:

(a) the removal of smoke from escape routes;

(b) the control of the spread of smoke and the removal of smoke and heat.

Requirements regarding fire ventilation can arise from statutory regulations, codes of practice, government circulars, conditions of licence, insurance, and fire brigade advice.

Fire ventilation may be required to operate either immediately (i.e. provision for permanent openings or openings automatically operated upon the actuation of a heat or smoke sensitive device) or be available for operation as and when required by the fire brigade (e.g. breakable pavement lights or manually operated openings).

The requirements for ventilation in the event of fire may, on occasion, be incompatible with those for normal ventilation. In most cases, larger flows of air or gases have to be allowed for, in directions sometimes different from those required for normal ventilation.

Refer to CP 3 : Chapter IV (currently being revised as Parts of BS 5588) and references [12], [13] and [14] for specific recommendations concerning fire ventilation requirements and practice.

7. Application

7.1 General. Clause 6 sets out basic data in relation to the main reasons for providing a supply of outside air. In order to determine the required air supply rate for a specific building, or room within a building, these data should be combined with a knowledge of the use to which the building is to be put. Table 4, taken from reference [15], lists recommended outside air supply rates for a range of building types, based broadly upon the information given in clause 6, and these may be used for making initial assessments in the design process. Where possible, when more detailed information is available, the designer should calculate outside air requirements on a room by room basis in order to obtain a more efficient design. Examples are given in appendix C, in tabular form, for a domestic living room, and in figure 3, in graphical form, for an office. In general, the largest rate calculated for the purposes set out in

Table 4. Recommended outdoor air supply rates for air-conditioned spaces

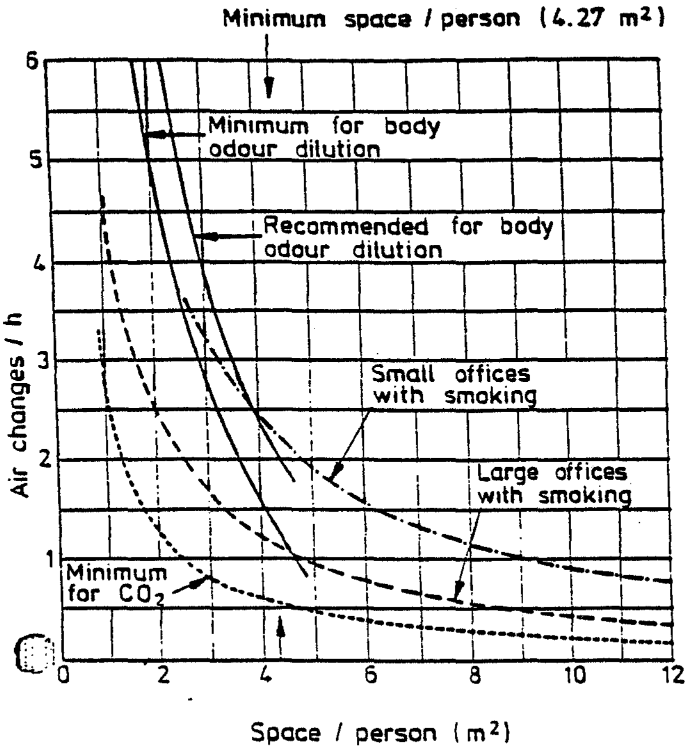
(Reproduced from reference [15] by permission of the Chartered Institution of Building Services)

Type of space	Smoking	Outdoor air supply		
		Recommended	Minimum (the greater of the two should be taken)	
		Per person	Per person	Per m^2 floor area
		litres/s	litres/s	litres/s
Factories*†	None	8	5	0.8
Offices (open plan)	Some			1.3
Shops, department stores and supermarkets	Some			3.0
Theatres*	Some			—
Dance halls*	Some	12	8	—
Hotel bedrooms†	Heavy			1.7
Laboratories†	Some			—
Offices (private)	Heavy			1.3
Residences (average)	Heavy			—
Restaurants (cafeteria)†‡	Some			—
Cocktail bars	Heavy	18	12	—
Conference rooms (average)	Some			—
Residences (luxury)	Heavy			—
Restaurants (dining rooms)†	Heavy			—
Board rooms, executive offices and conference rooms	Very heavy	25	18	6.0
Corridors	A per capita basis is not appropriate to these spaces			1.3
Kitchens (domestic)†				10.0
Kitchens (restaurant)†				20.0
Toilets*				10.0

*See statutory requirements and local bye-laws.
†Rate of extraction may be overriding factor.
‡Where queueing occurs in the space, the seating capacity may not be the appropriate total occupancy.

NOTE 1. For hospital wards and operating theatres see Department of Health and Social Security Building Notes.

NOTE 2. The outdoor air supply rates given take account of the likely density of occupation and the type and amount of smoking.



NOTE. Smoking is based on 26 m^3/h per smoker. Small offices may contain all smokers, large offices are assumed to reflect the adult population, i.e. half smokers. Minimum space is as specified in the Offices, Shops and Railway Premises Act.

Figure 3. Air requirements for people in a room 2.7 m high (Reproduced from reference [15] by permission of the Chartered Institution of Building Services)

clause 6, defines the required air supply rate. In all cases, however, any calculated rates will be subject to the overriding need to satisfy statutory or similar regulations.

It is important to note that ventilation is occasionally required in unoccupied rooms because of residual contaminants or odours following occupancy, transfer of contaminants from other parts of the building, contaminants arising from factors not dependent on occupation, such as combustion products or contaminants arising from building or furnishing materials.

7.2 Special applications. The provision of ventilation will be required in some types of buildings for special applications, including the following:

(a) *in factories and industrial processes,* to remove hot air, toxic and unpleasant contaminants, smoke and products of combustion in the event of a fire;

(b) *in garages or enclosed car parks and vehicle tunnels,* to remove exhaust gases (particularly carbon monoxide), petrol vapour and smoke in the event of a fire;

(c) *in hospitals,* to control cross-infection in special care units and to reduce the level of airborne bacteria in operating theatres;

(d) *in large commercial kitchens,* to remove excess heat, steam and cooking odours;

(e) *in underground rooms and floor areas above ground not provided with normally openable windows,* to remove smoke in the event of a fire;

(f) *in internal common access lobbies and corridors in blocks of flats and maisonettes,* to remove smoke resulting from a fire.

Normally the air flow rates required are such that the design will be based on mechanical ventilation. See reference [4] for specific requirements.

8. Provision for ventilation

8.1 General considerations

8.1.1 *Methods of ventilation.* In order to supply the air flow rates derived in clause 7, either natural or mechanical systems can be employed. This clause describes briefly the main characteristics of each system, and factors affecting the choice of system for any particular application are given in clause 9. Section three deals in detail with the design of natural ventilation systems, while the general design, planning and installation of mechanical systems is covered by BS 5720 and references [16] and [17].

It should be understood that uncontrolled infiltration of outside air will occur in all buildings, including those served by mechanical ventilation systems. In the latter case, the aggregate quantity of outside air entering the building will comprise that introduced mechanically together with an allowance for infiltration.

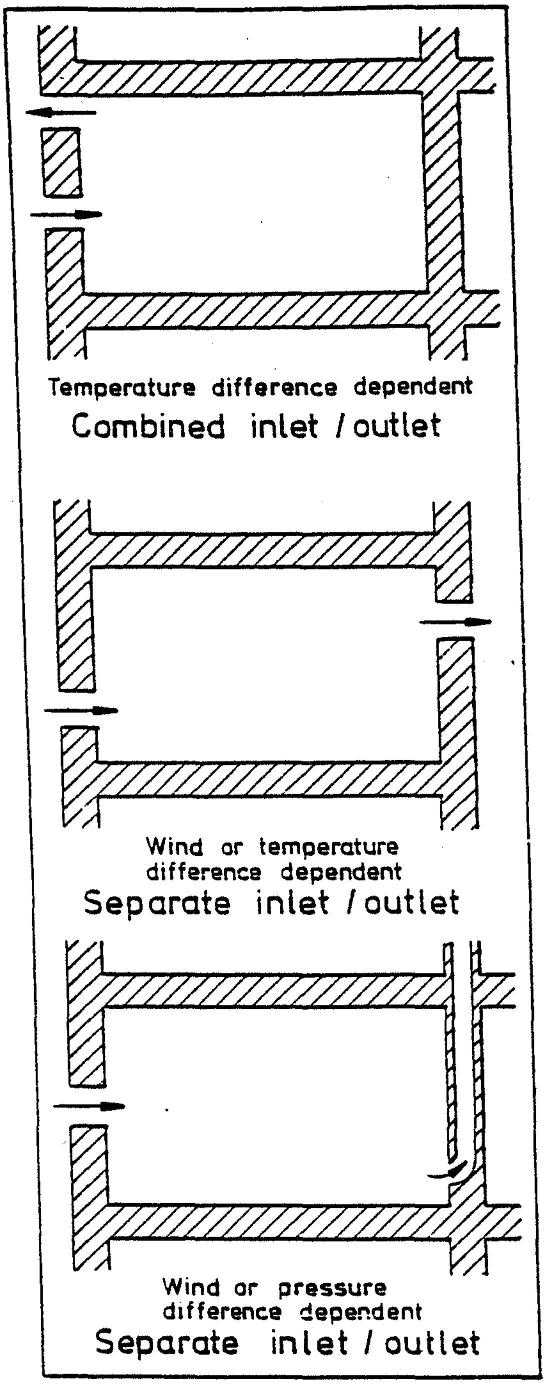
8.1.2 *Inlets and outlets.* Regardless of the method employed for ventilation, the supply of fresh air to a space should be complemented by the removal of an equal quantity of air from the space. In general, air inlets and outlets will be separate, although (see 15.2) significant air exchange can occur through a single large opening under certain conditions. Figure 4 shows typical possibilities for inlets and outlets, for both natural and mechanical ventilation systems.

8.1.3 *Natural ventilation.* Natural ventilation is the movement of air through openings in the building fabric, due to wind or to static pressures created by differences in temperature between the interior and exterior of the building (generally known as 'stack' effect), or to a combination of these acting together. The mechanisms of natural ventilation are described in detail in section three, but it should be noted here that natural ventilation is subject to the variability of wind speed, wind direction and air temperature. Not only will these affect the rate of fresh air supply, but they will also determine whether any opening will act as an inlet or outlet for the air in any space within the building, and hence the path that air takes as it moves from space to space within the building.

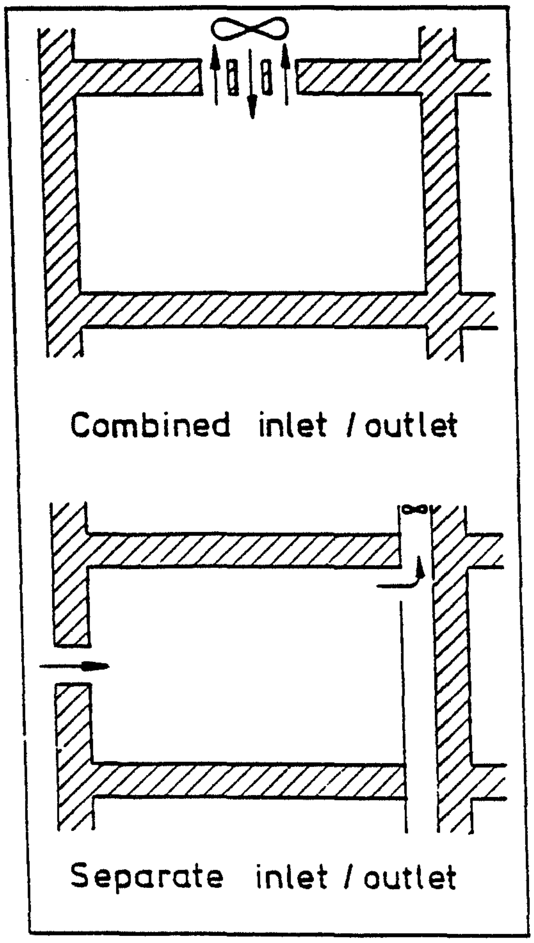
8.1.4 *Mechanical ventilation.* There are several methods of mechanical ventilation, the simplest being the supply or extraction of air from a space using a wall-mounted fan. In these cases an adequate opening should be supplied to allow the exit or entry of air, in order that the fan can operate satisfactorily. More complex systems involve the use of ducted air supply from centrally located fans, possibly providing supply and extraction of air, conditioning of the air and heat recovery from the extracted air.

The major advantage of mechanical ventilation is its controllability. In principle a mechanical system can be designed to satisfy the air requirements of any space within specified limits. In practice, constraints on its use are cost and space limitations.

8.1.5 *Effects of ventilation.* The major effect is the satisfaction of the recommendations set out in clause 7, by providing outside air for dilution or to make up for the extraction of any contaminant at its source.
The introduction of air from outside a space can affect



Natural ventilation



Mechanical ventilation

Figure 4. Diagrammatic sections illustrating the need for inlet and outlet openings (Illustrations of principles only)

the movement of air within the space. These aspects are discussed more fully in 8.2 and 8.3. In addition, it should be noted that the introduction of outside air imposes an energy load, and this should be taken into account in the overall design of the building and its services.

8.2 Air supply

8.2.1 *General.* Most of the recommendations set out in clause 6 can be considered aspects of contaminant control. In some cases, contaminants can be extracted at source. Air supply is then necessary to replace the air extracted with the contaminant. In general, the main action of air supply is to dilute contaminants, and this is achieved by the supply of the required air flow determined according to clauses 6 and 7.

8.2.2 *Air change rate.* The volumetric requirements set out in clause 7 are given in terms of flow rates. An alternative method of expressing these is the air change rate, defined as the volume flow rate divided by the volume of the space, usually stated as 'air changes per hour'. The origin of this form of expression lies in equation (6) in appendix A, where it can be seen that the ratio of flow rate to space volume determines the rate at which equilibrium is reached, but *not* the equilibrium concentration itself, i.e. if the contaminant is released at the same rate in a large room as in a small room, the air supply rate necessary to limit the contaminant concentration to a set level is the same, but the rate at which this level is reached in the smaller room is very much faster than in the larger room.

8.2.3 *Effectiveness of air supply.* In deriving the recommendations for outside air supply it has been assumed that the contaminant is always perfectly mixed with the air.

ıch good mixing can be promoted by an appropriate stribution of inlets and outlets. For example, here natural ventilation is used, openable windows could be evenly distributed along external walls.

particular case in which uniform mixing will not always ccur arises from contaminants whose density varies ıbstantially from air (see reference [6]), due either to ıherent density or to temperature difference. Where these ccur, stable layers can form which will not necessarily mix ith incoming fresh air. Special measures should be taken ɔ deal with such layers.

.3 Air movement

.3.1 *General.* The method of air supply to a space, ɔgether with other sources of air movement to that space, ıch as hot and cold surfaces, can contribute to the ıovement of air and hence to the pattern of air speed and emperature.

.2 *Comfort criteria.* Air movement is noticed because f its increased cooling effect on the body over that of till air. The lower limit of perceptibility is around 0.1 m/s.

Vh air speeds in a room are greater than 0.1 m/s, he resultant temperature should be raised from its still ir value to compensate for the cooling effects of the air ıovement (see reference [15]). Figure 5 gives suggested orrections. Speeds greater than 0.3 m/s are probably ınacceptable except in summer.

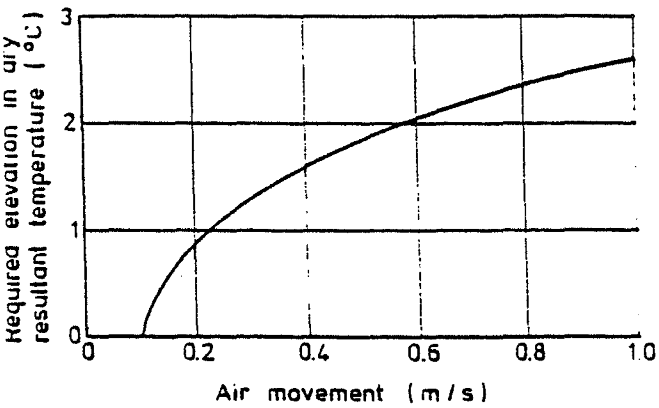


Figure 5. Correction to the dry resultant temperature to take account of air movement (Reproduced from reference [15], by permission of the Chartered Institution of Building Services)

9. Choice between natural and mechanical ventilation

9.1 Influencing factors

9.1.1 *General.* The quality, quantity and controllability of the air supply are the basic factors which influence the choice between natural and mechanical ventilation.

9.1.2 *Quantity.* The air supply rates required for individual rooms or spaces within a building should be determined in accordance with the criteria set out in clauses 6 and 7. In theory, almost any required quantity of outside air can be supplied by natural ventilation but, as noted in 8.1.3, account should be taken of the unreliability of this method and of practical limitations.

9.1.3 *Quality.* In cases where a building is located in an area where the outside air is polluted in some way, or where particularly clean air is required because of the nature of the process taking place within the ventilated space (e.g for certain scientific, medical and industrial applications), air will almost certainly need to be supplied mechanically in order that it can be filtered and, if necessary, conditioned. Exhaust air should be filtered, when necessary, to reduce pollution of the outside air; mechanical ventilation should be employed in such cases.

9.1.4 *Controllability.* Mechanical systems can be designed to provide a chosen ventilation rate, whereas natural ventilation systems can only be designed on a statistical basis. The natural ventilation rate will vary with meteorological conditions, the means of control and the way that these are used by the occupants. It follows that the degree of variation from the design requirement that is acceptable is a major determinant affecting the choice of natural ventilation.

9.2 Limitations of natural ventilation

9.2.1 *Control and conditions.* Precise control of the air supply is not possible. Neither the rate of ventilation nor conditions within the space can be controlled with any degree of precision.

9.2.2 *User interference.* Where it is possible to control natural ventilation by the use, for instance, of openable windows, or where the occupant may have access to permanent openings such as airbricks, these may be obstructed to reduce discomfort during high wind conditions. The ventilation rate will then be reduced substantially (see also clause 4).

9.2.3 *Building form, orientation and layout.* Spaces within a building and the built form itself need to be related appropriately in order to reduce resistance to cross-ventilation and stack effect. For instance, double banking of self-contained units (e.g. flats or maisonettes) with a central corridor (usually also the fire escape route) acts to prevent cross-ventilation. Generally, the overall width of a building needs to be limited. The arrangement of internal spaces may have to be ordered so as to avoid cross-contamination. Where possible, buildings should be orientated to gain the required effect from prevailing winds.

9.3 Need for mechanical ventilation

9.3.1 *Absolute necessity.* Situations where there is an absolute necessity for mechanical ventilation to be provided are as follows:

(a) rooms or spaces requiring ventilation, which cannot be ventilated by natural means;

(b) industrial or other premises where it is essential to remove dust, toxic or noxious contaminants at or near to their source;

(c) hospitals where it is essential to control cross-infection, for instance in special care units, and to reduce the level of airborne bacteria in operating theatres;

(d) where unfavourable external environmental conditions (e.g. noise, dust, pollution) exist;

(e) garages or enclosed car parks and vehicle tunnels, in order to remove exhaust gases (particularly carbon monoxide), petrol vapour and smoke in the event of a fire.

9.3.2 *Desirability.* Situations where it is desirable that mechanical ventilation should be provided are as follows:

(a) factories and industrial processes in order to remove hot air, moisture and contaminants generally;

(b) dwellings, in order to remove odours and excessive moisture from bathrooms and kitchens;

(c) assembly halls and lecture theatres where a high density of occupation is expected;

(d) situations where wind and stack effect might render natural ventilation impracticable, as with some tall buildings;

(e) large commercial kitchens.

Section three. Natural ventilation

10. Introduction

Natural ventilation is the movement of outside air into, through and out of a building due to the action of the naturally occurring agencies, i.e. wind and difference in air temperature between inside and outside. Whereas, in principle, a correctly designed mechanical ventilation system can supply the required quantity of air to the required place for the required time, natural ventilation is dependent upon the variability of the forces which govern it, and is consequently very difficult both to predict and to control.

The purpose of this section of the code is to outline the mechanisms which govern natural ventilation and to illustrate these for simple cases. It will be seen that while it is possible to attempt to predict the likely ventilation rates to be found in a fairly simple building, given its physical characteristics, including the position and size of openings, the computational problem for more complex buildings is substantial and will require the use of digital computers. Even more difficult to resolve is the design problem of specifying required openings to satisfy particular fresh air requirements. At present, little more can be attempted than the simple example given to illustrate the approach, but it is hoped that in due course the state of the art will be sufficiently improved to enable this section of the code to include guidance on open areas for the designers of new buildings.

11. Flow characteristics of openings

When a difference in pressure is applied across an opening, a flow of air takes place through the opening. The aerodynamics of this flow are complex but, by deeming openings to be classifiable within two general types, it is possible to specify simple formulae to relate the flow rate to the pressure difference. These categories are:

(a) cracks, or small openings with a typical dimension less than approximately 10 mm;

(b) openings with a typical dimension larger than approximately 10 mm.

Taking each of these in turn:

For cracks,

$$Q = kL\,(\Delta p)^{n} \qquad Q = l/s\ ? \qquad (1)$$

For L, the length of the crack in metres, and the applied pressure difference in pascals (N/m^2), table 5 gives a range of values of k for the cracks formed around the opening lights of closed windows. A suitable value for n is 0.67.

For larger openings,

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \qquad (2)$$

Table 5. Values of k for windows (in litres/s per metre of crack length, for an applied pressure difference of 1 Pa) (Reproduced from reference [26] : Crown copyright HMSO)

Window type	Value of k	
	average	range
Sliding	0.08	0.02 to 0.30
Pivoted	0.21	0.06 to 0.80
Pivoted (weather-stripped)	0.08	0.005 to 0.20

It is conventional to assign a value to the discharge coefficient, C_d, corresponding to that for a sharp-edged orifice, taken here as 0.61*. The value of A for other types of opening then becomes the equivalent area associated with that particular opening, i.e. the area of the equivalent sharp-edged orifice which would give the same flow rate as the opening concerned at the same applied pressure difference. For openings such as open windows, whose depth in the direction of flow is much smaller than the typical lateral dimensions, the equivalent area can be taken as the geometrical area. For openings where this is not the case, equivalent areas should be determined experimentally. Table 6 gives values obtained for air-bricks and similar openings.

A building can be regarded as a series of discrete cells connected to outside air and to each other by openings of the types discussed previously. Usually these cells will be rooms or circulation spaces, although floor, roof and wall voids may also need to be considered. Not all such cells will be inter-connected and some can be connected by more than one opening. Pressures generated by forces of wind and temperature difference produce a movement of air through these openings governed by the fact that the total flow of air into any cell should equal the outgoing flow rate. Clause 2 deals with the generation of pressure by wind and temperature difference.

Table 6. Equivalent area of ventilation openings (Reproduced from reference [26] : Crown copyright HMSO)

Opening	Overall size	Equivalent area
	mm	mm^2
Terracotta air-brick with square holes	225 x 75	1 400
	225 x 150	4 300
	225 x 225	6 400
Terracotta louvred air-brick	225 x 150	2 000
	225 x 225	4 300
Cast iron air-brick with square holes	225 x 75	7 200
	225 x 150	12 700
	225 x 225	19 600
Cast iron air-brick	225 x 75	3 100
	225 x 150	11 300
	225 x 225	19 200
Typical internal louvred grille	225 x 75	2 400
	225 x 150	7 200
	225 x 225	10 700

*Other values, in particular, 0.65, are sometimes given for C_d. This is because the value of C_d even for a sharp-edged orifice varies with the Reynolds number of the flow through it. The value of 0.61 corresponds to the theoretical value at very high Reynolds numbers. To avoid confusion, the value of C_d assumed in any particular application should be quoted in any list of equivalent areas.

12. Generation of pressure differences

12.1 Wind. The distribution of pressure at the surface of building will depend upon the following:

(a) the shape of the building;

(b) the wind speed and direction relative to the building;

(c) the location and surroundings of the building, particularly the presence of other buildings or similar large obstructions in close proximity.

It has been found that, for any particular wind direction, the pattern of flow around a building is virtually independent of wind speed, provided that the building has sharp corners. The surface pressure will vary with wind speed squared, if all other conditions including wind direction remain constant. In consequence, the instantaneous pressure, p, generated at a particular point on the external surface can be defined in terms of a single coefficient, C_p, as follows:

$$C_p = \frac{p - p_0}{0.5 \rho u_r^2} \qquad (3)$$

The surface pressure varies with time, due to turbulence in the free wind and that created by the building itself, or by upstream obstructions, but for present purposes the mean value is used. (A brief discussion of the effect of pressure fluctuation on ventilation rate is included in clause 15). If the mean values of surface pressure and surface pressure coefficient are written as $\bar{p}$ and $C_{\bar{p}}$, equation (3) may be rearranged to give:

$$\bar{p} = p_0 + C_{\bar{p}} \; (0.5 \rho u_r^2) \qquad (4)$$

p_0 is the static pressure in the free wind, and u_r is the reference wind speed, conventionally taken as the speed of the undisturbed wind at a height equal to that of the building under consideration.

Once the distribution of $C_{\bar{p}}$ has been determined for a single wind speed and particular wind direction, then surface pressure can be calculated readily for any other wind speed. To illustrate the general magnitudes of $C_{\bar{p}}$, table 7, taken from British Standard CP 3 : Chapter V : Part 2, contains values for very simple building shapes. Most buildings are considerably more complex than these and are generally surrounded by other buildings or obstructions. To determine detailed distributions of pressure coefficient it will be necessary to resort to wind tunnel tests on scale models.

12.2 Temperature difference. Air density varies approximately as the inverse of absolute temperature. The weight of two vertical columns of air at different temperatures, separated from each other by a vertical surface, will differ and a pressure difference across the surface results. Thus, if the air temperature within a building is higher than that outside, pressure difference will create an air flow through openings in the intervening fabric. Figure 6 illustrates the action of this pressure difference for a simple enclosure with one or two small openings. With small single openings, no flow takes place. With two openings, air flows in at the lower opening and out at the upper opening, because the internal temperature is higher than that outside the enclosure. The pressure difference across the wall of the enclosure becomes such as to ensure that the inflow equals the outflow. The level at which the pressures are equal is known as the 'neutral' level.

Table 7. Typical magnitudes of pressures created by wind and temperature difference

(a) Wind

Wind speed (u_r)	Pressure			
	$C_p = 0.1$	$C_p = 0.3$	$C_p = 0.5$	$C_p = 1.0$
m/s	Pa	Pa	Pa	Pa
1.0	0.06	0.18	0.30	0.59
4.0	0.94	2.83	4.72	9.44
7.0	2.89	8.67	14.45	28.91
10.0	5.90	17.70	29.50	59.00

(b) Temperature difference

Temperature difference	Pressure					
	H_t = 1 m	H_t = 3 m	H_t = 6 m	H_t = 10 m	H_t = 50 m	H_t = 100 m
K	Pa	Pa	Pa	Pa	Pa	Pa
1.0	0.04	0.12	0.24	0.40	2.02	4.05
4.0	0.16	0.49	0.98	1.64	8.18	16.36
10.0	0.42	1.25	2.51	4.18	20.88	41.76
20.0	0.87	2.60	5.20	8.66	43.29	86.59

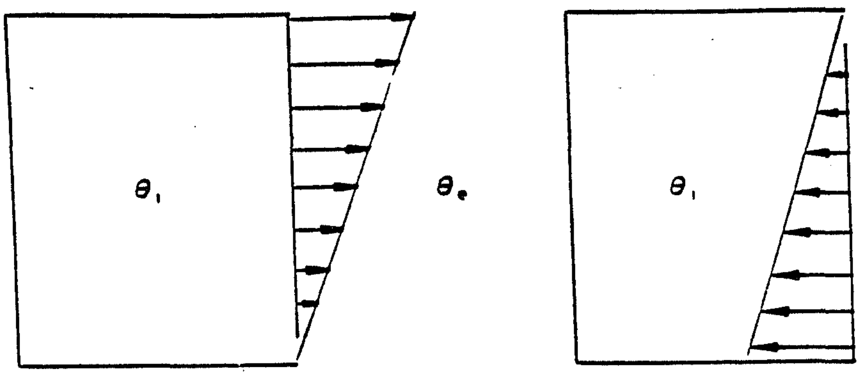
13. Meteorological variables

13.1 General. A major problem with any attempt to predict natural ventilation rates is the variability with time of the governing agencies, i.e. wind and external temperature. Unless the physical aspects of the building can be modified to accommodate changes in these parameters, then natural ventilation rates will also vary considerably with time. Window opening and closing can act as a crude form of 'modifier', particularly in summer, but in general it is necessary to consider the statistics of wind and temperature variation in order to choose suitable values for design purposes.

13.2 Wind. The natural wind is turbulent and its mean speed varies with height from the ground. The vertical profiles of wind speed and the turbulence characteristics vary with the stability of the atmosphere and the roughness of the terrain over which the wind is passing. Local topographical features such as hills and valleys can also affect wind profiles. All that will be considered here is the variation of mean wind speed with height (see reference [18]). For different types of terrain, the following simple formula may be used:

$$\frac{u}{u_m} = Kz^a \qquad (5)$$

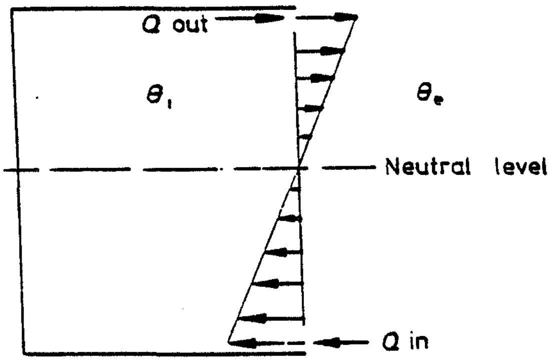
u is the wind speed at height z; u_m is the wind speed measured at a large number of sites in the United Kingdom by the Meteorological Office, and is quoted for an



(a) Opening at base of enclosure

(b) Opening at top of enclosure

$\theta_i > \theta_e$



(c) Openings at both top and base of enclosure

Figure 6. Pressures and flow created by temperature difference

equivalent height of 10 m in open countryside.
The constants, K and a, depend upon the terrain and are given in table 8. Given u_m and the type of terrain, it is therefore possible to estimate the speed of the undisturbed wind at any height, z.

It is now necessary to consider the geographical and statistical variation of u_m. Data on mean wind speed has been condensed (see reference [19]) to provide a description of the cumulative frequency of wind speed in terms of the wind speed exceeded for 50 % of the time at a particular site. This value of u_m will be referred to as u_{50}. Figure 7 is a map of the United Kingdom showing contours of u_{50}. Used in conjunction with the frequency distributions given in table 9, it is possible to determine the value of u_m exceeded for any chosen proportion of time at any site in the United Kingdom. In order to obtain this simplified relationship it has been assumed that the frequency distribution of wind speed at any site is independent of wind direction. This varies considerably at most sites in the United Kingdom but predominant directions can be obtained from wind 'rose' maps (see reference [20]).

The preceding information enables the reference wind speed, u_r, defined in clause 12, to be estimated for any given site. Appendix D illustrates this by means of a simple example.

13.3 Temperature. Ambient air temperature varies diurnally and from day to day, but can, for present purposes, by characterized by a monthly mean and a monthly mean daily variation for any particular site. Table 10 shows the monthly mean air temperature for five sites; further data can be obtained from references [21], [22] and [23]. An indication of the way in which the temperature varies over 24 h can be obtained from reference [20] which shows the daily mean temperature variation for Heathrow, London, together with the standard deviation associated with these means. For design purposes it is suggested that the monthly mean value be used.

Table 8. Factors for determining mean wind speed at different heights and for different types of terrain from the Meteorological Office wind speed, u_m, measured at 10 m in open country

(Reproduced from reference [26] : Crown copyright HMSO)

Terrain	K	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

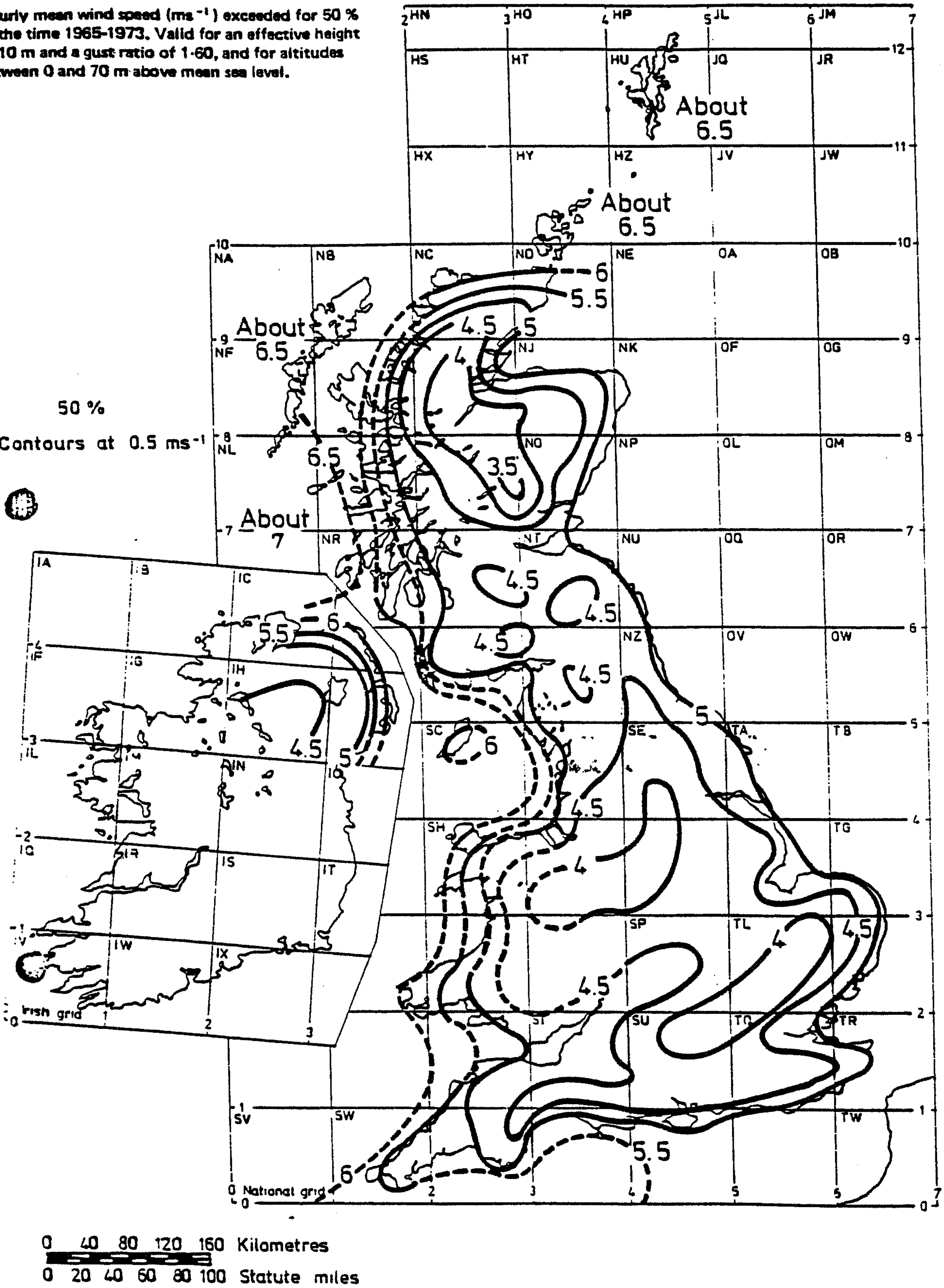


Figure 7. Contours of u_{50} for the United Kingdom (Reproduced from reference [26] by permission of the Controller of Her Majesty's Stationery Office)

Table 9. Values of the ratio of mean wind speed exceeded for a given percentage of time to the 50 % mean wind speed u_{50} (Reproduced from reference [26] : Crown copyright HMSO)

Percentage	Location	
	Exposed coastal	Sheltered inland
80	0.56	0.46
75	0.64	0.56
70	0.71	0.65
60	0.86	0.83
50	1.00	1.00
40	1.15	1.18
30	1.33	1.39
25	1.42	1.51
20	1.54	1.66
15	1.70	1.80
10	1.84	2.03

Table 10. Mean daily* air temperatures for twelve sites in the United Kingdom, 1941-1970
(Data from reference [21])

Region	North-East Scotland	West Scotland	Northern Ireland	Borders	West Pennines	East Pennines
Site	Aberdeen (Dyce)	Glasgow (Abbotsinch)	Belfast (Aldergrove)	Acklington	Manchester (Ringway)	Finningly
	°C	°C	°C	°C	°C	°C
January	2.3	3.1	3.5	2.9	3.3	3.3
February	2.6	3.5	3.8	3.1	3.7	3.8
March	4.5	5.5	5.7	4.9	5.7	5.8
April	6.7	7.9	7.9	7.1	8.3	8.7
May	8.9	10.7	10.4	9.3	11.3	11.5
June	12.0	13.6	13.3	12.3	14.3	14.7
July	13.5	14.7	14.4	14.1	15.7	16.3
August	13.3	14.5	14.3	13.9	15.5	16.0
September	11.7	12.7	12.7	12.4	13.7	14.1
October	9.1	9.9	10.1	9.7	10.5	10.8
November	5.3	6.0	6.4	6.1	6.5	6.7
December	3.3	4.2	4.6	4.0	4.3	4.5
Annual	7.7	8.9	8.9	8.3	9.4	9.2

Region	Midland	Wales	Thames Valley	Severn Valley	Southern	South-Western
Site	Birmingham (Elmdon)	Aberporth	London (Heathrow)	Briston (Filton)	Bournemouth	Plymouth (Mountbatten)
	°C	°C	°C	°C	°C	°C
January	3.1	4.7	3.7	3.9	4.3	5.9
February	3.3	4.6	4.3	4.2	4.5	5.5
March	5.4	6.3	6.5	6.3	6.5	7.1
April	8.1	8.2	9.4	8.9	9.1	9.2
May	11.0	10.7	12.5	11.7	11.8	11.5
June	14.1	13.3	15.8	14.9	14.9	14.3
July	15.9	14.7	17.4	16.5	16.6	15.9
August	15.5	14.9	17.0	16.1	16.5	15.9
September	13.4	13.7	14.9	14.1	14.6	14.5
October	10.2	11.2	11.5	11.1	11.7	12.1
November	6.3	7.9	7.2	7.1	7.7	8.7
December	4.1	5.9	4.8	5.1	5.5	7.1
Annual	9.7	9.7	10.4	10.0	10.3	10.7

*The values given are averages, for each calendar month and for the year as a whole, of the daily mean temperature calculated as the arithmetic mean of the daily maximum and daily minimum values.

14. Determination of natural ventilation rates

14.1 General considerations. In principle, the foregoing information enables the airflow through a building and, in consequence, the ventilation rate of spaces within the building to be estimated for a given wind speed and direction, provided that the following are known:

(a) the position and flow characteristics of all openings*;

(b) the detailed surface mean pressure coefficient distribution for the wind direction under consideration;

(c) the internal and external air temperatures.

However, it is difficult to obtain a solution in all but the simplest cases because of the large number of non-linear simultaneous equations which require to be solved. The only practicable method is to use a digital computer. A number of programmes are being developed and it is anticipated that, as they are validated by comparison with full-scale measurements, they will become increasingly available to designers and will be used to provide the basis for design guides. The value of the results produced by such programmes will depend upon the accuracy of the [illegible] listed in (a), (b) and (c) above. It is rare that these are known in detail for existing buildings, let alone at the design stage. More information is required on the pressure distributions for typical building arrangements and the position and flow characteristics of openings.

The general characteristics of natural ventilation can, however, be demonstrated by considering some simple cases. Figure 8 shows a simple, 'two-dimensional' representation of a building with no internal divisions,

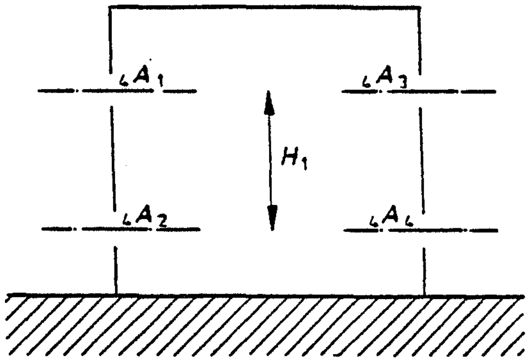
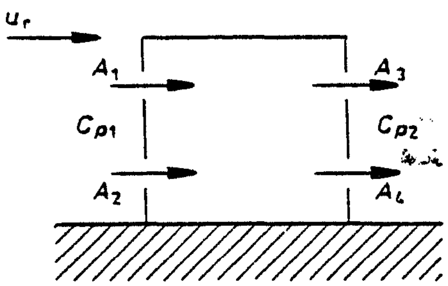
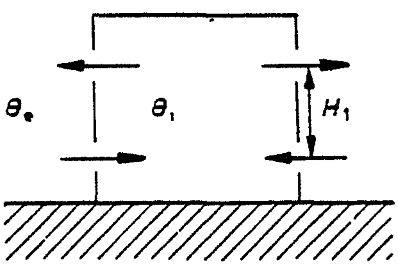
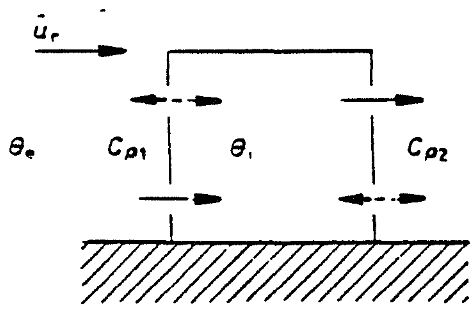


Figure 8. Arrangement of openings in a simple building

Table 11. Natural ventilation of a simple building
(Reproduced from reference [26] : Crown copyright HMSO)

Conditions	Schematic representation	Formula
(a) Wind only		$Q_w = C_d A_w u_r (\Delta C_p)^{1/2}$ $\frac{1}{A_w^2} = \frac{1}{(A_1 + A_2)^2} + \frac{1}{(A_3 + A_4)^2}$
Temperature difference only		$Q_b = C_d A_b \left(\frac{2\Delta\theta g H_1}{\bar{\theta}}\right)^{1/2}$ $\frac{1}{A_b^2} = \frac{1}{(A_1 + A_3)^2} + \frac{1}{(A_2 + A_4)^2}$
(c) Wind and temperature difference together		$Q = Q_b$ For $\frac{u_r}{\sqrt{\Delta\theta}} < 0.26 \left(\frac{A_b}{A_w}\right)^{1/2} \left(\frac{H_1}{\Delta C_p}\right)^{1/2}$ $Q = Q_w$ For $\frac{u_r}{\sqrt{\Delta\theta}} > 0.26 \left(\frac{A_b}{A_w}\right)^{1/2} \left(\frac{H_1}{\Delta C_p}\right)^{1/2}$

*It should be appreciated that, in practice, some openings exist unintentionally, e.g. junctions between building components, and that such openings will contribute to the ventilation actually achieved.

and therefore consisting of a single cell, with openings as shown, i.e. two (A_1 and A_3) at high level, and two (A_2 and A_4) at low level. These openings will be considered to be large and, consequently, the flow through them will be governed by equation (2) given in clause 11. Table 11 shows schematically the approximate pattern of air flow and gives the formulae from which the ventilation rate, Q, can be determined.

14.2 Wind only. Due to the difference in mean pressures between the windward and leeward faces, air flows in through the openings A_1 and A_2, and out through A_3 and A_4. A_w is the effective equivalent area of the four openings. It can be seen that openings in parallel can be added together arithmetically whilst those in series should be obtained from the reciprocal of their squares. It may also be noted that, as a consequence of equation (2), ventilation rate is proportional to wind speed and to the square root of the applied differential mean pressure coefficient, $\Delta \bar{C_p}$. Thus a range of $\Delta \bar{C_p}$ from 0.1 to 1.0 gives only an approximately 1:3 difference in ventilation rate for the same wind speed. The higher value of $\Delta \bar{C_p}$ is typical of an exposed building surrounded by no obstructions, whereas the value of 0.1 is more typical of a sheltered building, enclosed by other buildings or obstructions.

14.3 Temperature difference only. In this case the air flows in at the lower openings A_2 and A_4 and out through A_1 and A_3. The equivalent area is now A_b. The formula shows that ventilation rate is proportional to both temperature difference and height between openings.

14.4 Combined effect of wind and temperature difference. For a fixed wind speed, with a small temperature difference, the flow is similar to that for wind alone, but as the temperature difference increases the inflow of air at the upper opening is reduced and outflow on the leeward side is increased. The reverse occurs at the lower openings, where the temperature difference acts to increase the inflow. Depending upon the relative areas of the openings, a point is reached when the flows are reversed and, as the temperature difference is further increased, the flow approaches the pattern for temperature difference acting alone. In order to give an indication of the relative effects of wind and temperature difference, pressures generated by typical values of each are listed in table 7.

Even for this simple example, the ventilation rate of the space due to the action of both wind and temperature difference is not easy to calculate, but a reasonable approximation can be made by calculating the flow rates expected for the two conditions acting separately and taking the larger to apply to the combined case. For the simple example in figure 8 this leads to the expression $u_r\sqrt{\Delta\theta}$, given in table 11, which determines whether wind or temperature difference will dominate. The form of this expression indicates that taller, or more sheltered buildings will tend to have natural ventilation rates independent of wind speed for a large part of the colder months of the year.

An example is given in appendix E, using the formulae given in table 11.

15. Other mechanisms of natural ventilation

15.1 Introduction. Although the mechanisms of natural ventilation discussed in clause 12 will apply in most situations, there are cases which exist where other mechanisms are also of importance. It is the purpose of this clause to deal with these.

15.2 Natural ventilation of spaces with openings on one side only

15.2.1 *General.* In summer, ventilation rates in non air-conditioned buildings are of an order of magnitude larger than those required in winter, in order to assist in dissipating heat and maintaining comfortable conditions. These larger rates can usually be obtained readily by cross-ventilation according to mechanisms already discussed, except in the circumstance where large openings are available on one external wall only. Typical examples are offices, or school classrooms, where internal doors are kept closed for reasons of privacy or noise. In these situations cross-ventilation would be severely restricted by the limited openings around the closed internal doors. In fact, considerable exchange of air can take place at the external wall openings due to the wind or temperature difference.

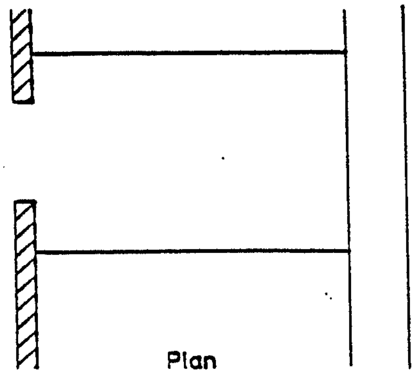
15.2.2 *Wind.* Exchange at a single opening can occur because of the turbulent nature of the airflow, or due to the interaction of the local airflow with the opening light, say of a side-mounted casement window. Table 12 gives a simple formula which enables the flow rate to be calculated in terms of the maximum area or opening of the window and the reference wind speed, u_r.

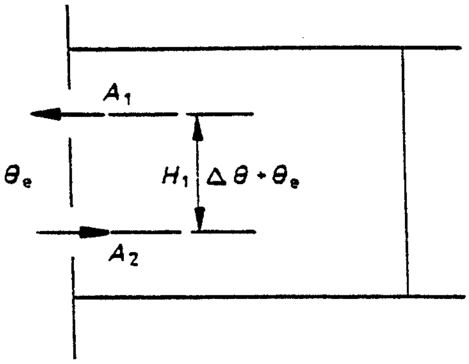
15.2.3 *Temperature difference.* The mechanism for temperature difference can apply equally well in the case of a single room as for a building. The appropriate formulae for two openings, displaced vertically, and for a single rectangular opening are given in table 12. For the single opening, air flows out from the warmer internal side of the opening and in through the lower part of the opening. Figures 9(a) and 9(b) show how the flow through a single opening window is modified by the presence of the opening light, for a side-mounted casement and a centre-pivoted window respectively.

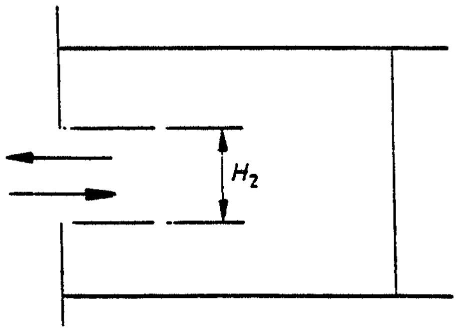
15.2.4 *Combined wind and temperature difference.* As in the case of cross-ventilation, the ventilation rate due to both effects acting together can be taken as the larger of the two individual rates.

15.3 Pressure fluctuation. The pressures generated at the surfaces of a building by the wind fluctuate due to the turbulent nature of the wind and to the interaction of the building and the wind which creates regions of flow separation and a highly turbulent wake. The use of mean pressures in clause 14 is, therefore, technically incorrect, but the error is small unless the difference between the mean pressures is small. Small pressure differences may arise from the effects of shelter, or the orientation of the building to the wind. Consider the example of a terraced house in the situation where the wind is parallel to the line of the terrace. The mean pressures at the two external faces would be approximately equal, giving rise to zero, or very small natural ventilation rate, if the formulae in table 11 were to be used. In practice, the instantaneous pressure difference can be quite large, giving a flow through the house from alternating directions. As far as the ventilation of the house is concerned the direction of flow is immaterial and the ventilation rate in practice is higher than that indicated theoretically. At present there is limited information available concerning this mechanism, but the available experimental results indicate, all other factors being equal, that the ventilation rate can be approximated by using a value of ΔC_p of 0.2 in the formula given in table 11.

Table 12. Natural ventilation of spaces with openings on one wall only
(Reproduced from reference [26] : Crown copyright HMSO)

<table>
<tr><th>Conditions</th><th>Schematic representation</th><th>Formula</th></tr>
<tr><td>(a) Due to wind</td><td>


</td><td>$Q = 0.025\,A u_r$</td></tr>
<tr><td>(b) Due to temperature difference with two openings</td><td>


</td><td>$Q = C_d A \left[\frac{\epsilon\sqrt{2}}{(1+\epsilon)(1+\epsilon^2)^{1/2}}\right]\left(\frac{\Delta\theta g H_1}{\theta}\right)^{1/2}$
$\epsilon = \frac{A_1}{A_2}$; $A = A_1 + A_2$</td></tr>
<tr><td>(c) Due to temperature difference with one opening</td><td>


</td><td>$Q = C_d \frac{A}{3}\left(\frac{\Delta\theta g H_2}{\bar{\theta}}\right)^{1/2}$
If an opening light is present
$Q = C_d \frac{A}{3} J(\phi)\left(\frac{\Delta\theta g H_2}{\bar{\theta}}\right)^{1/2}$
Where $J(\phi)$ is given in figure 5.</td></tr>
</table>

16. Fire ventilation

The role of natural ventilation in relation to fire protection measures is firmly established in the context of 'smoke control', particularly that associated with the protection of vertical escape routes. More recently, with the construction of complex enclosed shopping precincts, natural ventilation has been used to provide extraction systems for limiting the travel of smoke along covered malls (see reference [24]). Roof vents in single storey industrial premises were introduced earlier to restrict the spread of fire and smoke over large unobstructed floor areas (see reference [25]).

Methods of providing ventilation of staircase shafts, lobbies, corridors and floor areas are:

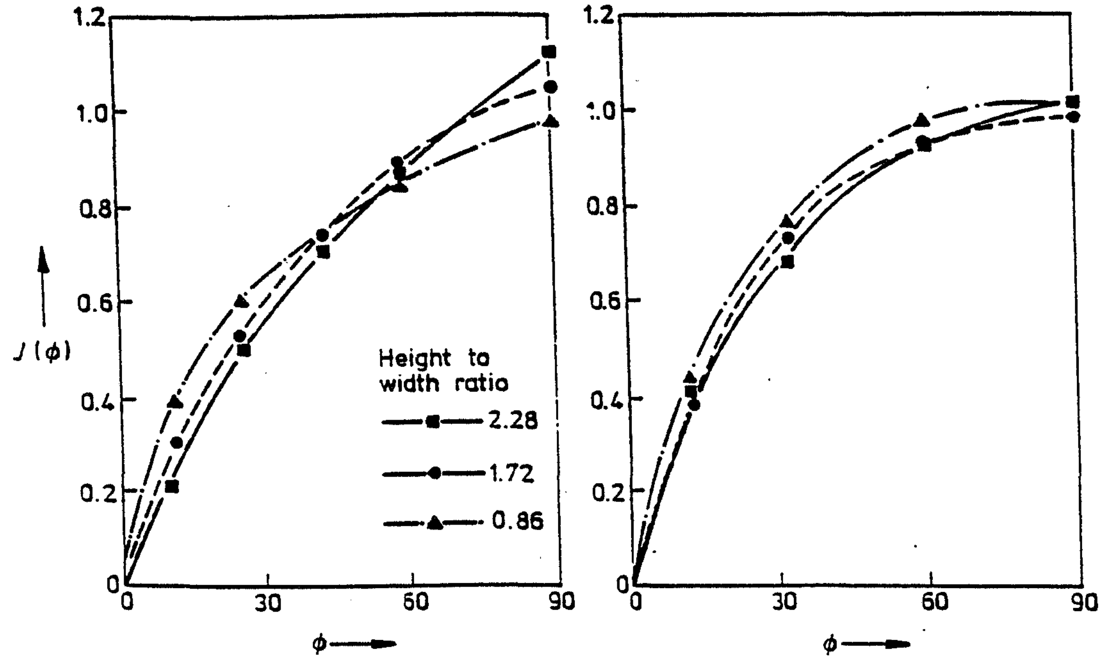
(a) permanent openings;

(b) closed openings capable of being operated manually;

(c) closed openings capable of being operated automatically;

(d) roofing materials of low melting point (provided that these do not cause dripping of molten products).

As can be expected from the discussion in clause 13, climatic conditions and local surroundings will have a strong influence on the effectiveness of natural ventilation methods for fire and smoke control. Although it will not always be possible to design for efficient control in all weather conditions, recommendations can be made (see 2.5 of CP 3 : Chapter IV : Part 1 : 1975) while recognizing their limitations.



(a) Side-mounted casement windows

(b) Centre-pivoted windows

Figure 9. Variation of $J(\phi)$ with angle of opening ϕ for (a) side-mounted casement windows and (b) centre-pivoted windows (Reproduced from reference [26] : Crown copyright HMSO)

Appendix A

Calculation of contaminant concentration

A.1 Concentration of contaminant. The concentration c, of a contaminant introduced at a constant rate into a ventilated space of volume, V, is given by:

$$c = \left[\frac{Qc_e + q}{Q + q}\right]\left[1 - e^{-\left(\frac{Q+q}{V}\right)t}\right] \qquad (6)$$

where

q is the inflow rate of the contaminant (in litres/s)

V is the volume of the ventilated space (in litres)

Q is the volume flow rate of the outside air (in litres/s)

c_e is the concentration of contaminant in the outside air

t is the time (in s) from the moment the inflow of contaminant starts.

The ratio, Q/V, is usually termed the ventilation rate, R, and is measured in air changes per hour. As t increases, the concentration reaches an equilibrium value, c_E, given by:

$$c_E = \left[\frac{Qc_e + q}{Q + q}\right] \qquad (7)$$

It should be noted that c_e depends only upon the volume flow rate of the outside air, Q, and not upon the room volume, V. The room volume affects only the rate at which c approaches the value c_E.

The rate of airflow Q required to give the equilibrium concentration c_E is:

$$Q = q\left[\frac{1 - c_E}{c_E - c_e}\right] \qquad (8)$$

If the incoming air is free of contaminant (i.e. $c_e = 0$), then the expressions simplify. Equation (6), with some rearrangement, becomes equation (9) below, and this leads to figure 10.

$$c = \left[\frac{1}{(1 + Q/q)}\right]\left[1 - e^{-(1+Q/q)\frac{qt}{V}}\right] \qquad (9)$$

If $q = 0$, but there is present an initial concentration, c_0, of contaminant, then the rate of decay of concentration is given by:

$$c = c_0 \, e^{-Rt} \qquad (10)$$

A.2 Measurement of ventilation rate. Measurement of ventilation rate is not easy but can be achieved using a tracer gas, providing that good mixing is obtained, by the following methods.

(a) *Decay rate.* A suitable quantity of tracer gas is liberated within the space and allowed to mix well. The concentration is monitored with time and the ventilation rate, R, determined using equation (10).

(b) *Continuous injection.* Tracer gas is liberated into the space at a constant measured rate. The equilibrium concentration is measured. Equation (8) enables Q to be calculated and the additional knowledge of V gives the ventilation rate, R.

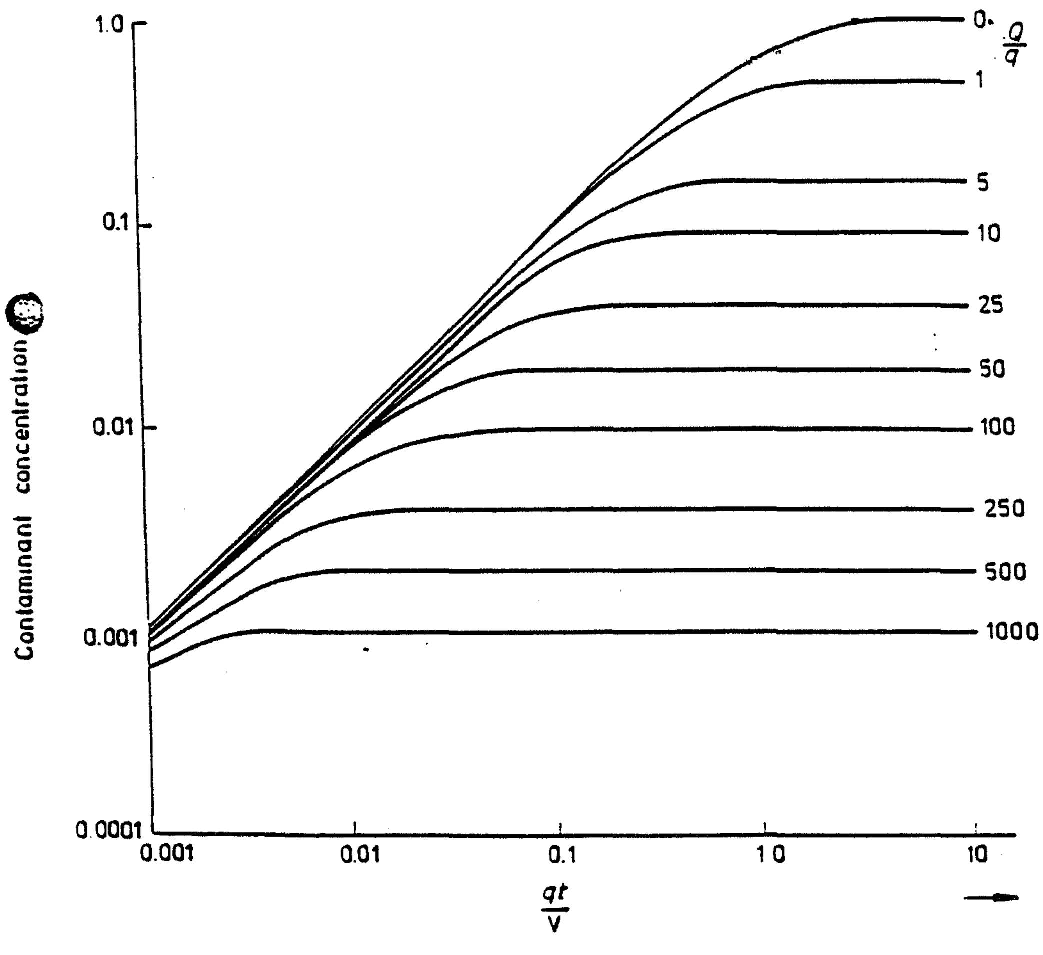


Figure 10. Variation of gas concentration c with t and ventilation rate Q for gas leakage rate q (Reproduced from reference [6] : Crown copyright HMSO)

A.3 Example calculation. Figure 11 shows a simple arrangement of two rooms in series. These are ventilated at a volume flow rate of 16 litres/s. Room A contains four people seated quietly and a 1.5 kW flueless kerosene heater. Room B contains a gas cooker operating at 1 kW. Calculate the equilibrium concentration of carbon dioxide in each room with:

(a) the kerosene heater off;

(b) the kerosene heater on.

The input rates of carbon dioxide are as follows:

gas cooker	:	0.027 litre/s per kW input
kerosene heater	:	0.037 litre/s per kW input
human breathing:		0.00004*M* litre/s per person (*M* is the metabolic rate in watts)

Case (a). The input rates are as follows:

Room A : (0.00004 × 100 × 4) litres/s
= 0.016 litre/s

Room B = 0.027 litre/s

The concentration of carbon dioxide in the outside air is 0.04 %. To calculate the concentration in room A, substitute the following values into equation (7):

Q = 16 litres/s; c_e = 0.0004; q = 0.016 litre/s;

$$\text{thus, } c_E = \frac{(16 \times 0.0004) + 0.016}{16 + 0.016}$$
$$= 0.0014 \text{ (i.e. 0.14 \%)}$$

To calculate the concentration in room B substitute the following into equation (7):

Q = 16 litres/s; c_e = 0.0014; q = 0.027 litre/s;

$$c_E = \frac{(16 \times 0.0014) + 0.027}{16 + 0.027}$$
$$= 0.0031 \text{ (i.e. 0.31 \%)}$$

Case (b). There is now an additional input of carbon dioxide from the heater equal to (0.037 × 1.5) litre/s which equals 0.056 litre/s. Thus resubstituting into equation (7) the concentration in room A is given by:

Q = 16 litres/s; c_e = 0.0004; q = 0.072 litre/s (i.e. 0.056 + 0.016)

$$c_E = \frac{(16 \times 0.0004) + 0.072}{16 + 0.072}$$
$$= 0.0049 \text{ (i.e. 0.49 \%)}$$

The concentration in room B is given by:

Q = 16 litres/s; c_e = 0.0049; q = 0.027 litre/s

$$c_E = \frac{(16 \times 0.0049) + 0.027}{16 + 0.027}$$
$$= 0.0066 \text{ (i.e. 0.66 \%)}$$

It is apparent that in case (b) the concentration in room B is higher than the 0.5 % recommended in clause 6. In consequence, a higher ventilation rate is required than would need to be specified if each room were considered separately.

Appendix B

Calculation of ventilation rates to reduce the risk of surface condensation under steady state conditions

The nomograph, figure 2, is used in the following way.

(a) Start in quadrant A. Choose outside air temperature and traverse vertically upwards to meet the chosen outside relative humidity. Traverse horizontally to the left into quadrant D, noting the position of this line for later use.

(b) Enter quadrant B from the top by drawing a line from the chosen outside air temperature to the chosen inside air temperature (on scale below quadrant A) and extend to meet the top of quadrant B. Traverse vertically down in quadrant B and then horizontally into quadrant C from the line for the chosen '*U*' value for outside wall or window.

(c) In quadrant C, traverse vertically upwards into quadrant D from the line for the chosen inside air temperature.

(d) The intercept in quadrant D of the last line with that found in (a) above will, by reference to the sloping lines, give the minimum volume of outside air required per kilogramme of moisture generated in the dwelling to avoid condensation on the surface being considered.

Appendix C

Determination of ventilation requirements

C.1 Example. Consider a domestic living room:

Size:	dimensions	3.5 m by 4 m by 2.3 m high
	floor area	14 m^2
	volume	32 m^3
Occupancy:	six adults	
	metabolic heat production	125 W each
	respiratory moisture	0.04 kg/h each
	smoking	six cigarettes per hour
Heating:	1 kW flueless kerosene heater	
Internal conditions:	20 °C	
	60 % r.h. (8.8 g/kg dry air)	
External conditions:	(a) 5 °C	
	95 % r.h. (5.2 g/kg dry air)	
	0.04 % CO_2, no other contaminants	
	(b) 10 °C	
	90 % r.h. (6.9 g/kg dry air)	
	CO_2 as in (a)	

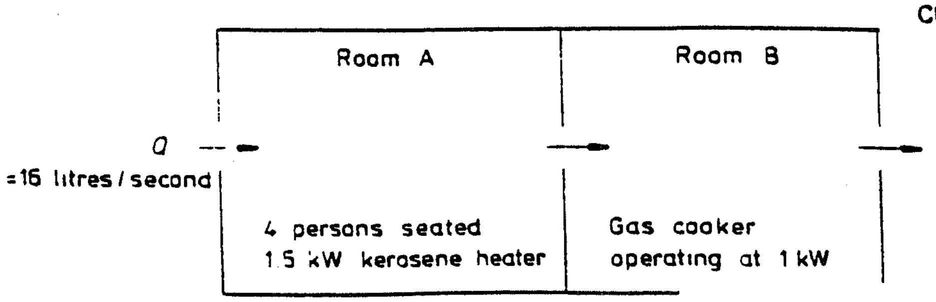


Figure 11. Interconnecting spaces

C.2 Required ventilation rates for different purposes

Purpose		*Required ventilation rate, litres/s*
Dilution of body odour		48
Dilution of tobacco smoke (six cigarettes per hour)		35
Dilution of CO_2 to 0.5 %		
(a) from human respiration, 6.4		
(b) from 1 kW flueless kerosene heater, 6.8		
	total	13.2
Control of humidity to 60 % r.h. (assuming no surface condensation)		
5 °C outside	(a) from human respiration, 18.2	
	(b) from 1 kW flueless kerosene heater, 6.1	
	total	24.3
°C outside	(a) from human respiration, 35.4	
	(b) from 1 kW flueless kerosene heater, 11.8	
	total	47.2
Dilution of SO_2 from flueless kerosene heater (0.06 % SO_2)		
(a) to 1 p.p.m. for continuous exposure		9.0
(b) to 5 p.p.m. TLV		1.8

In this example the required ventilation rate of 48 litres/s for odour dilution would determine the minimum requirement since it just exceeds the rate of 47.2 litres/s required to control the humidity when it is 10 °C outside.

NOTE. In this example only common contaminants have been taken into account.

Appendix D

Calculation of reference wind speed u_r

1 Procedure

D.1.1 Ascertain the following data:

(a) the geographical location of the building;

(b) the proportion of the time for which the reference wind speed is to be exceeded;

(c) category of terrain in which the building is situated;

(d) height of the building.

D.1.2 Using (a) in D.1.1, in conjunction with figure 7, determine the value of u_{50}.

D.1.3 Using (b) in D.1.1, in conjunction with table 9, determine the appropriate ratio; multiply u_{50} by this to determine the free wind speed in open country exceeded for the given proportion of time, e.g. u_m.

D.1.4 Using (c) in D.1.1, in conjunction with table 8, obtain K and a.

D.1.5 Using these values in conjunction with u_m determined in D.1.3 substitute into equation (5), setting z equal to the height of the building, and hence determine u_r.

D.2 Example

D.2.1 Determine the reference wind speed for the purposes of calculating natural ventilation rates, given that the chosen rate should be exceeded for 60 % of the time, for a building located in an urban area in the Midlands, with a height of 25 m.

D.2.2 Summary of given data:

(a) Location:	Midlands
(b) Proportion of time:	60 %
(c) Terrain:	urban
(d) Height:	30 m

D.2.3 From figure 7, u_{50} = 4.0 m/s.

D.2.4 From table 9, column 3, ratio for 60 % is 0.83, thus $u_m = 0.83 \times 4.0 = 3.3$ m/s.

D.2.5 From table 8, for urban terrain, $K = 0.4$, $a = 0.25$.

D.2.6 Using equation (5).

$$u_r = u_m K z^a$$
$$= 3.3 \times 0.4 \times (30)^{0.25}$$
$$u_r = 3.1 \text{ m/s}$$

Appendix E

Calculation of natural ventilation rates for a simple building

E.1 Example. Consider a building consisting of a single undivided space 25 m long, 10 m wide and 8 m high. Given that the building is situated in an open suburban area in the Manchester region, calculate:

(a) the natural ventilation rate achieved for over 60 % of the time due to wind;

(b) the ventilation rate due to the effect of a temperature difference of 6 °C in the absence of wind.

There are no ventilation openings on the shorter walls. On each of the longer walls there are openings of 2.5 m^2 at a low level, and 5.0 m^2 at a high level, separated by a vertical distance of 6.0 m, and evenly distributed along the length of the wall.

E.2 Procedure

(a) *Wind*

(1) *Determination of pressure coefficient difference*

Building height ratio = 0.8
Building plan ratio = 2.5
Thus, from table 13, the difference in mean surface pressure coefficients at the two long sides of the building for a perpendicular wind is 0.7 − (− 0.3) = 1.0, i.e. $\Delta C_{\bar{p}} = 1.0$

(2) *Determination of* u_r

(i) Location: Manchester region: thus from figure 7, u_{50} = 4.5 m/s

(ii) Proportion of time: 60 %: thus from table 9, correction factor = 0.83

(iii) Terrain: country with scattered wind breaks: thus from table 8, $K = 0.52$, $a = 0.20$

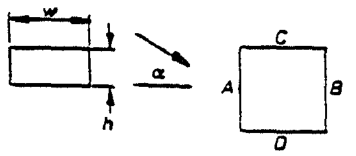
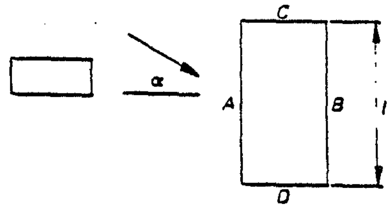
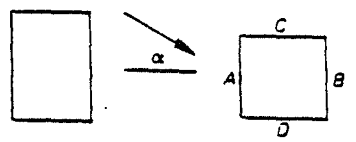
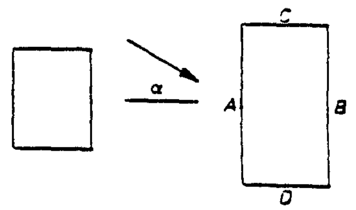
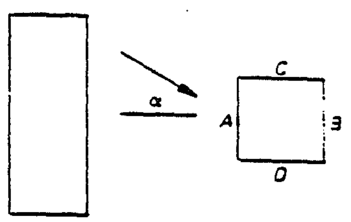
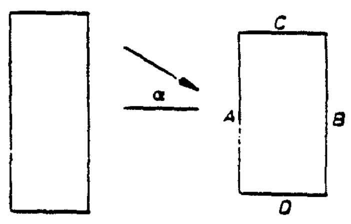
Thus, from equation (5), using the building height of 8 m,

$$u_r = 4.5 \times 0.83 \times 0.52 \times 8.0^{0.2}$$
$$= 2.9 \text{ m/s}$$

(3) *Determination of* A_w

$$\frac{1}{A_w^2} = \frac{1}{(5.0 + 2.5)^2} + \frac{1}{(5.0 + 2.5)^2}$$
$$A_w = 5.3 \text{ m}^2$$

Table 13. Mean surface pressure coefficients for vertical walls of rectangular buildings*

Building height ratio†	Building plan ratio†	Side elevation/Plan	Wind angle α	C_p for surface A	B	C	D
$\frac{h}{w} \leq \frac{1}{2}$	$1 < \frac{l}{w} \leq \frac{3}{2}$		0°	+0.7	−0.2	−0.5	−0.5
			90°	−0.5	−0.5	+0.7	−0.2
	$\frac{3}{2} < \frac{l}{w} < 4$		0°	+0.7	−0.25	−0.6	−0.6
			90°	−0.5	−0.5	+0.7	−0.1
$\frac{1}{2} < \frac{h}{w} \leq \frac{3}{2}$	$1 < \frac{l}{w} \leq \frac{3}{2}$		0°	+0.7	−0.25	−0.6	−0.6
			90°	−0.6	−0.6	+0.7	−0.25
	$\frac{3}{2} < \frac{l}{w} < 4$		0°	+0.7	−0.3	−0.7	−0.7
			90°	−0.5	−0.5	+0.7	−0.1
$\frac{3}{2} < \frac{h}{w} < 6$	$1 < \frac{l}{w} \leq \frac{3}{2}$		0°	+0.8	−0.25	−0.8	−0.8
			90°	−0.8	−0.8	+0.8	−0.25
	$\frac{3}{2} < \frac{l}{w} < 4$		0°	+0.7	−0.4	−0.7	−0.7
			90°	−0.5	−0.5	+0.8	−0.1

*This table is based on a table in CP 3 : Ch V : Part 2.

† l is the length of the major face of the building; w is the width of the building, i.e. length of the minor face.

(4) *Determination of ventilation rate*

Using the formula in table 11, section (a),

$$Q_w = 0.61 \times 5.3 \times 2.9 \times 1.0^{0.5}\ m^3/s$$
$$= 9.4\ m^3/s$$

The volume of the building is $25 \times 10 \times 8\ m^3$, i.e. $2000\ m^3$.

Thus the air change rate is,
$3600 \times 9.4/2000 = 17$ air changes/h

(b) *Temperature difference*

From the information given:
Temperature difference = 6.0 °C
Height between openings H_1 = 6.0 m

$$\frac{1}{A_b^2} = \frac{1}{[2.5+2.5]^2} + \frac{1}{[5.0+5.0]^2}$$

thus $A_b = 4.47\ m^2 \simeq 4.5\ m^2$

Taking $\bar{\theta} = 300$ K

$$Q_b = 0.61 \times 4.4 \times \left(\frac{2 \times 9.8 \times 6.0 \times 6.0}{300}\right)^{0.5}$$
$$= 4.18\ m^3/s \simeq 4.2\ m^3/s$$

The air change rate is,
$3600 \times 4.2/2000 = 7.6$ air changes/h

Appendix F

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*The Institution of Heating and Ventilating Engineers was incorporated into the Chartered Institution of Building Services in 1977 and some of the older publications may carry the initials IHVE rather than CIBS.

Standards publications referred to

BS 2869	Petroleum fuels for oil engines and burners
BS 5250	Code of basic data for the design of buildings: the control of condensation in dwellings
BS 5410	Code of practice for oil firing
	Part 1 Installations up to 44 kW output capacity for space heating and hot water supply purposes
	Part 2 Installations of 44 kW or above output capacity for space heating, hot water and steam supply purposes
BS 5440	Code of practice for flues and air supply for gas appliances of rated input not exceeding 60 kW (1st and 2nd family gases)
	Part 2 Air supply
BS 5588	Code of practice for fire precautions in the design of buildings
BS 5643	Glossary of refrigeration, heating, ventilating and air conditioning terms
BS 5720	Code of practice for mechanical ventilation and air conditioning in buildings
CP 3 : Ch IV	Precautions against fire
CP 3 : Ch V	Loading
	Part 2 Wind loads

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This British Standard, having been prepared under the direction of the Basic Data and Performance Criteria for Civil Engineering and Building Structures Standards Committee, was published under the authority of the Executive Board and comes into effect on 30 September 1980.

ISBN 0 580 11389 2

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The following BSI references relate to the work on this standard:
Committee reference BDB/53 Draft for comment 76/10444 DC

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Amendments issued since publication

Amd. No.	Date of issue	Text affected

BS 5925 : 1980

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