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ENGINEERING TRIPOS PART IIB
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Thursday 10 May 2007 9 to 10.30

Module 4D11

BUILDING PHYSICS

*Answer **three** questions, one from each of Sections A, B and C.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Attachments: "Building Physics Environmental Data"
CIBSE Psychrometric Chart

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator

Section A

1 Figure 1 shows a section through an element of wall construction.

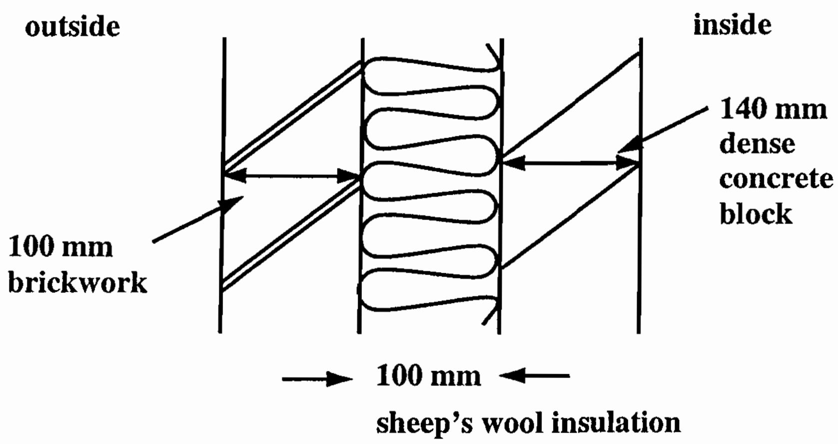

Fig. 1

(a) Using information from the data list on the next page, calculate the U-value of the wall element, assuming sheltered conditions for the external surface. [20%]

(b) This system is to be used for the walls of a teaching studio, an 8 m cube designed for 10 people who will occupy it 10 hours per day. The roof will have the same U-value, heat loss through the floor will be negligible, and no artificial lighting will be needed. Glazing can be put only on the East side because of the site conditions. There is concern that the studio may overheat on a typical June summer day. The architect's first proposal is for 8 m^2 of double glazing, and a ventilation rate of 5 changes per hour (constant throughout the 24 hour period).

Calculate :

(i) the mean environmental temperature over a 24-hour period, and [30%]

(ii) the estimated peak environmental temperature. [40%]

Discuss briefly whether this peak temperature is likely to be acceptable. [10%]

(cont.

Data

Thermal conductivity:

dense concrete block	1.13	W/mK
brick	0.77	W/mK
sheep's wool	0.045	W/mK

Internal wall surface resistance: 0.123 m^2K/W

External wall surface resistance :

sheltered	0.08	m^2K/W
normal	0.055	m^2K/W
severe	0.03	m^2K/W

Gain from occupants: assume 100 W/person

Mean solar gain (beam and diffuse) in June on an East-facing wall: 207 W/m^2

Peak intensity of solar gain (beam and diffuse) in June on an East-facing wall: 768 W/m^2

Mean outdoor temperature in June 18.7 °C, peak 24.5 °C

Solar gain factors for double glazing (clear/clear):

mean 0.62

alternating (for a heavyweight building) 0.44

Double glazing :

U-value	2.9 W/m^2K
Y-value (admittance)	3.1 W/m^2K

Wall and roof construction:

Y-value (for walls and roof) 4.6 W/m^2K

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2 Figure 2 shows a vertical cross-section of an architect's proposal for a naturally-ventilated lecture hall of area 100 m^2 designed for 100 students, with a total internal heat production of approximately 10 kW. There is negligible heat loss through the fabric of the structure and no wind.

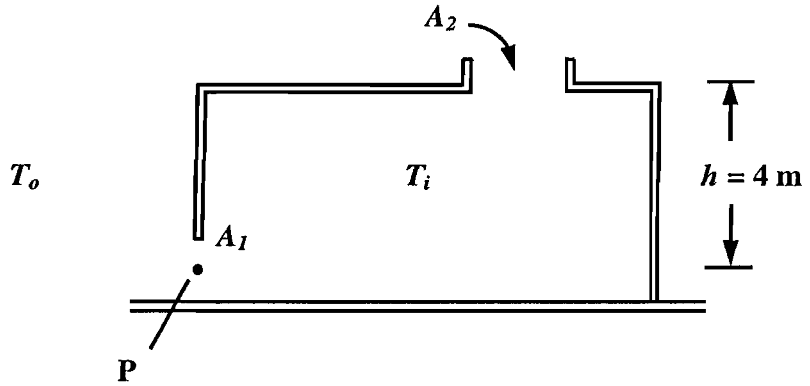

Fig. 2

(a) Assuming $A_1 = A_2 = 4$ m^2; $T_o = 22$ °C db, 19 °C wb; $T_i = 25$ °C db, 22 °C wb; calculate:

(i) the volume flow rate through the space;

(ii) the hourly air-change rate of the space; and

(iii) the velocity of air movement through the openings.

Discuss whether this flow is compatible with the heat gains and temperatures assumed. [50%]

(b) It is proposed to introduce a cooling coil at position P, using water at 15 °C taken from a borehole in an aquifer, to cool the incoming air. Describe the processes that take place and, using the psychrometric chart provided (which should be handed in with your answer), plot the movement towards the final state of the air, assuming that the cooling coil is 100 % effective. How would you assess the flow-rate needed to keep the rise in water temperature below 1 °C? [25%]

(c) An alternative conditioning process is also under consideration, spraying water at 19 °C into the incoming air stream. On the psychrometric chart plot the approximate path of this process. Discuss briefly which of the two processes would be the preferred option. [25%]

Section B

3 A lecture theatre is a simple rectangular box of length 14 m (front to back), width 9 m and ceiling height 4.5 m, with large windows on one side. Sound absorption coefficients at 500 Hz are as follows :

front and back walls, plastered	0.02
window wall	0.10
wall opposite windows, plaster	0.05
floor (carpeted)	0.05
ceiling (25 mm acoustic plaster)	0.15

(a) Define 'reverberation time', explaining how it is measured, and calculate :

(i) the reverberation time for the empty room at 500 Hz ; [25%]

(ii) the extra absorption needed to reduce the absorption time for the empty room to 1.1 s at 500 Hz. [15%]

(b) Discuss why a reverberation time of order 1 s is desirable, what form the extra absorption should take, and where it should be positioned. Is an audience of 80 people, with average area say 1.5 m^2 and absorption coefficient 0.3, likely to have significant effect on the reverberation time? Would you advocate artificial amplification of the lecturer's voice in such a lecture theatre? [40%]

(c) Discuss briefly the proposition that the type of music developed in the different historical epochs has been significantly affected by the acoustic characteristics of the spaces in which the music was played. [20%]

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4 Two rectangular unfurnished offices with a common partition wall each have dimensions 4 by 4 by 3 m high. The mean sound absorption coefficient is 0.2 in both rooms. In an experiment on sound transmission between the rooms, the sound pressure level in the 250 Hz octave band is 82 dB in the source office and 51 dB in the receiving office.

(a) Estimate the sound reduction index R of the partition wall. [30%]

(b) Outline briefly any assumptions you are making in applying a formula for R. How would you estimate the likely effect on R of a closed door in the partition wall? [30%]

(c) Outline and contrast the acoustic requirements for (i) a meeting room and (ii) an open-plan office. How might these requirements be met in various situations ? Consider carefully the case where meeting room and open-plan office are adjacent. What arrangements would you suggest if a client wished to have an unwalled space for meetings of up to six people within an open-plan office? [40%]

Section C

5 (a) Define 'daylight factor' and explain briefly how this concept can be used to inform the design of the form and the façade of a building. [20%]

(b) Discuss the limitations of the use of the daylight factor at points, and the average daylight factor in a room, and the implications of these limitations. [20%]

(c) Calculate the average daylight factor for the room shown in Fig. 3, assuming that the average internal reflectance is 50 %, the transmittance of the glazing is 72 %, and the maintenance factor is 80 %. [20%]

(d) For what proportion of the occupied year will this room achieve an average illuminance of at least 300 lux from daylight? [20%]

(e) Describe, and demonstrate through calculation, how the average daylight factor in this room could be improved without changing the total window area. [20%]

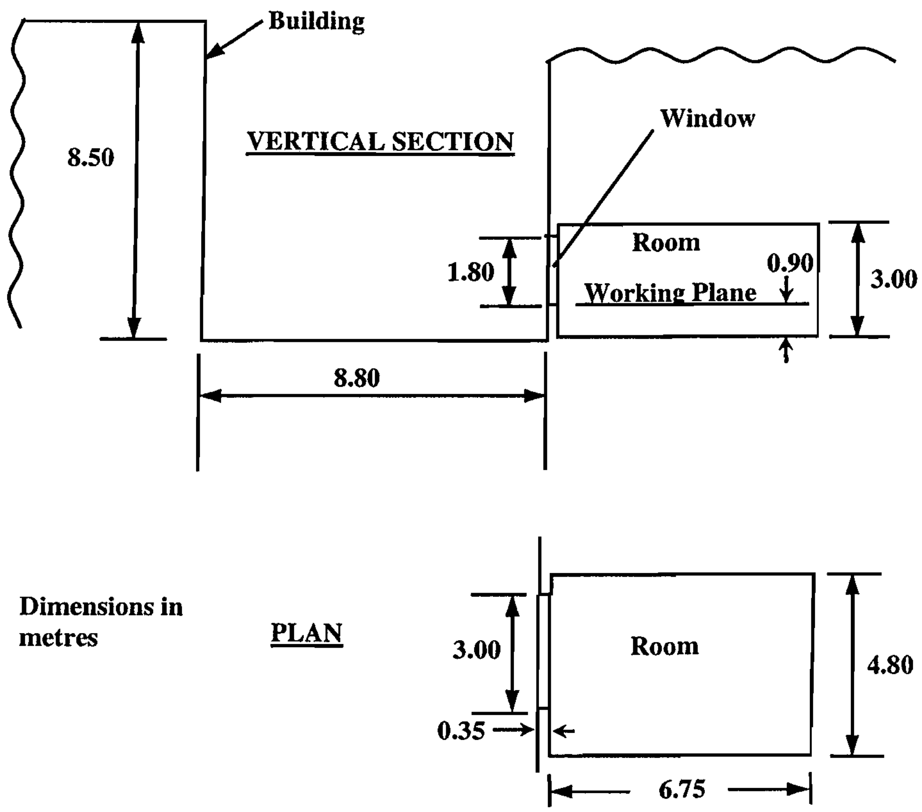

Fig. 3

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6 Figures 4, 5 and 6 are images of three stereotypical museum projects that you may wish to refer to when answering the questions below.

(a) With respect to the lighting design and operation of museums, discuss why the dual functions of presentation and conservation might be in conflict. [30%]

(b) Describe how two strategic approaches to lighting design – which can be termed the 'closed box' and the 'daylight machine' – are attempts to resolve the above conflict. Discuss the two strategies, and comment on the relative merits of each approach, giving quantitative illustrations if possible. [40%]

(c) Explain why light exposure can be demonstrated to be a critical parameter in the conservation of art, and how this knowledge has impinged on museum design strategies. Comment on how this reveals that building design is a cross-disciplinary activity. [30%]

Fig. 4

(cont.

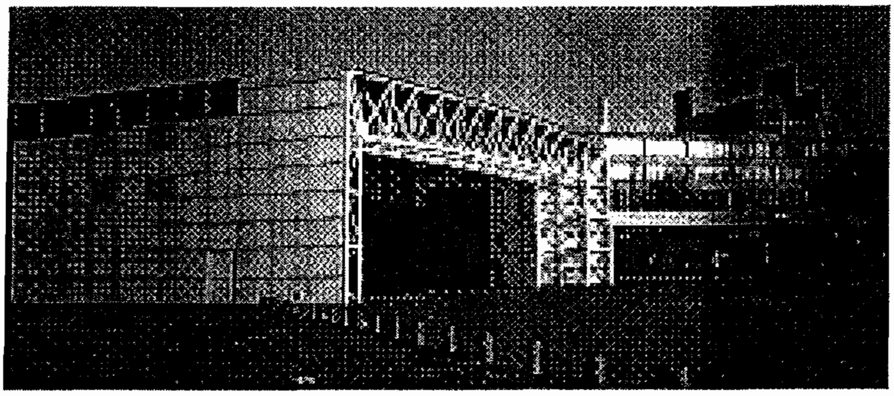

Fig. 5

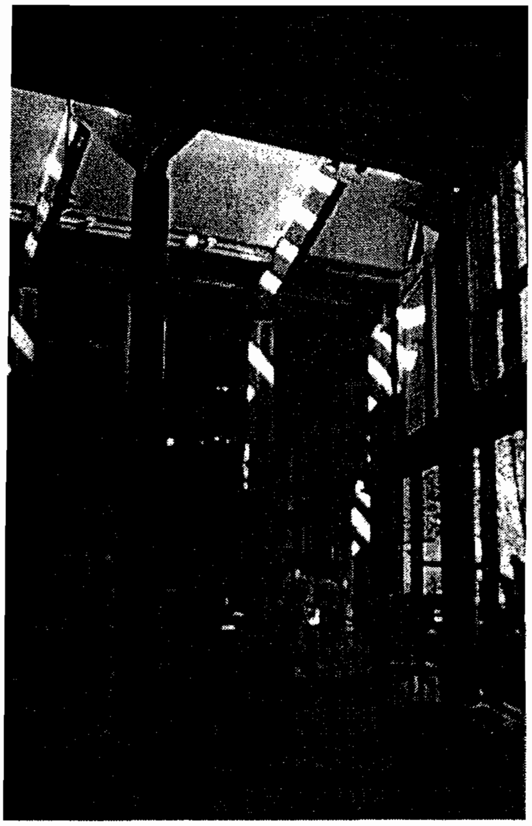

Fig. 6

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1. Lighting

(a) Definitions — units

Luminous flux – rate of flow of light energy – lumens (1m)

Illuminance – density of light flux reaching a surface – lumens/m^2 or lux (1x)

Luminous intensity – light flux per unit solid angle from a point source, i.e. power to emit in a particular direction – candela (cd) (1 cd ≡ 4 π 1m)

(b) Artificial light

Recommended illuminances, on horizontal working plane, vary from 150 lux for storage areas, through 500 lux for general offices, to 1500 lux for precision bench work.

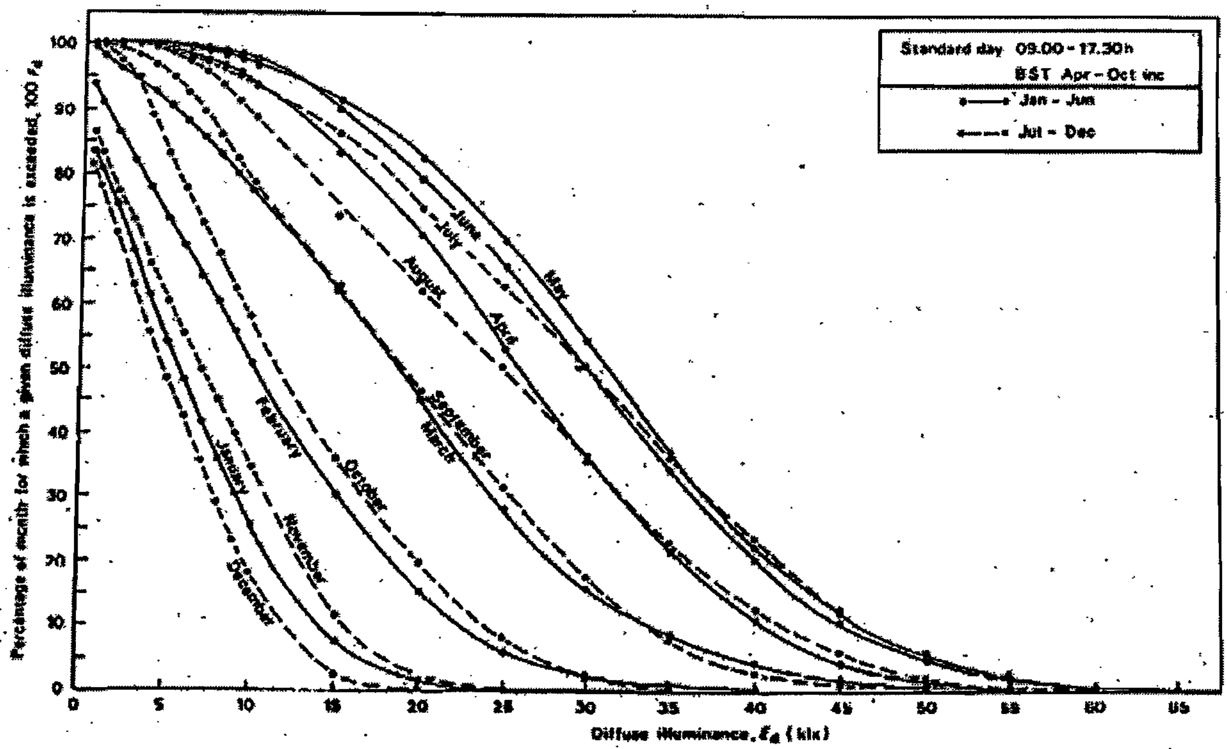
"Utilisation factor" is the proportion of light emitted by the luminaires which actually reaches the working plane.

Typical luminous efficacies (lumens/Watt): tungsten filament (GLS) 12, tubular florescent 60, low pressure sodium 180, daylight 115.

(c) Daylight

Sky as a diffuse source: sky luminance B_θ from elevation θ above horizon, where B_Z is luminance at the zenith: $B_\theta \approx B_Z(1+2\sin\theta)/3$ "CIE sky"

Example of monthly daylight availability curves for Bracknell; Percentage of working time exceeded vs diffuse illuminance level in *klx*.



Average daylight factor (%) in a room is approx. TWMd/A(1 – ρ^2) where T is glazing transmittance; W is net window area; M is 'maintenance factor' (i.e. cleaning); d (degrees) is the angle at the window centre in the vertical plane between the vertical and the highest external building obstruction; A is the total area of all internal surfaces; and ρ is the weighted mean reflectance of the internal surfaces.

2. Thermal matters

(a) Temperatures

Air temperature in shade T_a – the 'dry bulb' temperature, usually in degrees C db.

'Wet bulb' temperature, C wb, in a small damp sponge in air current (taken with T_a indicates humidity).

'Mean radiant temperature' T_r – the uniform surface temperature of a surrounding black enclosure delivering the same radiant heat to the point in question as arrives in the actual non-uniform space (in practical rooms, approx. the mean surface temperature T_m of all the enclosing surfaces).

Radiant heat flow is roughly $Q_r = A\,\varepsilon\,\sigma\,(T_b^4 - T_r^4)$ where A and T_b (K) are the surface area and temperature of the radiating body, ε is emissivity (usually 0.95, but 1.0 for a 'black' body), and σ is 5.67×10^{-8} W/m^2K^4.

'Globe temperature' (measured inside a small black sphere) is roughly the 'operational temperature', the mean of T_a and T_r.

'Environmental temperature' T_e in a room is $(T_a + 2T_m)/3$.

'Corrected effective temperature' CET depends on globe and wet-bulb temperatures, and air velocity – the wind-chill effect – and is obtained from charts.

'Neutral temperature' (CET in C at which most people feel comfortable) is
$T_n = 11.9 + 0.564\ T_o \pm 2.5$ (Humphreys) for a sedentary occupation, where T_o is the mean outdoor temperature for the month in question.

(b) Thermal Comfort

Comfort will depend on many factors, not just the temperature but also such things as the humidity, the freshness of the air, and the amount of clothing being worn (0.1 clo for shorts only, 1.0 clo for a business suit, 2.5 clo for a heavy overcoat).

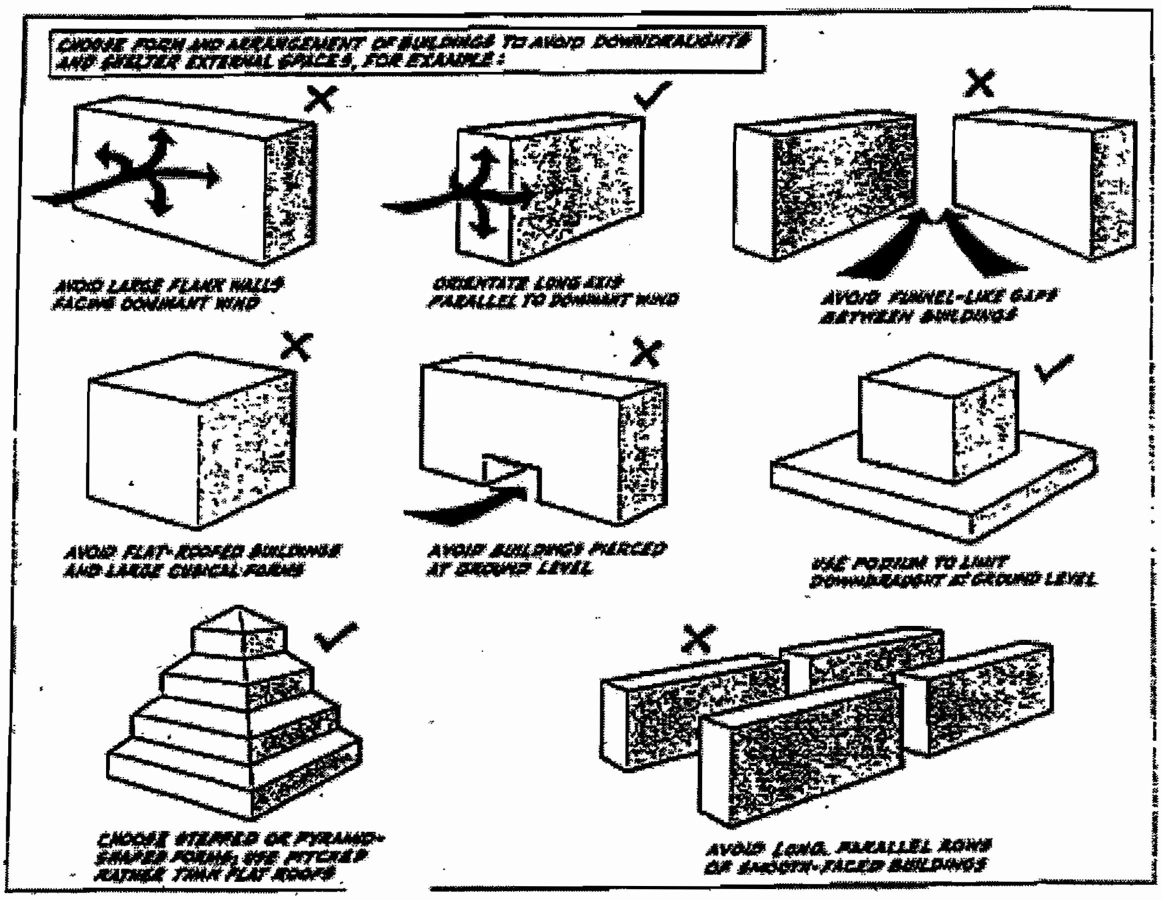
Also important will be the metabolic rate M (ranging from 70 W when sleeping, through 150 W when typing, 300 W for fast walking, to 650 W for hard sustained work); the rate W watts at which work is being done; and the rate H watts of loss of heat, which will depend on radiation, convection, and evaporation from the skin, as well as heat and water-vapour losses in breathing.

Fanger introduced the Predicted Mean Vote (PMV) for people's sensation of comfort on a scale of – 3 to + 3 (very cold to very hot). His equation has over 15 terms, based on metabolic rate, work being done, temperature etc, with empirical constants and factors based on surveys of large numbers of people – and with some subsequent dispute whether the equation is correct in all circumstances.

Fanger also investigated the 'Predicted Percentage Dissatisfied' at a given PMV, suggesting the relation $PPD = 100 - 95\ \exp\{-(0.04\ PMV^4 + 0.22\ PMV^2)\}$.

3. Ventilation

(a) Reducing the wind sensitivity of buildings (from Building Research Establishment, Digest 350)



Wind pressure coefficients (tabulated) ; $C_P = \dfrac{p - p_{ref}}{\frac{1}{2}\rho U_{ref}^2}$;

where $U_{ref} = U_{ambient}$ is typically taken as wind velocity 10 m above ground level.

(b) Orifice flow

$$\Delta p = K \frac{1}{2} \rho U^2 \text{ , with } K \approx 1$$

whence $$U = \sqrt{\frac{2\Delta p}{\rho}}$$

Q (volume flow rate) = $C_D \times U \times Area$
C_D = discharge coefficient due to streamline contraction.

4. Acoustics

(a) Fundamentals and definitions

Velocity of sound in air at 20 °C : $c \approx 344 m/s$ when air density $\rho \approx 1.2 kg/m^3$

Consider root mean square pressure fluctuation $\bar{p}$ Pa and standard reference level $p_o = 2.0\times10^{-5}$ Pa at 1000Hz. Sound pressure level (SPL) defined as $20 \log_{10} (\bar{p}/p_o)$ decibels.
Sound intensity (rate of energy transmission across given surface):

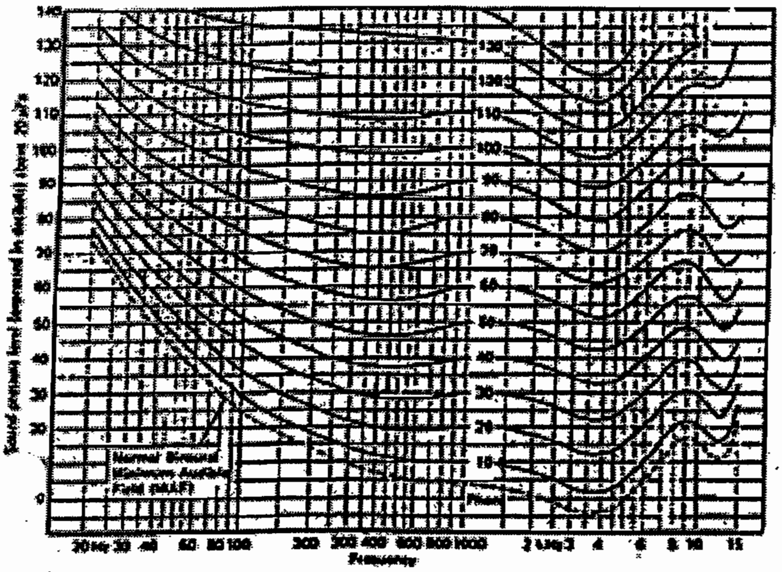
$$I = \frac{\bar{p}^2}{\rho c}: \quad IL = SPL = 10 \log (I/I_o): \quad I_o = \frac{p_o^2}{\rho c} \approx 10^{-12}$$

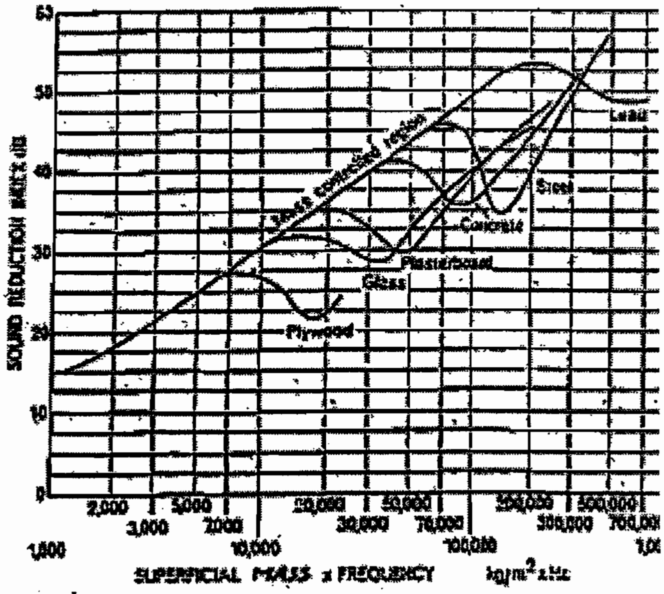
Sound energy density (energy per unit volume):

$$D = \frac{\bar{p}^2}{\rho c^2}: \quad SPL = 10 \log (D/D_o): \quad D_o = \frac{p_o^2}{\rho c^2}$$

Source power W watts : SWL = 10 log ($W/10^{-12}$)

Human ear: curves of equal perceived loudness (men) on left below: sound pressure level in dB versus frequency in Hz.





So adjusted curves (e.g. dBA from 40 phon line) to allow for ear characteristics varying with frequency.

Addition and comparison of incoherent sound: add mean square pressures to find overall mean square and hence SPL (or L_{eq} using average over time for varying sound levels).

(b) Acoustics of room-like enclosures (volume V, total surface S)

From uniform omnidirectional source W, at radius r (m) :
direct SPL = SWL – 10 log 4π - 20 log r

CIBSE PSYCHROMETRIC CHART