P L E A
NOTES

note 5

Passive and Low Energy Architecture International
DESIGN TOOLS AND TECHNIQUES

CLIMATE ANALYSIS

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IN ASSOCIATION WITH THE UNIVERSITY OF QUEENSLAND DEPT. OF ARCHITECTURE

CLIMATE ANALYSIS

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PREFACE

This is the fifth in our series of PLEA Notes. Two others, that were almost ready a year ago, have not yet materialised, due to circumstances beyond our control, but we haven't given up.

The present Note fits in well with the series title: "Design tools and techniques". It is aimed at the first stage of the design process, the "pre-design analysis" – or as one of the forefathers of climatic design, Otto Koenigsberger named it: the *forward analysis*. This is the crucial stage of design, before a formal concept is born, before a sketch design is produced.

We believe that the result of climate analysis should be one of the most important ingredients in the melting pot of design thinking, together with the client's brief and the very large number of architectural concerns. Once a sketch design has been produced, the designer is committed to it, (s)he may modify it but will rarely change it. So it had better be right in the first instance.

I repeat what was said in the Preface of previous Notes: the editor would be grateful for any comments, corrections, observations or suggestions. Proposals for new titles and offers of contributions would be welcome. If this series is to continue, we need your cooperation. It is not a commercial venture, we consider it as a service to the profession, especially to students, to further environmental responsibility in architecture.

Any communications should be sent to the address below, where these Notes can also be ordered.

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INTRODUCTION

Concern for the depletion of fuel resources, or for damage of the global environment (such as climate change caused by greenhouse gas emissions), both demand energy conservation. A prerequisite of sustainability is the conservation of energy both in investment (embodied energy) and in operational energy terms.

Whether the motivation is energy conservation, bioclimatic architecture, solar design, passive and low energy architecture, climatic design or just plain good architecture, the essence of the designer's task is

- to survey the given (climatic) conditions and compare these with
- the conditions required by humans and their activities.

This comparison should reveal the nature of the climatic (especially thermal) problem and indicate what the building should do to alleviate this problem. The present work therefore consists of three parts:

In Part 1 the climate itself is discussed, first at the global scale, then its elements, its classification and the problems and presentation of climatic data.

Part 2 deals with comfort and its relationship to the given climatic conditions, in order to delineate the nature of the climatic (thermal) problem and define the control task.

Part 3 is devoted to climatic design decisions, to what the building can do, the selection of control strategies as well as the translation of those strategies into actual solutions.

The appendices give technical information on some of the topics discussed and present some calculation methods.

1 CLIMATE

The Oxford dictionary definition of *climate* is

(Region with) prevailing conditions of temperature, humidity, wind, etc.

If the term *weather* means the state of the atmospheric environment, then *climate* is

the integration in time of the weather conditions, characteristic of a certain geographical location

or as Michael Glantz (of the US National Center for Atmospheric Research) once put it:

climate is what you expect, weather is what you get.

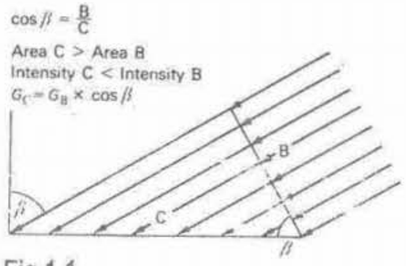


Fig.1.1
The cosine rule

1.1 Global climate

The earth as a whole is in thermal equilibrium: the energy input by solar radiation is matched by the emission of low temperature radiation towards space. This equilibrium ensures that the earth's temperature remains constant. (If the emission mechanism is impaired, such as by the effect of CO_2 and other 'greenhouse gases', earth's temperature will increase, increasing the radiant emission, until a new equilibrium is established with that higher temperature.)

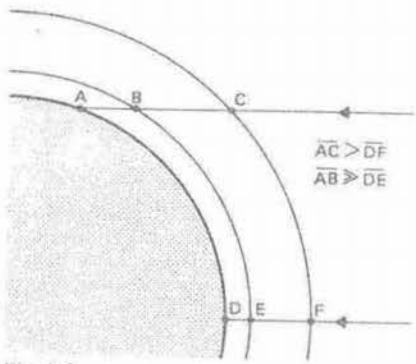


Fig.1.2
Paths through the atmosphere

Solar radiation input is highest in the equatorial regions, for two reasons:

- Fig.1.1 illustrates the cosine rule: with oblique incidence a beam of radiation is spread over a larger area, thus its intensity is reduced, must be multiplied by the cosine of the angle of incidence
- Fig.1.2 shows that the path of solar radiation through the atmosphere is longer at higher latitudes, thus more of it is absorbed.

The long-wave infrared emission is practically uniform from the globe in all directions. This causes higher temperatures near the equator and lower ones near the poles. Earth's climate is driven by the heat transfer mechanisms (ocean currents, winds) from the equatorial regions towards the poles. Seasonal variations are due to the fact that the earth's axis is tilted by 23.45° from the normal to the plane of its path, the ecliptic (Fig.1.3), hence the belt of maximum heat input is shifting between the tropics of Cancer and Capricorn.

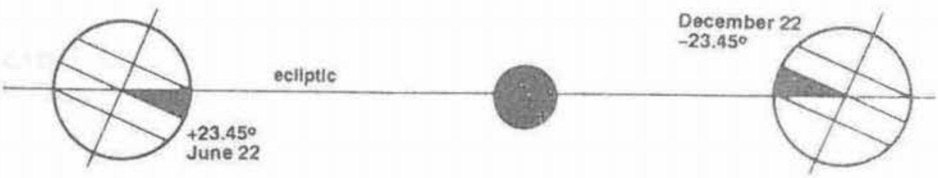


Fig.1.3 Cross section of the eclipic

The depth of the atmosphere is usually taken as 80 km (to the level of the *mesopause*, where the pressure is practically zero) although the *ionosphere* extends to double this. As the diameter of earth is some 12 750 km, if the earth were represented by a soccer football the depth of the atmosphere would be about 1.5 mm. Furthermore, half the total mass of the atmosphere is contained in the first 9 km and practically all life is contained in the 18 km deep *troposphere*. To continue the football analogy: this troposphere would be less than 0.4 mm thick. And all energy transfers and weather phenomena take place within this layer.

Fig.1.4 is a diagrammatic cross section of earth with its atmosphere, as well as an elevational view. At the equator the warm air rises and flows off to north and south in the stratosphere (and subsequently descends as it cools, in the subtropic high-pressure zones). This rising air mass will draw in air at ground level from both north and south, thus creating a tropical front. The position of the tropical front (the inter-tropical convergence zone, ITCZ) is shown at equinox date, but it moves north and south seasonally.

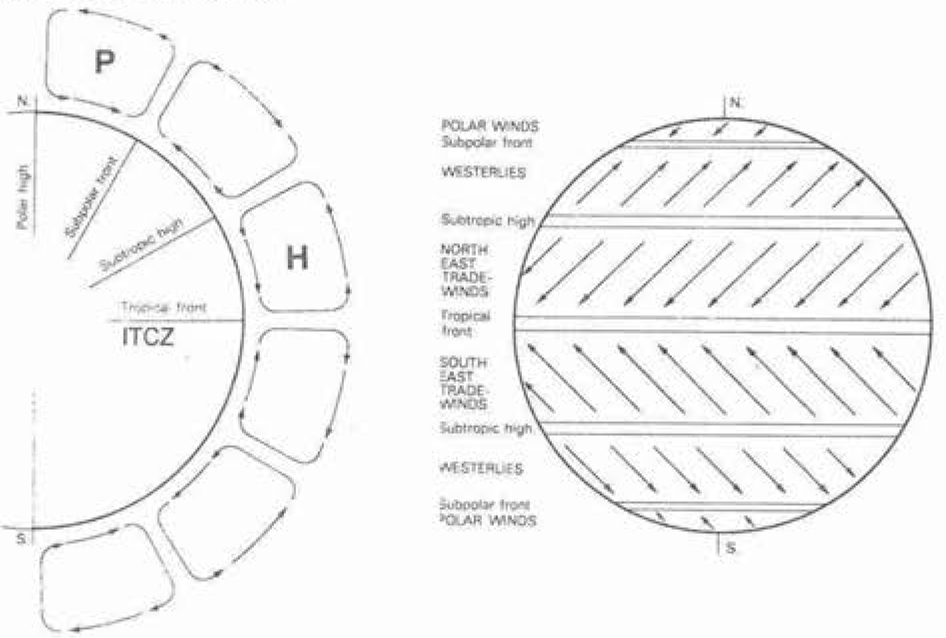


Fig.1.4 Global wind pattern

In the zone of trade winds the surface winds should flow south or north towards the ITCZ, but are deflected by the *Coriolis force*. The earth rotates from west to east. At the subtropic high belt the earth's circumferential velocity is less than at the equator. An air particle would travel at the same velocity as the surface. Driven towards the equator by thermal forces it will lag behind the faster moving equatorial terrain: it will 'slip' with respect to the earth's surface, turning the north wind to north-east and the south wind into south-east. The circulation between the ITCZ and the subtropic high-pressure zone is known as the *Hadley cell* ('H' in Fig.1.4)

The subtropic high belt (around 30° latitudes) is characterised by descending air masses. Precipitation cannot occur in descending air*, hence most of the earth's deserts are located in this belt. At ground level this air mass will spread out towards north and south. The part moving towards the higher latitudes is moving faster than the ground surface, so it will overtake it, it will turn into north-westerly (southern hemisphere) or south-westerly (in the northern hemisphere). Latitudes 30°-60° are the belt of mid-latitude westerlies.

At the locations of maximum cooling, ie at the poles, the descending air flow will spread out at ground level, and will move towards lower latitudes, deflected by the Coriolis force to be south-easterly or north-easterly: known as the polar winds. The subpolar front is formed where

* as the air descends its pressure and temperature increase, so the relative humidity decreases; the descending warm air is referred to as "Föhn".

this air mass meets the above mentioned westerlies. This circulation is referred to as the *polar cell* ('P' in Fig.1.4).
If the above were strictly obeyed, all isobar lines of the weather reports should run parallel to the latitude circles. This does not occur, for the following reasons:

A descending air mass is not a sheet but forms a large vortex. At high altitude the circumferential velocity is greater than at ground level, so a descending air particle will overtake the ground surface. Moving towards the equator, subjected to the Coriolis force, it will slip behind the ground surface. When moving away from the equator, it will overtake the surface. Thus a rotational movement develops around a high pressure zone, which is clockwise in the northern hemisphere and anticlockwise in the southern.

A rising air mass suffers the opposite effects and will form a vortex around a low pressure zone, which is anticlockwise in the northern and clockwise in the southern hemisphere. This is referred to as cyclonic circulation. The descending air mass shows an anticyclonic circulation (note the southern hemisphere agreement: anticyclone anticlockwise, whilst in the northern hemisphere anticyclone is clockwise!).

In the zone of mid-latitude westerlies (the Ferrel westerlies) the circulation pattern is highly variable. As Fig.1.5 shows, these upper-air westerlies (esp. jet streams) form a wave pattern and both cyclonic and anticyclonic circulations tend to break away from these waves.

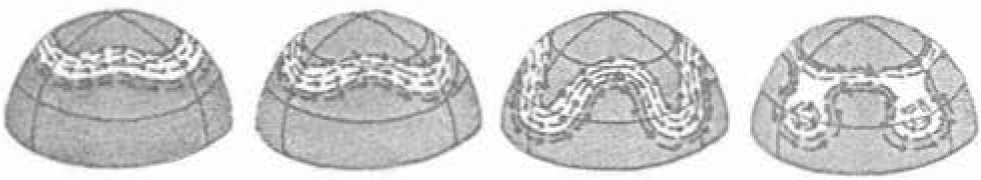


Fig.1.5 The development of mid-latitude cyclonic cells

These global air movements are responsible for the distribution of heat and some levelling out of temperature differences caused by the uneven solar input. It has been estimated that in the absence of these heat transfer processes the mean temperature at the equator would be 33°C (instead of the present 27°C) and at the North Pole it would be -40°C (rather than -17°C, as it is now). The winds also transport moisture, evaporating especially from the large ocean surfaces and are the main contributors to rainfall patterns (or the lack of rain).

1.2 Elements of climates

The climate of a given location is depicted by climatic data: measured values of climatic elements over a long time (at least 10 years). Meteorologists measure a large number of climatic variables, but the designer is not particularly interested in variables such as barometric pressure (which is the most important factor in synoptic meteorology), but would rather concentrate on those that affect human comfort or are otherwise directly relevant to building design. Here the following will be reviewed: temperature, humidity, wind, solar radiation, precipitation and some special characteristics.

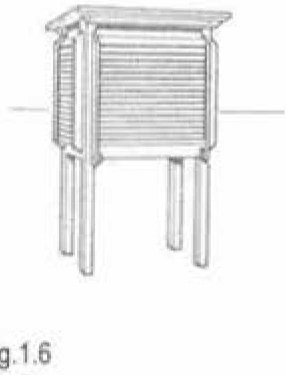


Fig.1.6
The Stevenson screen

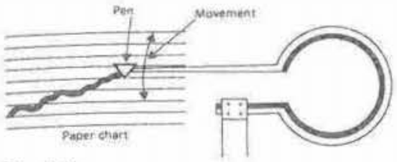


Fig.1.7
Bimetallic thermometer

1.2.1 temperature

This is usually measured in a Stevenson screen (Fig.1.6), 1.2 to 1.8 m above the ground, as the dry bulb or 'true air' temperature. Various sensors can be used with automatic data-logging equipment, such as thermocouples, platinum resistance sensors or IC (integrated circuit) devices, but the most accurate and reliable are still the mercury-in-glass thermometers. Readings can be taken at specified times of the day (eg six 3-hourly readings at 6, 9, 12, 15, 18, 21 hours) or a maximum-minimum thermometer can be used to give the instantaneous reading, plus the lowest and highest temperature since the last reading. Mechanical thermographs are still in use in some places, based on a bi-metallic thermometer (Fig.1.7), drawing a continuous temperature curve on a paper chart, which is stretched over a cylinder, driven by a clock-work mechanism.

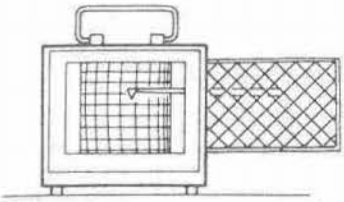


Fig.1.8
A hygrograph

1.2.1 humidity

This is most often expressed as relative humidity, ie the actual moisture content or absolute humidity of the air (in g/kg) expressed as a percentage of the saturation point humidity of the air at the same temperature. A *hygrograph* (Fig.1.8) may be based on the moisture expansion-contraction of human hair or some plastic fibres, or on changes of electrical conductivity of some materials. The two recorders may be combined in one instrument known as the *thermo-hygrograph* (Fig.1.9).

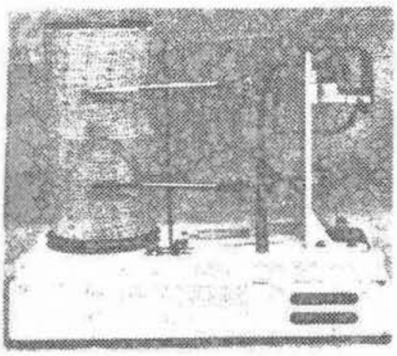


Fig.1.9
A thermo-hygrograph
(cover removed)

The most reliable instruments are still the wet-and-dry bulb thermometers or psychrometers.*

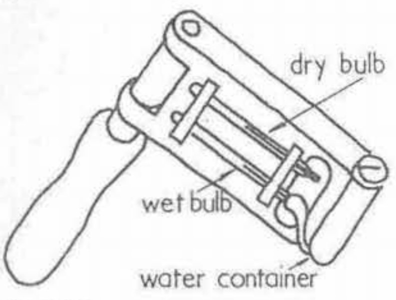


Fig.1.10
A whirling psychrometer

The most generally used is the hand-held whirling psychrometer (Fig.1.10) which consists of two identical thermometers, one has its bulb surrounded by a wick, which is kept moist from a water container. It must be whirled around to obtain the maximum possible evaporation from the wet bulb. Evaporation, thus the cooling effect is inversely proportionate to the humidity of the air. The difference between the dry and wet bulb readings (the 'wet bulb depression') indicates the cooling effect. Either from a psychrometric chart or by a special slide rule or even just a table of numbers this can be converted to one of the many forms of expression of humidity, such as

- relative humidity RH (%)
- absolute humidity AH (g/kg)
- humidity ratio (non-dimensional: g/g or kg/kg)
- dew-point temperature DPT (°C)
- vapour pressure vp (kPa)

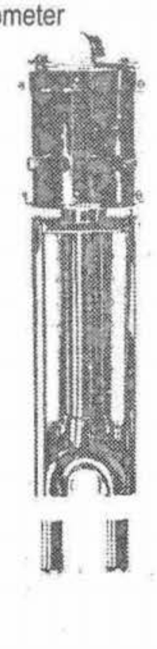


Fig.1.11
The Assman
psychrometer

Such psychrometers can be screen mounted (in the Stevenson screen) or aspirated, such as the Assman psychrometer (Fig.1.11). These have a built-in fan, (with a clockwork mechanism) to drive a continuous air stream across the wet bulb. Any other form of temperature sensor can be used not only for the dry-bulb but also for the wet bulb thermometer. The psychrometric chart is valid only for the aspirated or whirling

* to be precise: a hygrometer is any instrument used to measure humidity of the air, whilst a psychrometer is a type of hygrometer based on the measurement of DBT and WBT

psychrometers. The screen mounted (non-aspirated) types need their own conversion charts (see also Appendix 4).

Continuous or automatic recordings are still fairly rare. Most meteorological stations measure the humidity twice a day: at an early morning hour (eg. 6.00 h) and at an early afternoon hour (eg 14.00 or 15.00 h). The former is likely to give the highest and the latter the lowest relative humidity value for the day.

1.2.3 wind

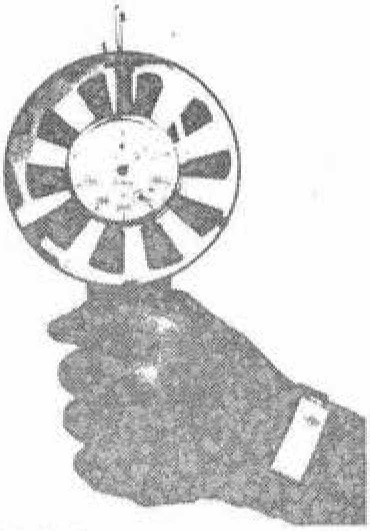


Fig.1.12
A propeller anemometer

Winds are variable not only in terms of velocity, but also in direction. Wind velocity may be measured by a range of different *anemometers*. The propeller type anemometers (Fig.1.12) are often used to measure the *wind run*, ie the cumulative value of wind speed over a specified time period. The wind run divided by the time will then give the average velocity for that period. This device is either hand-held or must be attached to a vane, which ensures that the propeller is always facing the direction the wind comes from.

An alternative is to use a cup-type anemometer (Fig.1.13), which is mounted on a vertical axis and will respond to wind of any direction. The output of this device can give a readout through a mechanical system or electrically, and both can be recorded by various devices, mechanically, by an anemograph, or electronically. The direction of the wind must be measured and recorded separately.

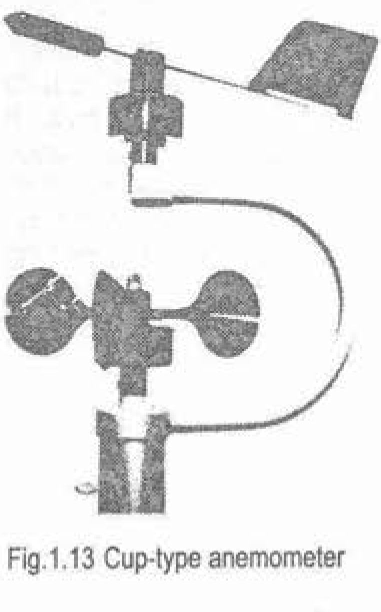


Fig.1.13 Cup-type anemometer

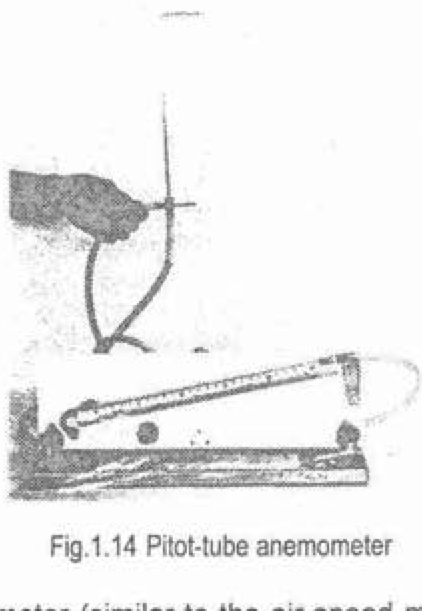


Fig.1.14 Pitot-tube anemometer

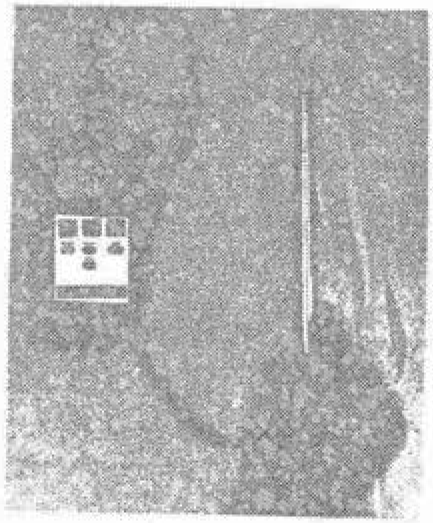


Fig.1.15 Hot wire anemometer

The Pitot-tube (Fig.1.14) anemometer (similar to the air-speed meter of aeroplanes) measures the difference between the static pressure (the barometric pressure) and the dynamic pressure caused by the wind. This pressure difference is indicative of the wind speed. This device must also face the direction of wind. For low air velocities the most accurate instrument is the hot-wire anemometer (Fig.1.15). A known small current heats a small wire filament and its temperature is measured. This gives the cooling rate, which is the function of air velocity.

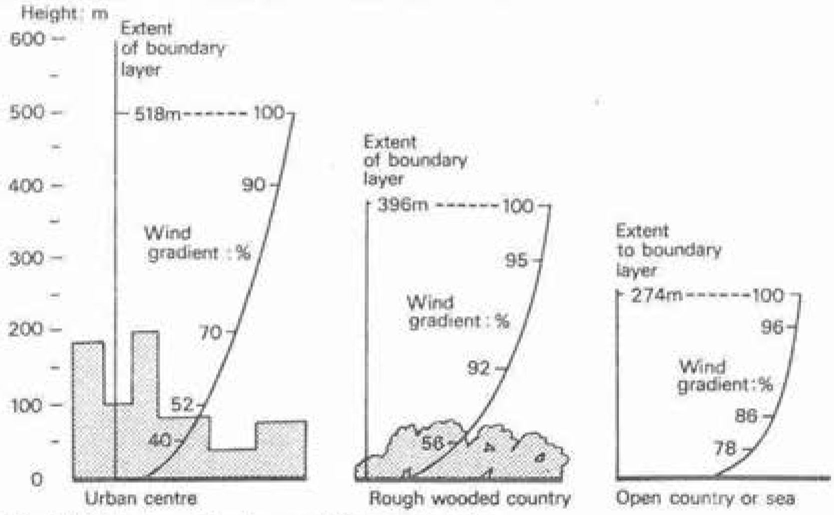


Fig.1.16 Wind gradients over different terrains

Free wind velocities are usually recorded in open, flat country (eg at airports) at a height of 10 m. In urban areas the 10 m should be taken above the general level of obstructions. Velocities near the ground, or within the boundary layer, would be a good deal lower than the free wind velocity, depending on the depth of the boundary layer, ie the velocity profile (Fig.1.16), which is a function of terrain characteristics.

Velocity is measured in m/s (or in km/h), but much data can still be found in obsolete units, such as ft/min, mph (mile per hour) or knots (nautical miles per hour). A 'wind force scale' developed by Beaufort in 1806, based on visual observation is still in use in some instances. Appendix 1 gives the definitions of the 12 categories.

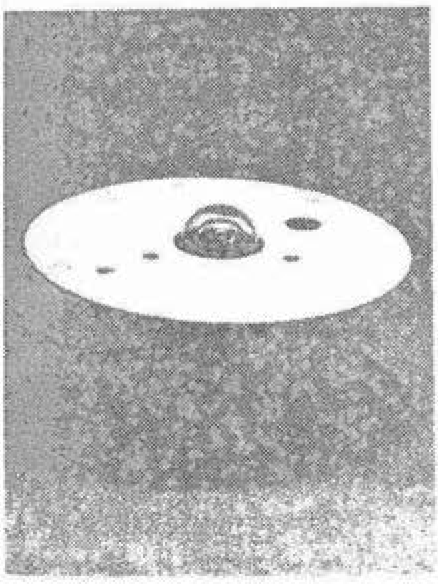


Fig.1.17
A pyranometer

1.2.4 solar radiation

Solar radiation is the driving force of climates, but it also affects buildings directly.

Most meteorological stations measure the duration of clear sunshine only, which can be recorded by an *actinograph*. The power density of solar radiation is measured by a *pyranometer* (Fig.1.17) and expressed as instantaneous *irradiance*, in W/m^2, or it can be integrated as energy density over a defined period (hour, day, month or year) as *irradiation*, in Wh/m^2 (sometimes converted to MJ/m^2). Some publications still use an old unit of irradiation, the "langley": 1 Ly = 1 g.cal/cm^2 = 41.868 kJ/m^2 = 11.63 Wh/m^2 and for irradiance the time unit must be specified: 1 Ly/s = 41.868 kW/m^2 or 1 Ly/min = 697.8 W/m^2.

Most often the global radiation incident on a horizontal plane is measured, which includes both the direct beam component and the diffuse component. If a shadow band is attached to the pyranometer (Fig.1.18), this could exclude the beam component and measure only the diffuse radiation (irradiance or irradiation). The *pyrheliometer* (Fig.1.19) is used to measure the beam component of solar radiation only, on a plane normal to the direction of the beam. This has a built-in tracking mechanism to aim the sensor continuously at the sun. These instruments are based on a thermopile sensor, which gives a millivolt output proportional to the incident radiation. Less accurate, but much less expensive instruments are based on photovoltaic sensors.

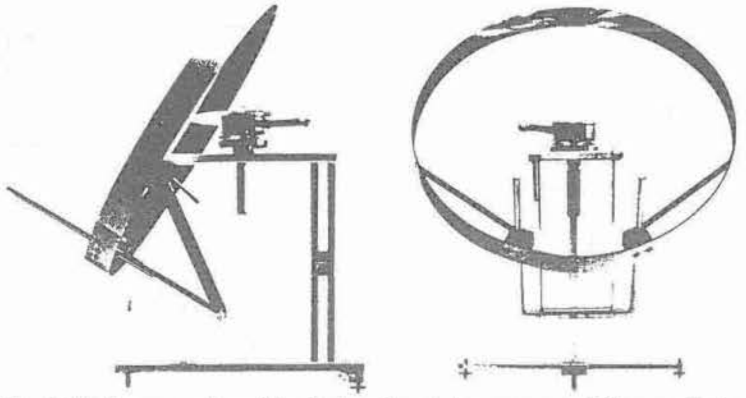


Fig.1.18 Pyranometer with shadow band: to measure diffuse radiation

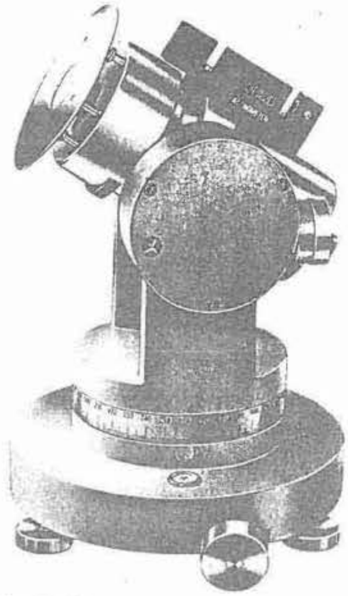


Fig.1.19 Pyrheliometer

If solar radiation is not measured at a site, observation of sky conditions (cloud cover) may allow its estimation. This is based on visual observation and it is rather inexact, but it has indicative value. Cloud cover is expressed either as a percentage (%) or in octas (eighths) or tenths of the sky hemisphere. Thus 5 tenths, 4 octas or 50% would have the same meaning: half the sky is covered by clouds.

Cloud cover has a significant effect in reducing outgoing long-wave radiation. Table 1.1 (adopted from Geiger, 1959) shows the magnitude of this effect (the cloudless clear sky is taken as 100%).

1.2.5 precipitation

Rain gauges measure the precipitation, not only rain, but snow or hail as well (after it has melted), in mm per given time (day, month, year). This information is not directly relevant for building designers, only inasmuch as it may be indicative of the climate type. Rain intensity, expressed in mm/h is important for the design of gutters, downpipes and drains.

If rainfall coincides with high winds, the watertightness of windows and several other elements may be critical. The driving rain index is the product of annual rainfall in m (not in mm !) and the average wind velocity for the year in m/s, thus its dimension is m^2/s.

Up to 3 m^2/s the location is considered to be 'sheltered'; between 3 and 7 m^2/s it would be 'moderate' and above 7 m^2/s it is taken as 'exposed'. This is only a rather general classification for exposure, the actual risk of rain penetration will depend on instantaneous (say 10-minute) rain intensity and simultaneous wind velocity.

Table 1.1
The effect of cloud cover

cloud cover (tenths)	outgoing radiation
0	100%
1	98%
2	95%
3	90%
4	85%
5	79%
6	73%
7	64%
8	52%
9	35%
10	15%

1.2.6 special characteristics

In many instances the regular climatic data are supplemented by a range of indicative numbers, such as

- number of days a certain temperature is exceeded
- number of frost days
- occurrence of fog
- frequency of hail-storms
- frequency of thunderstorms
- possible dust-storms, tornadoes or cyclones
- any risk of earthquakes.

These may be rare events, but must be considered in design as a single occurrence may cause damage.

1.3 Climate classification

There is an almost unlimited number of different climates on earth, so for convenience and comprehension these should be grouped into a limited number of climate types. The ancient Greeks distinguished only three types: torrid, temperate and frigid zones. Today several dozen different classification schemes exist. These are of two kinds (Flohn 1969):

- genetic systems, based on the causes of climates and
- applied systems, based on the effects of climates, such as natural vegetation, evapo-transpiration: systems for particular purposes.

Probably the most widely used applied classification is the Köppen system. Originally (in 1900) based on vegetation, but revised in 1918 on the basis of temperature, rainfall and seasonal variations. In subsequent years further refined by the cooperation of Geiger. The Köppen-Geiger (1936) system distinguishes 5 main categories: A tropical, B Dry, C Warm temperate, D snow climates and E ice climate.

There are two further levels of subdivision. For example D indicates a severe winter climate, Df indicates that it is moist all seasons and Dfa means that it has a hot summer. Fig.1.20 shows a world map with the Köppen-Geiger climate zones and Table 1.2 is a summary of the climate types distinguished.

Thornthwaite developed his first scheme in 1931, largely based on vegetation and it included a number of complex indices. He had some 32 main types, further subdivided. He revised his scheme in 1948, based on the relationship of precipitation and evapo-transpiration. This became a system widely used by agriculturalists.

The classification that gained wide acceptance in architecture is based on the nature of the thermal problem in relation to human thermal comfort:

A. cold climates, where the problem is the lack of heat, causing excessive body heat loss
B. warm climates, where there is too much heat, causing inadequate heat dissipation
C. moderate climates, where there is a seasonal variation between the above two

Group B would need a subdivision according to how the climate affects the various heat dissipation mechanisms of the body. Several authors suggest the sub-categories of hot-dry and warm-humid climates. For warm climates the subdivision proposed by Atkinson (1953) became generally accepted among architects:

1 warm-humid equatorial climate
  1a island or trade-wind climate
2 hot-dry desert or semi-desert climate
  2a maritime desert climate
3 composite or monsoon climate (combination of 1 and 2)
  3a tropical highland climate.

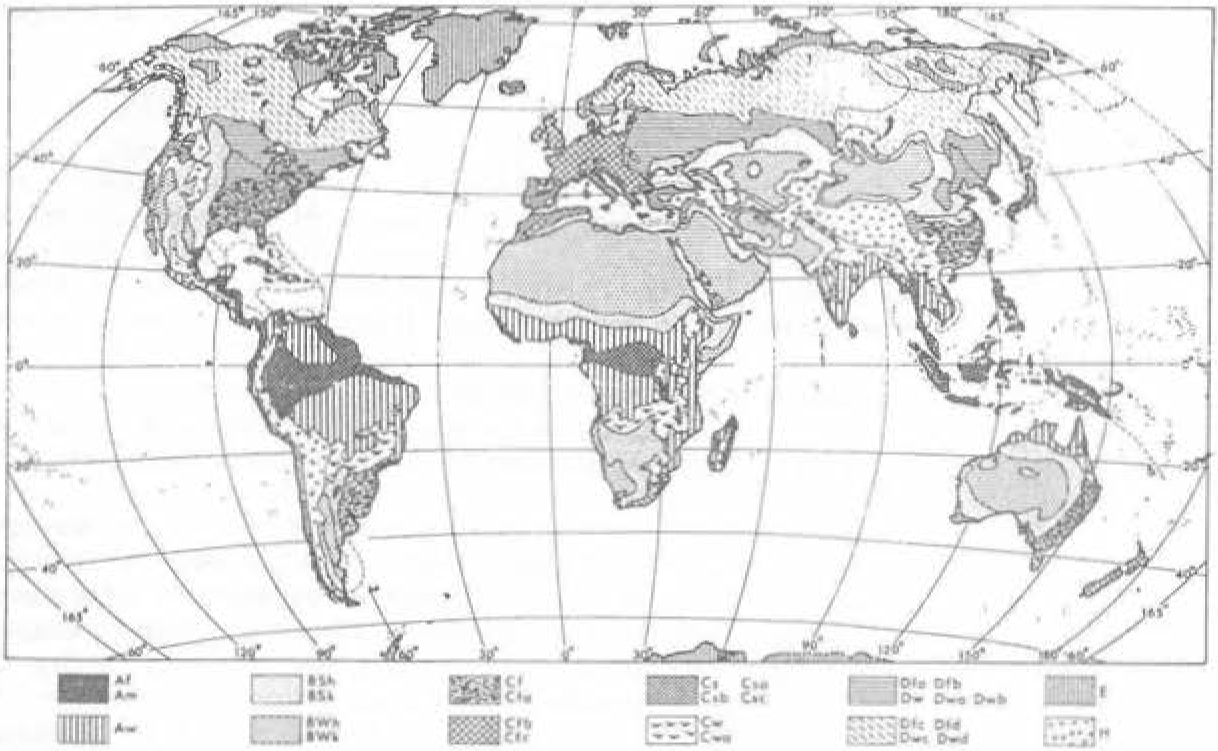


Fig.1.20 The Köppen - Geiger climate zones of the world

Table 1.2
The Köppen-Geiger climate classification

type	main group	second subgroup	third subgroup
Af	hot	rainy all seasons	
Am		monsoonal rain	
Aw		dry winter	
As		dry summer	
Bsh	dry	semi-arid steppe	very hot
Bsk			cold or cool
Bwh		arid	very hot
Bwk			cold or cool
Cfa	mild winter	moist all seasons	hot summer
Cfb			warm summer
Cfc			cool short summer
Cwa		dry winter	hot summer
Cwb			warm summer
Csa		dry summer	hot summer
Csb			warm summer
Dfa	severe winter	moist all seasons	hot summer
Dfb			warm summer
Dfc			short cool summer
Dfd			very cold winter
Dwa		dry winter	hot summer
Dwb			cool summer
Dwc			short cool summer
Dwd			very cold winter
ET	polar climate	short summer allows tundra vegetation	
EF		perpetual ice and snow	

The simplicity of this schema is attractive. It helps in obtaining an overall concept of the nature of a climate. However, any classification would conceal some local differences, so the use of this classification system is no substitute for the consideration of the given local climate in some detail.

1.4 Climatic data

The problem with the huge amount of data collected at meteorological stations is its interpretation, in other words the problem of data versus meaning. The purpose is to characterise the climate of a given location. Clearly, the raw data must be processed and presented in a meaningful form. What is the form and amount of data that would convey a meaning and would give an adequate characterisation of the climate?

At one extreme, long term (say 10 years) of hourly data of (eg) temperature can be averaged, to say that the mean temperature of the location is (say) 20.5°C. This single figure conveys some information, but conceals the daily, seasonal and annual variations.
At the other extreme we may have 10 years of hourly data of (say) 12 climatic elements, - this is over a million data items. Fig.1.21 shows just one day's data for Melbourne. It is difficult to extract any meaning from this, short of electronic processing.

```
0         1         2         3         4         5         6
0123456789012345678901234567890123456789012345678901234567890

ME7812 1 0 128 621015  0 0622222    0  0    0 0  02
ME7812 1 1 121 601019 29 2122222    0  0    0 0  02
ME7812 1 2 113 581014  0 0300000    0  0    0 0  02
ME7812 1 3 111 591014  0 0322222    0  0    0 0  02
ME7812 1 4 108 601014  0 0222222    0  0    0 0  02
ME7812 1 5 106 611014  0 0200000    5  4   29 21162
ME7812 1 6 119 611014  0 0222222   65 55   61 91102
ME7812 1 7 131 621014  0 0322222  317 91 634211022
ME7812 1 8 144 621014  0 0300000  482135 64433 932
ME7812 1 9 156 631014  0 0322222  414266 21144 842
ME7812 110 168 641013  0 0322222  729217 61756 722
ME7812 111 180 651013  0 0300000  821227 65067 522
ME7812 112 184 651012 12 8222222  996105 93?73 162
ME7812 113 188 661012 24 8222222  996100 944723292
ME7812 114 1?2 661011 36 8100000  928 96 934632992
ME7812 115 195 711010 31 8122222  814 92 917522832
ME7812 116 199 771010 26 8022222  655 89 876402722
ME7812 117 202 821009 21 8000000  462 87 789282642
ME7812 118 194 801009 24 8022222  255 75 624172552
ME7812 119 187 771008 27 8022222   68 35 299 62472
ME7812 120 179 751008 31 8000000    0  0    0 02477
ME7812 121 169 761008 21 8022222    0  0    0 0
ME7812 122 158 761008 10 802227.    0  0    0 0  02
ME7812 123 148 771008  0 0000000    0  0    0 0  02
```

Fig.1.21 One day's data for Melbourne from the CSIRO "weather tapes"

We must distinguish climatic data requirements for three different purposes:

1) to create a qualitative understanding of the climate for the human user
2) to provide the basis for manual calculations or simple computer programs
3) to give the climatic input for detailed hour-by-hour simulation programs.

1.4.1 data for qualitative understanding

Graphic representations are particularly useful for this purpose. The *climate graph* developed by Koenigsberger et al (1974) gives an idea of the climate at a glimpse, especially when comparing such graphs. Fig.1.22 shows four such climate graphs, for the four basic climate types, which represent the following climate elements:

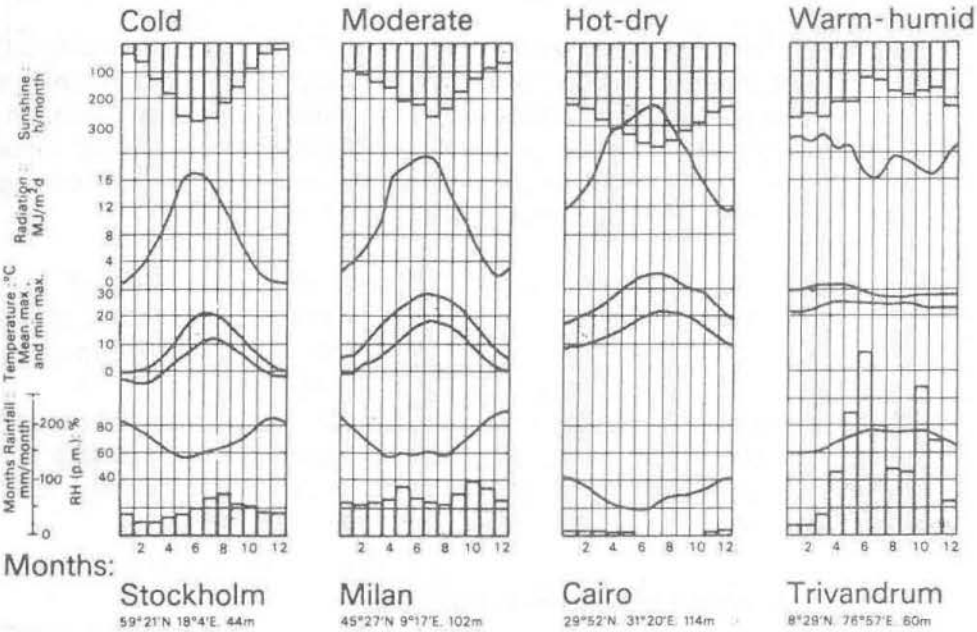


Fig.1.22 Climate graphs for the four basic climate types

a) Sunshine hours per month: a histogram, with its scale downwards from the top of the frame. Note the differences: very pronounced seasonal variations in Stockholm, reduced in Milan (more hours in winter but fewer in summer); much more all year round in Cairo, still with a large seasonal variation; for Trivandrum an almost even annual distribution, reduced only during the monsoon (coinciding with the largest rainfall).

b) Solar irradiation (in MJ/m²day): the line graph confirms the above differences. Stockholm: the curve narrow and pointed for summer; broader for Milan; even broader and much higher for Cairo and an almost level distribution for Trivandrum, with two dips coinciding with maximum rainfall.

c) For temperatures two lines are shown: the daily maxima and minima enclosing a shaded area. Sometimes the 86th %-ile of the daily maxima and 14th %-ile of minima* are added.

d) The humidity curve represents the afternoon (14:00 or 15:00 h) relative humidity (%); note the sharp contrast between Cairo and Trivandrum (often a second curve is shown to give the morning humidity, but this is fairly high in all climates).

e) The most striking difference is in rainfall, indicated by the bottom histogram (mm/month).

A more detailed and larger scale versions of these have been used by Szokolay (1982) to present the climate of some 50 locations in Australia.

* one day is about 14% of the week, thus the 86th%-ile value would be exceeded one day a week and it may drop below the 14th %-ile value one day per week

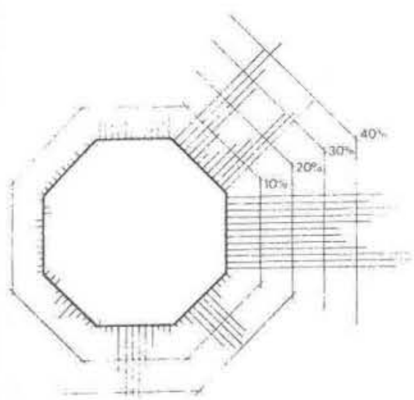


Fig.1.23
Annual wind graph (15.00 h)

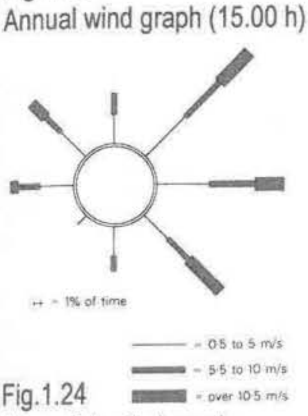


Fig.1.24
A monthly wind graph

9 am January

Calm 25 — 1859 observations

km/h	N	NE	E	SE	S	SW	W	NW	All
1-10	1	1	1	9	22	3	1	1	39
11-20	1	*	*	5	21	2	*	1	30
21-30	*			1	4	*	*	*	6
>30				*	*	*			1
All	2	1	1	15	47	5	1	2	100

3 pm January

Calm 5 — 1854 observations

km/h	N	NE	E	SE	S	SW	W	NW	All
1-10	6	5	3	2	2	1	*	1	20
11-20	12	14	9	8	4	*	*	1	50
21-30	2	3	5	10	3	*	*	*	23
>30	*		*	2	*	*	*		3
All	20	22	17	22	10	1	1	2	100

Fig.1.25
Wind frequency analysis

For wind data two forms of graphs are often used. The octagonal one (Fig.1.23) has 12 lines on each side, representing the 12 months in a clockwise sequence. The length of each line represents the frequency of wind coming from that direction in that month. There is no indication of velocity. Usually two roses are presented, one for 9:00 and one for 15:00 h. Such roses are normally supplemented by stating the average wind velocity for each month as well as the maximum gust velocity.

The alternative is to use a separate graph for each month (sometimes for each quarter-year), such as that shown in Fig.1.24. Here different line thicknesses represent different velocity categories, whilst the length of each line or line segment represents frequency.

The Bureau of Meteorology in Australia presents these data also in numerical form as a "wind frequency analysis". Fig.1.25 shows the frequency analysis for January (in Cairns): one table for 9 am and one for 3 pm. 12 such pairs of tables describe the whole year. This example is based on 59 years of data (some items are missing, but the total number of observations is shown). Numbers indicate % frequencies for 8 directions and 4 velocity categories. The last column gives frequencies of each velocity band for all directions and the bottom line for each direction and all velocities.

1.4.2 data for simple calculations

The minimum data requirement is that shown in Fig.1.26. After stating the latitude (which would be necessary for solar calculations) the eight lines give the following data for each month:

1) TMax = mean maximum temperature (°C)
2) sdMax = standard deviation of daily maxima (K)
3) TMin = mean minimum temperature (°C)
4) sdMin = standard deviation of daily minima (K)
5) Tsd = standard deviation of the daily mean (K)
6) RHam = relative humidity (%), morning (6:00 or 9:00 h)
7) RHpm = relative humidity (%), afternoon (14:00 or 15:00 h)
8) Rain = rainfall, total for the month (mm)
9) Irad = mean daily irradiation (MJ/m² or Wh/m²)

Climatic data for CAIRNS
Latitude = -16.9

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
TMax :	31.4	31.3	30.1	29.0	27.3	25.8	25.3	26.6	28.0	29.4	30.6	31.4	degC
sdMax:	1.6	1.7	1.8	1.6	1.5	1.7	1.4	1.2	1.2	1.3	1.1	1.3	K
TMin :	23.5	23.7	23.0	21.5	19.6	17.8	16.5	17.6	18.8	20.5	22.4	23.3	degC
sdMin:	1.2	1.2	1.2	1.4	2.0	2.2	2.7	2.3	2.0	1.7	1.6	1.4	K
Tsd :	1.1	1.2	1.3	1.2	1.5	1.7	1.8	1.5	1.4	1.3	1.2	1.1	K
RHam :	71	75	78	76	75	74	72	70	65	64	64	66	%
RHpm :	62	65	65	63	62	59	56	54	52	53	57	59	%
Rain :	399	441	464	177	91	51	30	26	36	35	84	167	mm
Irad :	5800	5615	4950	5064	4333	4195	4766	5367	6044	6952	6680	6592	Wh/m2

Fig.1.26 Minimum data requirements for simple calculations

The mean temperature can then be found as the average of (1) and (3). The standard deviation of the mean has been calculated as described in Appendix 6.

The standard deviation values are useful to give an indication of the distribution and variability of temperatures and are used in the *variable base degree-hour* method (Appendix 6).

Some climatic data sources give the number of heating degree days (or degree hours) for each month, to a standard base temperature. In practically all countries (except the USA, where °F is still used) this is normally taken as 18°C. With reference to Fig.1.27 it can be seen that if a continuous graph of temperature is plotted, the area enclosed by this curve and the base temperature line represents the cumulative temperature deficit. If the horizontal dimension is hours and the vertical scale is °C, the temperature deficit for each hour being in K, then the product, the area is in K.h (Kelvin-hours). The Kelvin-hour term is preferred, to avoid confusion with Farenheit degree-hours.

The number of Kelvin-days (or Kelvin hours) is a climatic parameter often used in heating requirement calculations (Appendix 6).

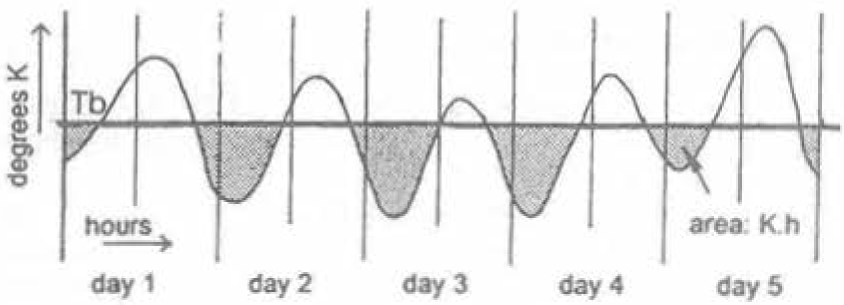


Fig.1.27 Definition of degree-hours

1.4.3 data for computer programs

Since the development of detailed simulation programs for the thermal response of buildings (which can quickly perform heat flow calculations in hourly time steps for the whole year), efforts were made to produce agreed sets of hourly climatic data, representative of particular locations. Many research projects examined the problem of compiling a truly representative data set, without the smoothening effect of taking average values, but avoiding the possibly erratic nature of a selected year's data. The subject has quite a large literature. Most systems now construct a composite year's data by selecting periods of actual data from many years of recording, nearest to the averages of that period.

In Australia the CSIRO compiled such "weather tapes", but these data are now available on diskettes. In the USA such a set is referred to as TMY (typical meteorological year), in Denmark as "reference year", in the UK as "example weather year", a Dutch source refers to it as "synthetic reference climate", similarly to the German "syntetisches Referenzjahr" and the EU calls it TRY (test reference year), a term also adopted in Australia..

1.5 Microclimate

Published climatic data are usually those measured in open spaces, very often at airports. These adequately describe the macroclimate. The term microclimate is used for any smaller scale variants, and it can mean different scales for different professions (for the plant biologist it may mean the climate around a single leaf).

What is important in our field is to remember that the climate at the site may not be the same as that reflected by the published data from the nearest meteorological station. There may be a difference from that station to the particular site, but there may be differences within the site and the building to be built may also exert an influence and cause further differences. The following paragraphs can only provide some general qualitative guidance on the effect of some factors.

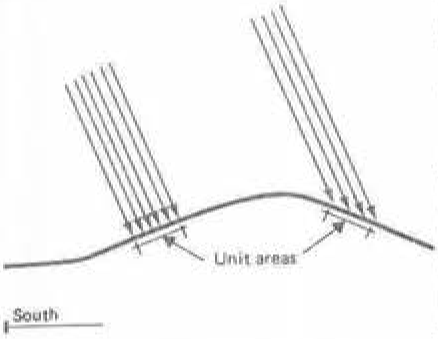


Fig.1.28 Hillside irradiation (northern hemisphere)

1.5.1 topography

A hill-slope facing the equator will receive more solar radiation than a horizontal and one facing the poles will have its irradiation reduced (Fig.1.28). An east facing slope receives increased radiation in the morning and a west facing one in the afternoon. Increased irradiation means increased surface temperatures. These surfaces in turn warm the air and may cause rising currents. Hills also influence precipitation: a windward slope diverts the air flow upwards, it will cool and may discharge its moisture content (Fig.1.29). Conversely, there is little or no precipitation on leeward slopes. This effect can be quite pronounced with hills over 300 m higher than the surrounding terrain. Fig.1.30 shows that the driving rain exposure of windward sides of hills is worse, due to the resulting vector: the path of droplets is nearer to the horizontal.

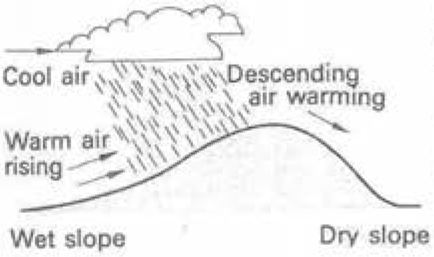


Fig.1.29
Hillside precipitation

In the absence of macroclimatic winds local heating may cause anabatic air flow, moving upwards along a sloping valley, or the opposite: a katabatic (cool) air flow downwards. The latter can reach quite noticeable velocities and temperature drops, with consequences such as frost damage to orchards.

1.5.2 ground surface

Fig.1.30
Hillside driving rain

Reference to Fig.1.16 shows that the ground surface has a retarding effect on moving air and causes turbulent flow. The depth of air thus affected is the boundary layer. This may be less than 300 m over smooth terrain, but over urban areas it can exceed 500 m.

Surface qualities also affect solar heating. Hard, dry surfaces are heated more than areas with vegetation cover. This is the primary cause of the "heat island" effect over dense city areas (other causes may be anthropogenic heat emissions and atmospheric pollution; eg CO_2 emissions may reduce radiant losses and thus enhance the heating effect). The rising air, as it cools, may discharge its water content. Such urban areas may have a higher rainfall than the surrounding countryside (Fig.1.31).

Fig.1.31
Precipitation over cities

1.5.3 water bodies

The proximity of large bodies of water (sea or lakes) has a mitigating effect on temperature fluctuations. It is not unusual to find that near the sea-shore the diurnal temperature variation is reduced to 7 - 8 K, whilst only 10 - 15 km inland it may be over 12 K.

During the day, when the land is heated more than the water, on-shore winds are generated (Fig.1.32) and, especially on clear nights when the land surface is strongly cooled, whilst the water remains warm, an off-shore wind results (Fig.1.33).

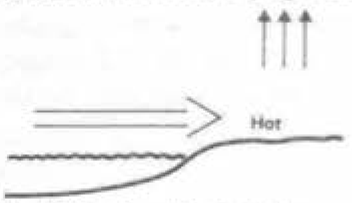


Fig.1.32 Coastal wind: day

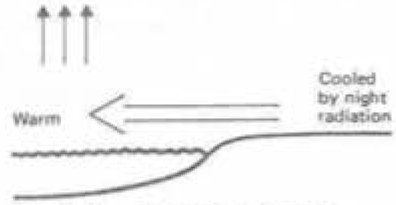


Fig.1.33 Coastal wind: night

1.5.4 3-D objects

Horizontally long barriers would reduce wind speed by 50% to a leeward distance of some 10 times their height and by 25% up to 20 times their height. Within this distance the air flow is not only reduced in velocity, but it also becomes more turbulent and at places even reversed in direction. A mountain range, a chain of hills, but also some man-made objects, such as buildings, may have such effects.

Microclimatic effects are noticeable even around single buildings. As Fig.1.34 illustrates, the sunlit side of a slab-type block with paved foreground may cause an upward current, which would draw cooler air through ground level openings from the shady garden behind. Even at domestic scale buildings differences of 2 K in air temperature have been reported between the sunny and shady sides.

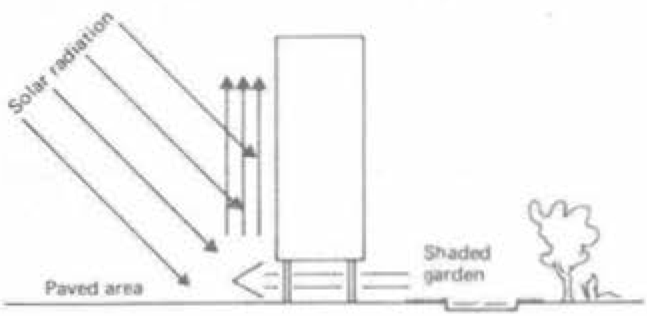


Fig.1.34 Microclimatic effect of one building

2 COMFORT

Human thermal comfort is dependent on four environmental variables:

- air temperature
- humidity
- air movement
- radiation

(other contributing factors as well as a range of comfort indices are examined in some detail in PLEA Note 3: Thermal comfort).

Appendix 2 lists some 26 different measures of comfort or comfort conditions, showing the factors allowed for in each case. It is agreed by most research workers that at or near comfort conditions the best measure of thermal sensation is the air (dry bulb) temperature, within very wide limits of humidity.

As comfort depends on the dissipation of the body's metabolic heat production, discomfort will occur when this dissipation is insufficient or too much. Heat dissipation from the body can take the form of convection (possibly conduction, if in contact with colder surfaces), radiation and evaporation. In still air, around 18 - 20°C, if there is no conductive contact, the heat dissipation will be distributed as

- radiation 45%
- convection 30%
- evaporation 25%

Convection is a function of air velocity. Radiation depends on the temperature of surrounding surfaces. This in turn, in the absence of heating or cooling, depends on outdoor air temperature and solar radiation. Evaporation depends on the partial pressure of water vapour in the atmosphere, which is a symptom of moisture content.

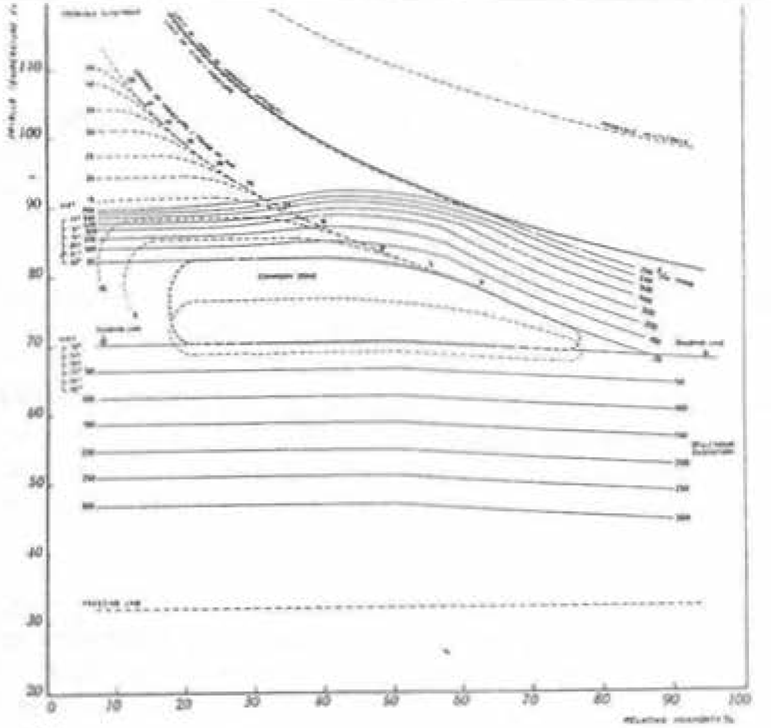
2.1 Graphic representation

The relationship of climate and comfort can be examined graphically. Architects tend to think in visual terms. This is probably the reason for Olgyay's *bioclimatic chart* becoming so generally accepted (Fig.2.1). Olgyay (1953) was the first to relate climate to comfort in graphic form. His chart is simply temperature on the vertical scale and relative humidity on the horizontal one. The aerofoil-shape in the middle delineates the range of acceptable conditions as the *comfort zone*.

This is valid for people engaged in sedentary activity and wearing 1 clo of clothing ('normal' business suit). The version shown is valid for moderate climates of the US, around 40° latitude. Olgyay suggested the following adjustments:

- the zone should be elevated by 1 K for every 12° latitude reduction
- the zone should be lowered by 0.6 K for every 0.1 clo added
- every 1 met (approx. 100 W) increase in activity level can be compensated by 2.5 K reduction in temperature.

Lines above the comfort zone elevate the upper comfort limit with the presence of air movement of various velocities and lines below the comfort zone show the lowered limits for increases of MRT above the DBT or for solar radiation received.



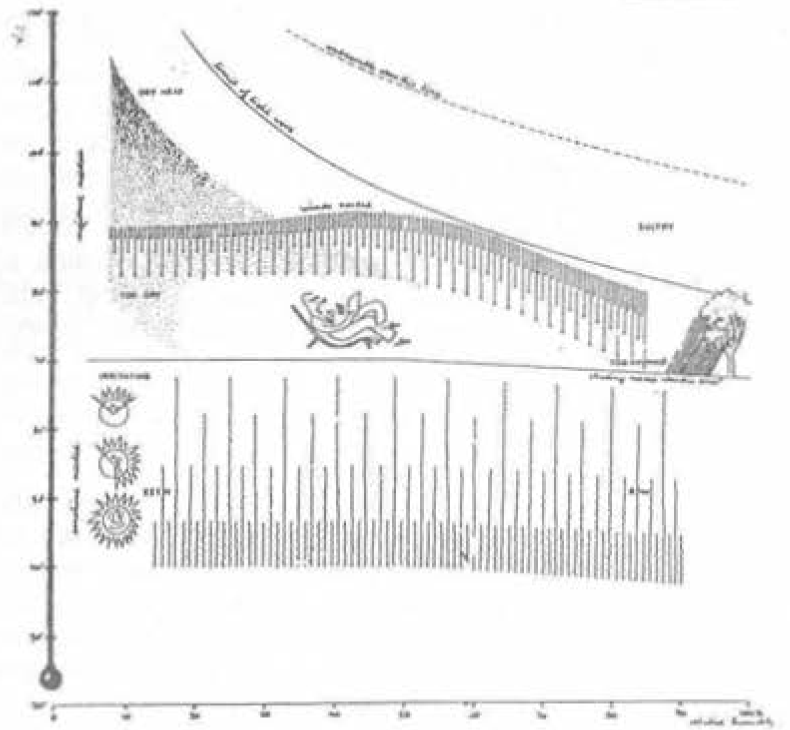


Fig.2.1 Olgyay's bioclimatic chart and its graphic explanation

The chart as shown describes the person/environment relationship to ensure comfort. It can then be extended to relate these requirements to the given climate, by plotting the climatic conditions on the same chart. This can be done several ways: if hourly temperature and humidity data are available, then each of the 8760 hours of the year can be represented by one dot. If only monthly mean data are available, then plot one point for the mean maximum temperature with the afternoon humidity and another for the mean minimum temperature with the early morning humidity. The line connecting the two points would indicate the range of average conditions for the month and the area around the 12 monthly lines would show the range of conditions for the year.

The position of this area relative to the comfort zone would indicate the control task and suggest some solutions (eg increased ventilation air flow when it is to hot, or utilising solar energy when it is too cold). Givoni (1969) used the psychrometric chart as the base of his 'building bioclimatic chart', for plotting the comfort zone and its extensions. Fig.2.2 shows an example of these.

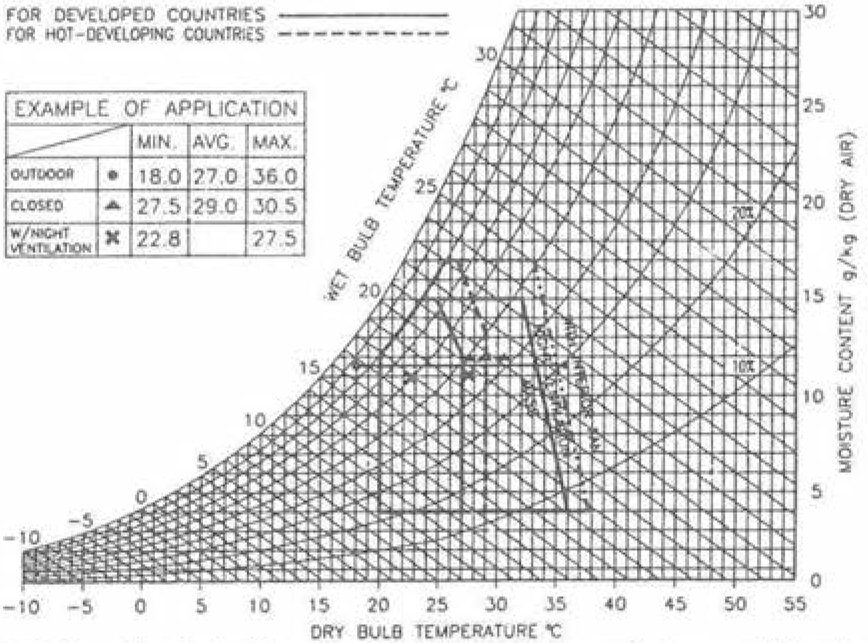


Fig.2.2 Givoni's 'building bioclimatic' chart with the comfort zone and its extension for nocturnal convective cooling (as revised in 1992), note the peculiar distinction between developed and developing countries

In 1979 Milne and Givoni contributed a chapter to Watson's book on *Climatic design*, further developing the method. Arens et al.(1980) revised the bioclimatic chart in the light of recent findings both in its original format and based on the psychrometric chart (Fig.2.3). Markus and Morris (1980) plotted over 50 'comfort charts' in psychrometric format, for various permutations of clothing, air velocity and activity level, showing the comfort zones for 70 and 80% of the population. Neither author used these charts to plot the climate.

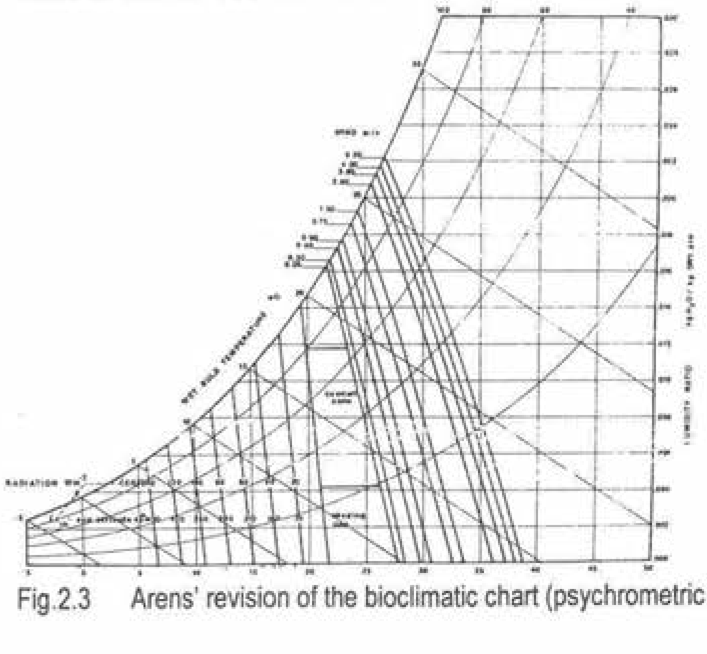


Fig.2.3 Arens' revision of the bioclimatic chart (psychrometric format)

Wooldridge (1979) plotted the coincident values of DBT and AH on the psychrometric chart by showing the number of hours per year in each cell of the chart when that condition occurred (Fig.2.4).

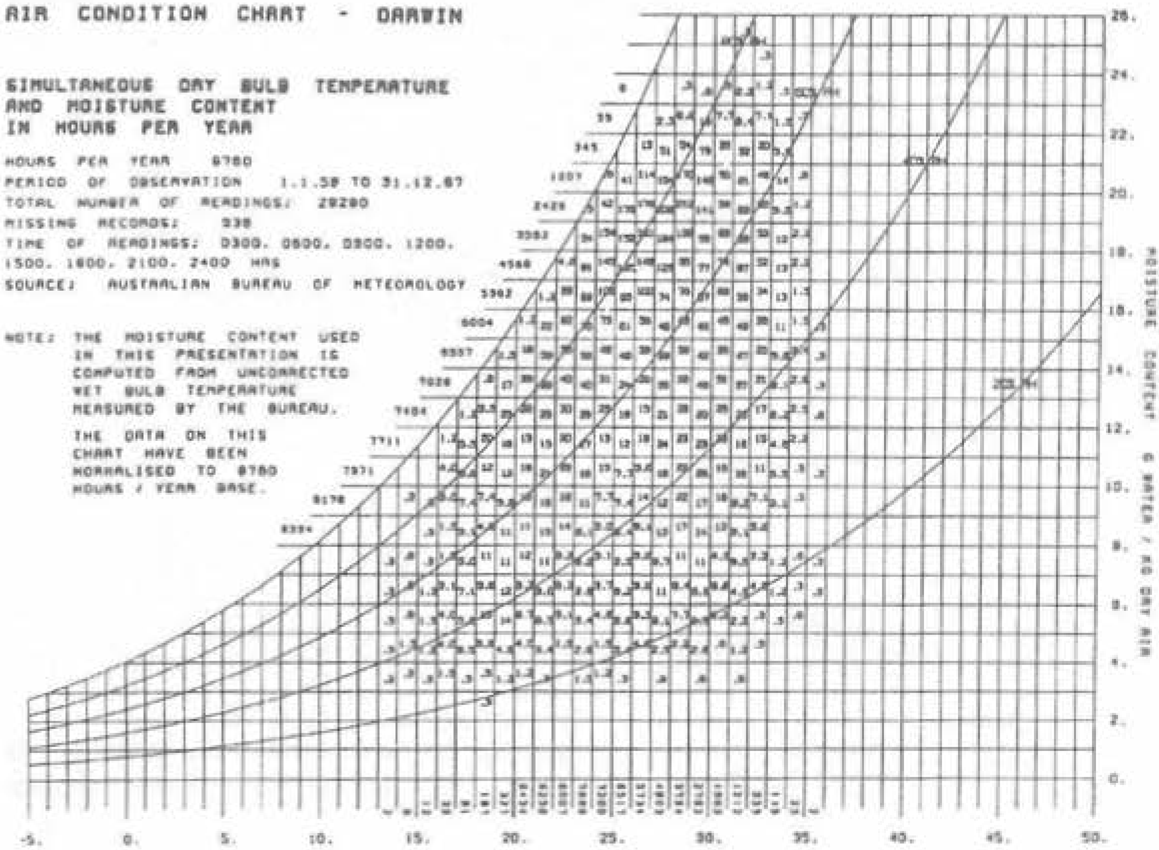


Fig.2.4 Coincident dry-bulb temperatures and moisture content plotted on the psychrometric chart (Wooldridge, 1979) in terms of hours per year

2.2 Limits of comfort

A well supported common-sense approach to comfort limits was proposed by Drysdale (1952):

- up to 27°C the DBT is the best measure of comfort
- above this humidity must be considered: add 1 K for each 10% increase in RH over 40%
- at the same time the cooling effect of air movement can be considered: subtract 1 K for each 0.15 m/s over (0.05 m/s), up to 1 m/s, but not beyond 37°C
- if the surface temperature of the ceiling or a wall exceeds 38°C then for every 5 K increase add 1 K. (If several surfaces exceed 38°C then repeat this for each surface).

The limits of comfort with respect to humidity conditions is by no means settled. In the past these were defined in terms of relative humidity, eg 20% and 80%. Some workers now suggest that the upper limits should be set in terms of wet bulb temperatures, eg 18°C WBT for winter and 20°C WBT for summer. In 1974 ASHRAE adopted the limits in terms of vapour pressure: 0.65 and 1.9 kPa (originally 5 mm and 14 mm Hg), which correspond to approximately 4 and 12 g/kg moisture content.

The argument for this is the following:

- cooling depends on evaporation of moisture from the skin
- evaporation rate is a function of vapour pressure difference
- the temperature of the skin is 33 - 34°C, thus the vapour pressure at the skin surface is practically constant, around 5.3 kPa
- thus the evaporation rate is primarily the function of vapour pressure in the immediate atmosphere.

This definition is rational, therefore it is adopted in the present work.

For temperature limits, until recently, the 'constancy theory' of comfort was dominant. This theory took a set of comfort limits to be applicable to all humans, anywhere, and did not recognise acclimatisation. Only recently was this proven to be untenable and the 'adaptive model' became widely accepted.

The *adaptive model* of thermal comfort expresses the *neutrality temperature** as a function of prevailing outdoor temperatures. We adopt the Auliciems (1981) correlation, which gives

Tn = 17.6 + 0.31 x To.av ... eq.2.1)

where To.av is the outdoor mean temperature of the month.
(with the proviso that 18 < Tn < 28)
the range of comfort can then be taken as from Tn-2 to Tn+2 °C.

2.3 The proposed method

The simplest way to compare comfort conditions with the given climate is to plot the monthly mean maximum and minimum temperatures across the 12 months, superimposing the comfort band, calculated as above. This can be supplemented by the 14th %-ile of the minima and the 86th %-ile of the maxima, as in Fig.2.5. Thus it is probable that for five days a week the temperatures will be between the two dotted lines.

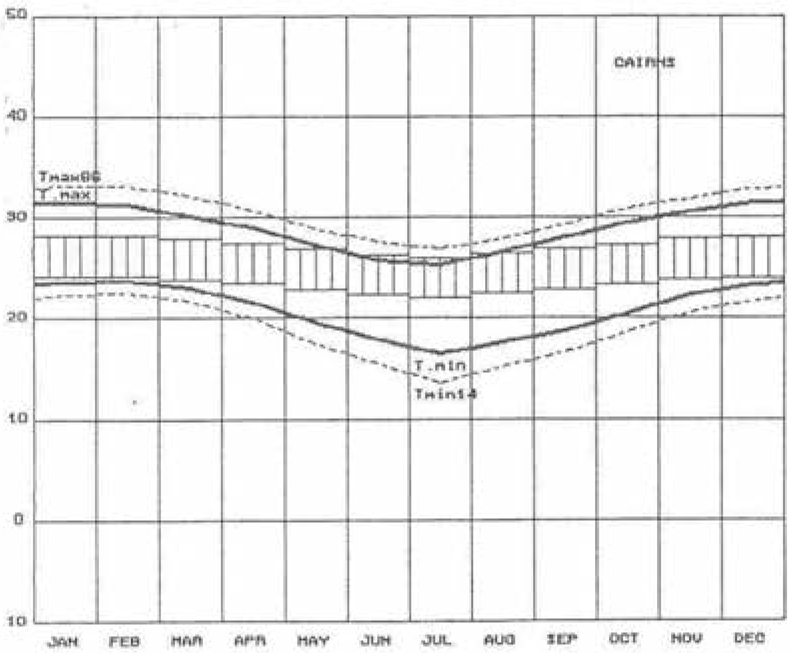


Fig.2.5 Temperature plot against the comfort band

* the group mean of individual preferences, neither too cold nor too warm, ie thermally neutral

This is however only to give an impression of the thermal problem. The main shortcoming of the method is that it does not consider humidity.

After studying the 26 measures of comfort listed in Appendix 2, the ET* (new effective temperature) scale for the measurement of comfort has been adopted. This coincides with the DBT at the 50% RH level. It recognises that at lower humidities a higher temperature will cause the same sensation, but at high humidities the temperature must be lower for the same thermal sensation. Appendix 3 shows the psychrometric chart with the ET* lines superimposed and Fig.2.6 shows a reduced scale version of the same. Up to 14°C these ET* lines coincide with the vertical DBT lines, but beyond this they show an increasing slope.

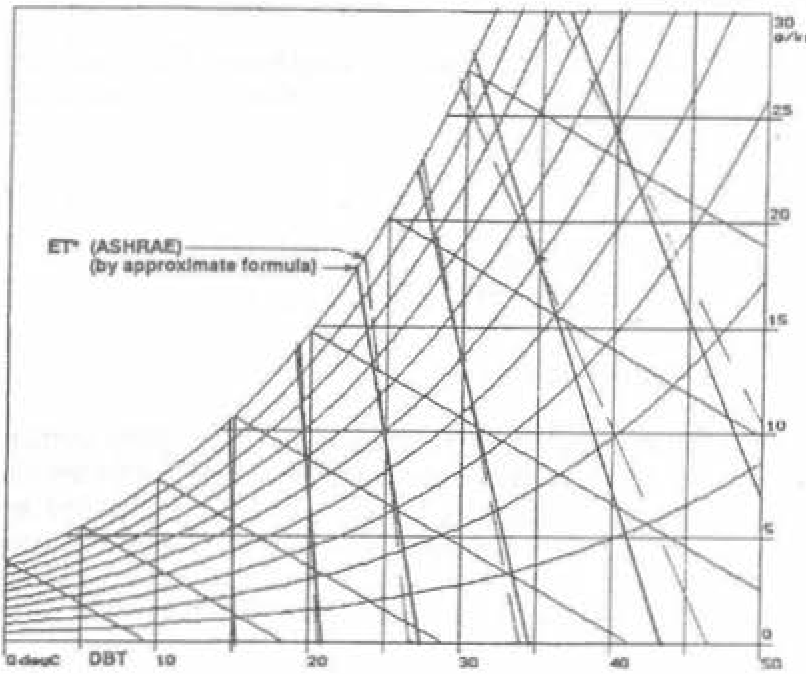


Fig.2.6 ET* lines on the psychrometric chart; regularised lines, the ASHRAE originals are shown by dashed lines (Szokolay 1981).

Thus the range of acceptable conditions (the comfort zone) for a given location can be defined by the following method:

1) take the mean temperature of the coldest month and find the neutrality temperature Tn from eq. 2.1
2) plot this on the 50% RH curve of the psychrometric chart and mark the limits 2 K below and 2 K above Tn
3) draw the ET* lines corresponding to these limits to form the side boundaries of the comfort zone

> the slope of the ET* lines is defined by the displacement (dT) of the horizontal axis intercept, for temperature T:
> $dT = 0.023 \bullet (T-14) \bullet AH_{T(50\%)}$
> eg for 30°C: $dT = 0.023 \bullet (30-14) \bullet 13$ g/kg $= 4.78$
> thus the axis intercept is $30 + 4.78 \approx 34.8$ °C

4) draw in the top and bottom humidity limits (horizontal lines) at the 12 g/kg and 4 g/kg levels. This completes the comfort zone for the coldest month.
5) repeat steps 1 to 4 for the warmest month of the year.

The climate can then be represented by 12 monthly lines plotted on the same chart by a method similar to that mentioned above for Olgyay's bioclimatic chart:

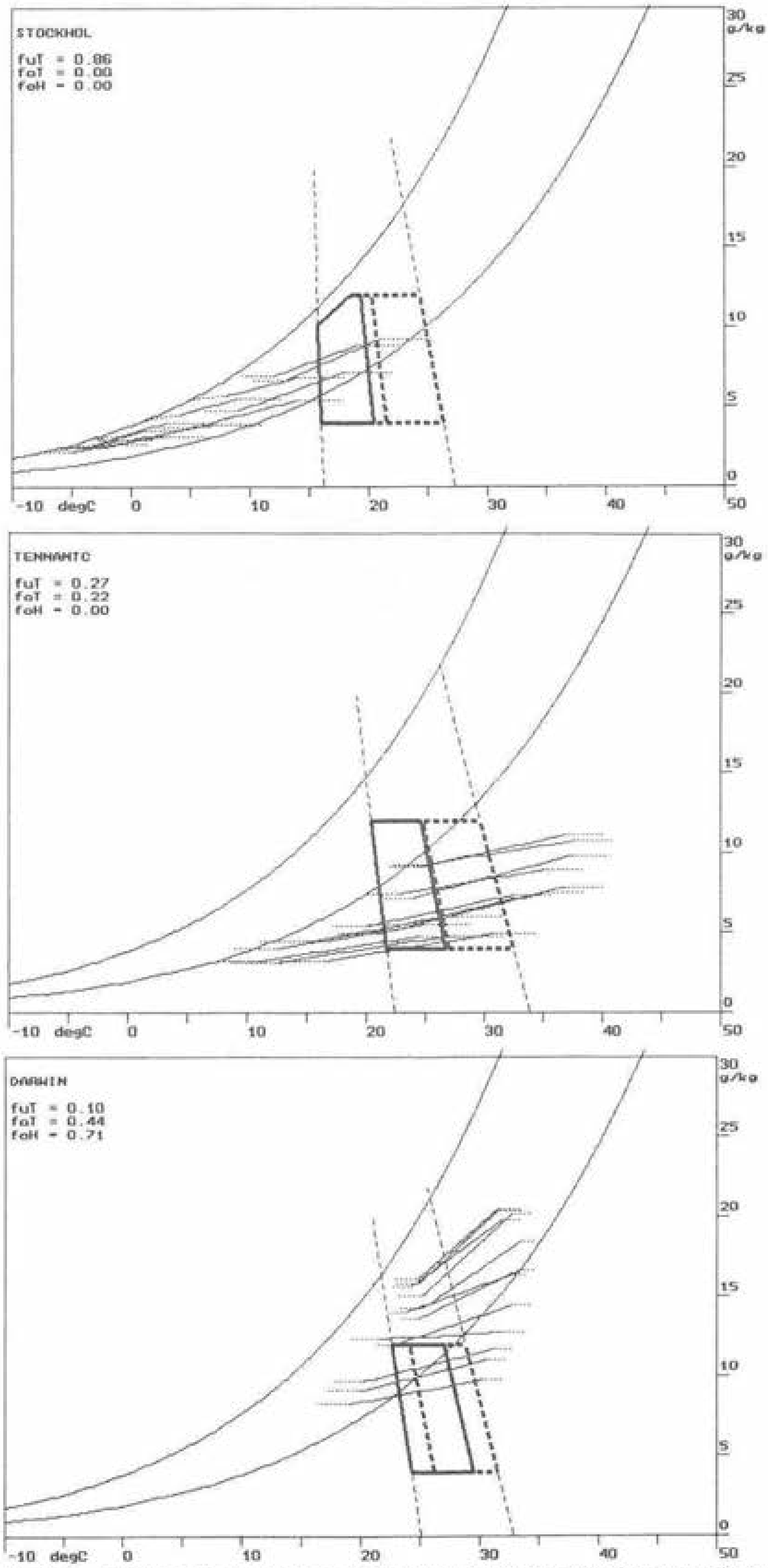


Fig.2.7 Winter and summer comfort zones vs climate plots for three climates (for clarity only the 50% and 100% RH curves are shown)

6) plot a point for the mean maximum temperature with the afternoon humidity
7) plot a second point for the mean minimum temperature with the morning humidity
8) connect the two points by a straight line
9) repeat steps 6 - 8 for each of the 12 months.

Fig.2.7 illustrates the position of summer and winter comfort zones compared with the climate plot for three different climates. The dotted line horizontal extensions to the climate lines extend up to the 86th %-ile of the temperature maxima and down to the 14th %-ile of the minima (14% of the week = one day, thus the former would be exceeded one day a week and the latter would not be exceeded one day a week)..

2.3.1 a quick assessment

The nature of the climatic problem can be quickly assessed by considering these 12 climate lines:

1) measure the aggregate length of the 12 lines
2) measure the length of lines below (to the left of) the lower winter comfort limit (**uT** in Fig.2.8), express this as a fraction of the total (1); this can be referred to as **fuT**, or fraction under-temperature
3) measure the length of lines above (to the right of) the upper summer comfort limit (**oT** in Fig.2.8) , express this as a fraction of the total (1); this will be the **foT**, or fraction over-temperature
4) measure the length of lines above the 12 g/kg humidity limit (**oH** in Fig.2.9), express this as a fraction of the total (1); this will be the **foH**, or fraction over-humid.

This method does not claim to be accurate, but these three non-dimensional numbers give a good indication of the nature of the climatic problem. The three numbers can be generated automatically (eg by the CLIMANAL module of the ARCHIPAK program) and a monthly breakdown can also be obtained. Compare the examples given in Figs.2.8 and 2.9. The former is obviously a hot-dry climate (foH = 0.03 and the long lines indicate large diurnal variations), whilst the latter is a warm-humid one (foH = 0.71, or 71%).

Note that the above definition of thermal neutrality (Tn) and the comfort zones are valid for still air conditions ($v<0.25$ m/s) and for people engaged in sedentary activities (1 – 1.2 met)*. For higher activity levels (eg some work places, sports facilities) the Tn should be lowered by 2.5 K for every met increase in metabolic rate (but not below 15°C), thus the comfort zone would be shifted to the left.

* the unit of metabolic rate: 1 met = 58 W/m^2 of body surface area or some 100 W for an average person

HALLSCRK

	fuT	foT	foH
1	0 %	54 %	21 %
2	0 %	50 %	19 %
3	0 %	40 %	0 %
4	13 %	20 %	0 %
5	41 %	0 %	0 %
6	63 %	0 %	0 %
7	69 %	0 %	0 %
8	51 %	0 %	0 %
9	26 %	10 %	0 %
10	0 %	37 %	0 %
11	0 %	50 %	0 %
12	0 %	54 %	0 %
Yr:	22 %	26 %	3 %

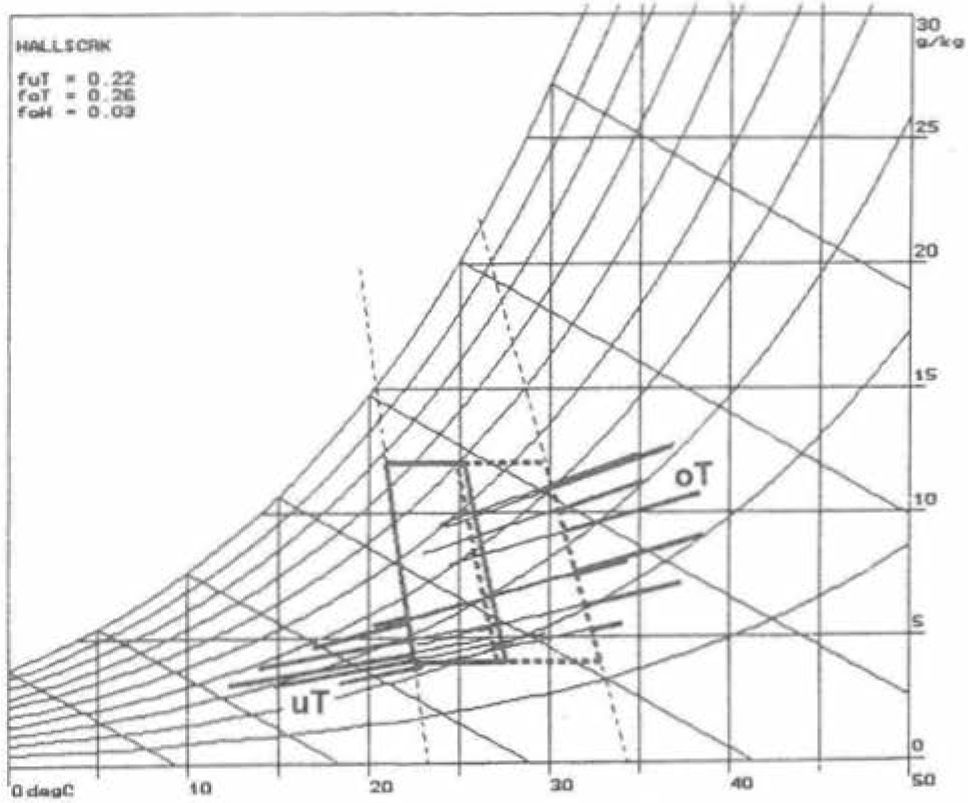


Fig.2.8 A hot-dry climate plot and the three indicators
Heavy lines indicate the uT (under-temperature) and oT (over-temperature) conditions

DARWIN

	fuT	foT	foH
1	0 %	69 %	100 %
2	0 %	68 %	100 %
3	0 %	63 %	100 %
4	0 %	55 %	100 %
5	9 %	31 %	100 %
6	30 %	12 %	0 %
7	38 %	5 %	0 %
8	26 %	18 %	0 %
9	0 %	44 %	99 %
10	0 %	64 %	100 %
11	0 %	70 %	100 %
12	0 %	72 %	100 %
Yr:	10 %	45 %	71 %

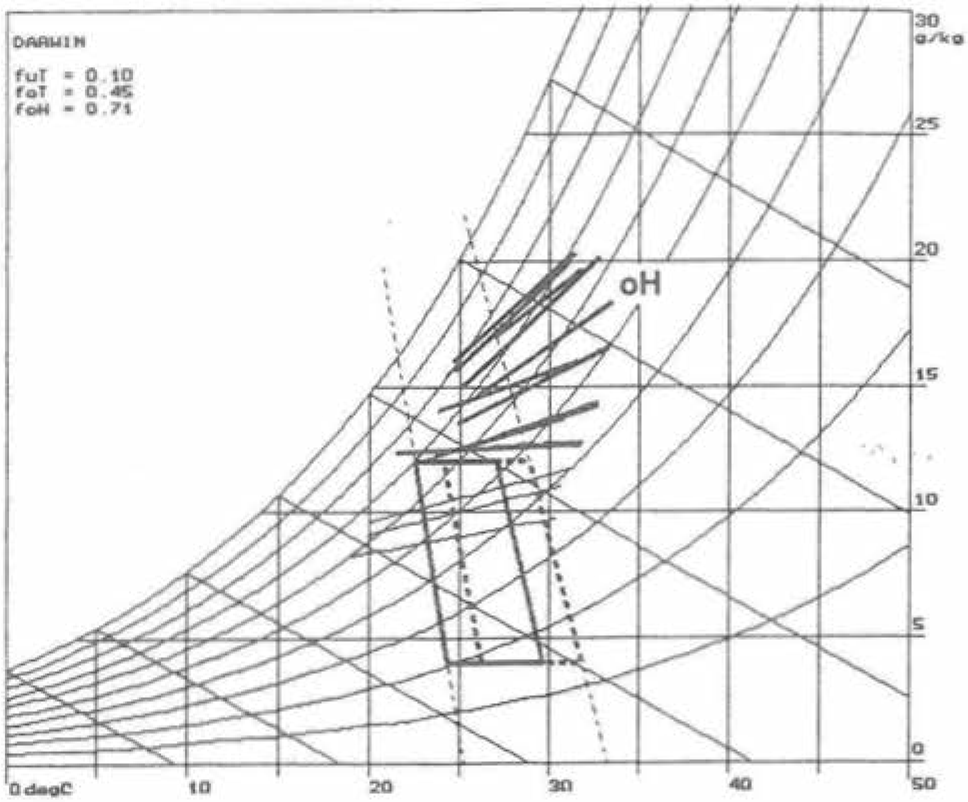


Fig.2.9 A warm-humid climate plot and the three indicators
Heavy lines indicate the oH (over-humid) conditions

CLIMATE ANALYSIS

location:

AMT [ ]

	J	F	M	A	M	J	J	A	S	O	N	D
1 relative humidity, am												
pm												
average												
humidity category												
2 temperature, mean max												
day comfort:upper												
lower												
thermal stress												
3 temperature, mean min												
night comfort:upper												
lower												
thermal stress												
4 monthly mean range												
5 rainfall over 150?												
6 diagnosis 1												
2												
3												
4												
5												
6												

HUMIDITY CATEGORIES

if RH	<30%	30-50	50-70	>70%
then:	1	2	3	4

COMFORT LIMITS

	AMT	humidity category 1	2	3	4
day	> 20	26-33	25-30	23-28	22-27
	15-20	23-31	22-29	21-27	20-25
	< 15	21-30	20-27	19-26	18-24
	AMT	1	2	3	4
night	> 20	17-25	17-24	17-23	17-21
	15-20	14-23	14-22	14-21	14-20
	< 15	12-21	12-20	12-19	12-18

IF stress day	n't	rain	humid. categ.	mean range	THEN
H			4		1
H			2,3	<10°	1
O			4		2
		>150			3
			1,2,3	>10°	4
	H		1,2		5
H	O		1,2	>10°	5
C					6

indicator totals 1	2	3	4	5	6

	1	2	3	4	5	6		
LAYOUT				0 - 10			1	orientation N and S (long axis E - W)
						5 - 12		
				11, 12		0-4	2	compact courtyard plan
SPACING	11,12						3	open spacing for breezes
	2 - 10						4	as 3, but wind protection
	0, 1						5	compact estate layout
AIR MOVEMENT	3 - 12						6	single banked rooms, for permanent air movement
	1, 2			0 - 5				
				6 - 12			7	double banked rooms, for temporary air movement
	0	2 - 12						
		0, 1					8	no air movement required
OPENING SIZES				0, 1		0	9	large: 50 - 80%
						1 - 12	10	medium: 30 - 50%
				2-5				
				6 - 10			11	small: 20 - 30%
				11,12		0-3	12	very small: 10 - 20%
						4 - 12	13	medium: 30 - 50%
OPENING POSITION	3 - 12						14	in N and S walls, at body height on windward side
	1-2			0-5				
				6 - 12			15	as 14, but openings also in internal walls
	0	2 - 12						
PROTECTION OF OPENINGS						0-2	16	full permanent shading
			2 - 12				17	rain protection
WALLS AND FLOORS				0-2			18	light, low capacity
				3-12			19	heavy, over 8 h time lag
ROOFS	10-12			0-2			20	light, reflective, cavity
				3-12			21	light, well insulated
	0-9			0-5				
				6 -12			22	heavy, over 8 h time lag
EXTERNAL FEATURES					2 - 12		23	outdoor sleeping area
			3 - 12				24	ample rainwater drainage

Fig.3.1 The modified Mahoney climate analysis table

3 PASSIVE CONTROLS

The ideal solution for the designer would be to achieve comfortable indoor conditions by passive controls alone, but even if no such solution is found, these passive controls - in most cases - could work together with active controls (heating/cooling systems) and significantly reduce the energy requirement. Two systems of analysis will be described: the first produces design advice, the second assists in selecting the appropriate passive control strategy.

3.1 Mahoney tables

One method, developed by Carl Mahoney and first published by the UN: (Koenigsberger et al. 1971) compares climatic data with an empirically established set of comfort limits and translates the results into design recommendations. Fig.3.1 shows a modified version: the original four tables combined into one (Szokolay, 1982).

Before starting, calculate the annual mean temperature (AMT) either as the average of the 24 numbers (monthly mean maxima and minima), or if the 12 monthly means are given, then the average of these. Enter this in the first box.

In **section 1** enter the relative humidity am and pm values and calculate the average for each month (if the averages are given, these can be entered directly into the third line). With reference to the "Humidity categories" table (top right) establish the humidity category for each month ('1' is very dry and '4' is very humid).

In **section 2** enter the mean maximum temperature for each month. From the "Comfort limits" table find the daytime limits according to the AMT (first column, three bands) and the humidity category (in the heading) and enter these in the following two lines. Find the thermal stress for each month: if the mean max. is above the limits, enter 'H' (hot) in the last line; if it is within the limits, enter '0' (no stress) and if it is below the limits, enter 'C' (cold).

In **section 3** repeat the above, entering the mean minima and comparing these with the night-time comfort limits.

In **section 4** enter the mean range of temperatures for each month, ie the differences between the first line values in sections 2 and 3 (MeanMax - MeanMin).

In **section 5** tick the month when the rainfall is greater than 150 mm.

In **section 6**: diagnosis, there are 6 lines for the 6 "indicators", which are selected according to the "IF - THEN" table on the right. All conditions in any one line must be satisfied to qualify for the indicator shown in the last column. Each month may have one or more indicators: tick the box on the line corresponding to the indicator number. When completed, count the ticks in each line and enter the number into the end-box. Transfer these numbers into the boxes labelled "indicator totals", which is the heading for the second half of the table. Advice will be produced in this table under 9 headings: from LAYOUT to EXTERNAL FEATURES.

CLIMATE ANALYSIS

location:
CAIRNS

AMT **24.7**

	J	F	M	A	M	J	J	A	S	O	N	D	
1													
relative humidity, am	71	75	78	76	75	74	72	70	65	64	64	66	
pm	62	65	65	63	62	59	56	54	52	53	57	59	
average	66.5	70	71.5	69.5	68.5	66.5	64	62	58.5	58.5	60.5	62.5	
humidity category	3	4	4	3	3	3	3	3	3	3	3	3	
2													
temperature, mean max	31.4	31.3	30.1	29	27.3	25.8	25.3	26.6	28	29.4	30.6	31.4	
day comfort: upper	28	27	27	28	28	28	28	28	28	28	28	28	
lower	23	22	22	23	23	23	23	23	23	23	23	23	
thermal stress	H	H	H	H	O	O	O	O	O	H	H	H	
3													
temperature, mean min	23.5	23.7	23	21.5	19.6	17.8	16.5	17.6	18.8	20.5	22.4	23.3	
night comfort: upper	23	21	21	23	23	23	23	23	23	23	23	23	
lower	17	17	17	17	17	17	17	17	17	17	17	17	
thermal stress	H	H	H	O	O	O	C	O	O	O	O	H	
4													
monthly mean range	7.9	7.6	7.1	7.5	7.7	8	8.8	9	9.2	8.9	8.2	8.1	
5													
rainfall over 150?	✓	✓	✓										
6													
diagnosis 1	✓	✓	✓	✓						✓	✓	✓	7
2													
3	✓	✓	✓	✓								✓	5
4													
5													
6													

HUMIDITY CATEGORIES

if RH	<30%	30-50	50-70	>70%
then:	1	2	3	4

COMFORT LIMITS

	AMT	humidity category 1	2	3	4
day	> 20	26-33	25-30	23-28	22-27
	15-20	23-31	22-29	21-27	20-25
	< 15	21-30	20-27	19-26	18-24
	AMT	1	2	3	4
night	> 20	17-25	17-24	17-23	17-21
	15-20	14-23	14-22	14-21	14-20
	< 15	12-21	12-20	12-19	12-18

IF stress day	n't	rain	humid. categ.	mean range	THEN
H			4		1
H			2,3	<10°	1
O			4		2
		> 150			3
			1,2,3	>10°	4
	H		1,2		5
H	O		1,2	>10°	5
C					6

indicator totals					
1	2	3	4	5	6
7	0	5	0	0	0

	1	2	3	4	5	6	✓	No.	
LAYOUT				0 - 10			✓	1	orientation N and S (long axis E - W)
						5 - 12			
				11, 12		0-4		2	compact courtyard plan
SPACING	11,12							3	open spacing for breezes
	2 -10						✓	4	as 3, but wind protection
	0,1							5	compact estate layout
AIR MOVEMENT	3 - 12						✓	6	single banked rooms, for permanent air movement
	1, 2			0 - 5					
				6 - 12				7	double banked rooms, for temporary air movement
	0	2 - 12							
		0,1						8	no air movement required
OPENING SIZES				0,1		0	✓	9	large: 50 - 80%
						1 - 12		10	medium: 30 - 50%
				2-5					
				6 - 10				11	small: 20 - 30%
				11,12		0-3		12	very small: 10 - 20%
						4 - 12		13	medium: 30 - 50%
OPENING POSITION	3 - 12						✓	14	in N and S walls, at body height on windward side
	1-2			0-5					
				6 - 12				15	as 14, but openings also in internal walls
	0	2 - 12							
PROTECTION OF OPENINGS						0-2	✓	16	full permanent shading
			2 - 12					17	rain protection
WALLS AND FLOORS				0-2			✓	18	light, low capacity
				3 - 12				19	heavy, over 8 h time lag
ROOFS	10-12			0-2				20	light, reflective, cavity
				3 - 12			✓	21	light, well insulated
	0-9			0-5					
				6 - 12				22	heavy, over 8 h time lag
EXTERNAL FEATURES					2 - 12			23	outdoor sleeping area
			3 - 12				✓	24	ample rainwater drainage

Fig.3.2 A worked example of climate analysis

Scan this table from left to right. When the indicator total in the heading corresponds to the number or falls between the number limits encountered, then place a tick into the empty box at the end, next to the serial number of specification statements. All conditions encountered on a line must be satisfied to qualify for that specification item. Each of the 9 sections can only have one item ticked, it will be the first one encountered when scanning line-by-line and left to right. If there is no tick in a section, then that section is N/A (not applicable). When the first coincidence embraces two lines of specification, then continue to the right, the next coincidence will select the appropriate specification statement. (Note: window percentages refer to the wall area).

The specification statements ticked will constitute the design recommendations. Note however, that these are valid for warm climates. If the AMT is below 18°C, the advice given may be misleading. Fig.3.2 is the same climate analysis table, showing a worked example.

Several computerised versions of this system exist, including a module of the ARCHIPAK program, which reads the climatic data for the nominated location from a data-base and automatically produces the recommendations, such as those shown in Fig.3.3. The analysis itself (the 'diagnosis') can be printed out optionally, such as that shown in Fig.3.4. Note that here '+' means 'H' and '-' means 'C'.

RECOMMENDATIONS for CAIRNS

Layout :	orientation: north-south (long axis east-west)
Spacing:	open spacing to allow for breezes
Air movement :	single banked rooms for full cross-ventilation
Opening sizes:	large : 50-80% of wall surface
Opening position:	in N and S walls, at body level on windward side
Opening protection:	full permanent shading
	rain protection is required
Walls and floors :	lightweight, of low thermal capacity
Roof construction:	lightweight, well insulated
External features:	adequate rainwater drainage is important

Fig.3.3 Printout of the climate analysis program based on the Mahoney tables

Climate analysis for CAIRNS AMT= 24.7

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean range(K):	7.9	7.5	7.2	7.5	7.6	7.9	8.8	9.0	9.2	8.9	8.3	8.1
Humidity cat.:	3	4	4	3	3	3	3	3	3	3	3	3
Day up. limit:	28.0	27.0	27.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
Day low limit:	23.0	22.0	22.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Mean max.temp:	31.4	31.3	30.1	29.0	27.3	25.8	25.3	26.6	28.0	29.4	30.6	31.4
Day-stress :	+	+	+	+	0	0	0	0	0	+	+	+
Night up.lim.:	23.0	21.0	21.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0	23.0
Night low lim:	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Mean min.temp:	23.5	23.7	23.0	21.5	19.6	17.8	16.5	17.6	18.8	20.5	22.4	23.3
Night-stress:	+	+	+	0	0	0	-	0	0	0	0	+
Indicator tot:	*1= 7		*2= 0		*3= 5		*4= 0		*5= 0		*6= 0	

Fig.3.4 The 'diagnosis' part - an optional printout

3.2 Control strategies

The possible passive thermal control strategies can be summarised as follows:

For underheated conditions:
- passive solar heating
- mass effect: thermal storage

For overheated conditions:
- mass effect: thermal storage
- same with night ventilation
- air movement effect
- evaporative cooling
- indirect evaporative cooling.

Now the task is to delineate the range of outdoor conditions under which the particular control strategy could ensure indoor thermal comfort, or in other words: define the zone of outdoor temperatures and humidities within which the particular control strategy has the potential of creating acceptable indoor conditions. We will refer to this as the *control potential zone*, or **CPZ**. (Szokolay 1986).

It will be a separate task to examine how such potential can be realised, how such a strategy can be translated into an actual design.

3.2.1 passive solar heating

The main determinant of the success of this strategy is the global solar irradiation available on a correctly oriented (equator-facing) vertical window (Hv). We take the worst case: the coldest month. Climatic data usually gives the average day's horizontal irradiation (Hh). Hv may be obtained from another source or by using another program, but the method given in Appendix 5 may also be used for finding the Hv value from a given Hh.

At this pre-design analysis stage there is no design proposal yet, so the following estimate is based on a hypothetical 100 m^2 house, with 20% (20 m^2) solar aperture (window or solar wall) facing the equator and we assume an overall system efficiency (or utilisability) of $\eta = 0.6$. A well-designed house, with good insulation is assumed, so the envelope conductance is taken as 100 W/K, with 40 W/K ventilation- (infiltration-) conductance.

Thus the critical building parameter assumptions are

- solar aperture $Aw = 20\ m^2$
- system efficiency $\eta = 0.6$
- building conductance $q = 140$ W/K

where $q = qc + qv$
qc (envelope conductance) $= \Sigma(A \bullet U)$ for all elements of the envelope
qv (ventilation conductance) $= 0.33 \bullet N \bullet V$
N = number of air changes per hour, V = volume of building in m^3

Tn is the 'neutrality temperature' calculated from equation 2.1 for the coldest month, but any intended indoor design temperature can be substituted. If the lower limit of comfort is T_L = Tn - 2 then the condition of success is that

daily useful gain	=	daily heat loss	
$Hv \bullet Aw \bullet \eta$	=	$q \bullet (T_L - To) \bullet 24$	... eq.3.1)
$Hv \bullet 20 \bullet 0.6$	=	$140 \bullet (T_L - To) \bullet 24$	

from which the limiting value of To (the lowest outdoor temperature at which the heat loss can be compensated by the solar gain) can be expressed as

$$To = T_L - 0.0036 \bullet Hv \qquad \text{... eq.3.2)}$$

{ here the coefficient 0.0036 is

$$\frac{20m^2 \bullet 0.6}{140W/K \bullet 24h} = \frac{12m^2}{3360Wh/K} = 0.0036m^2K/Wh$$

and this, multiplied by Hv in Wh/m^2 will give the dimension K which can be subtracted from the T_L °C }

This algorithm is built into the CLIMANAL module of the ARCHIPAK program (giving two To boundaries, for efficiency η = 0.5 and 0.7). It is however useful to remember that, if any of the above building parameters are known and differ from those assumed, these can be substituted into eq. 3.1 and a different coefficient produced

Fig 3.5 is a printout of the above program and shows that with 0.5 efficiency the passive solar heating CPZ extends down to 7.3°C and with η = 0.7 this limit becomes 3.4°C.

(in this example Tn =19.3°C, thus T_L = 17.3°C, Hv = 3315 and the coefficients are 0.003 for η = 0.5 and 0.0042 for η = 0.7)

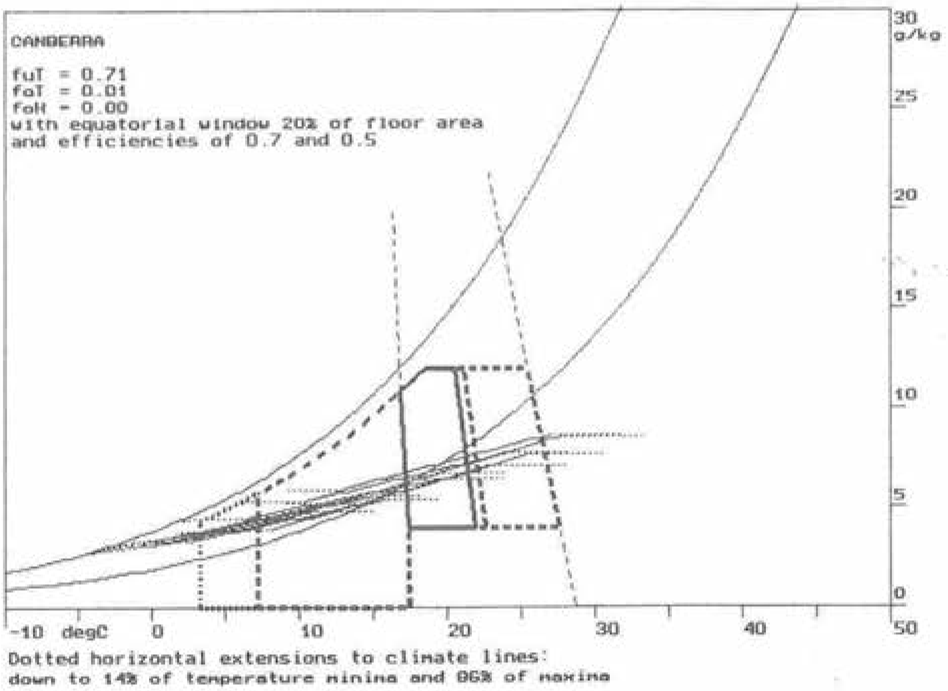


Fig.3.5 The comfort zones and passive solar heating CPZ for Canberra

3.2.2 mass effect

Winter:
If the diurnal range of temperatures is dT and the mean is To.av, then the outdoor varies between To.av-0.5•dT and To.av+0.5•dT. In a building of very high mass the Ti will be constant and equal to the To.av (in the absence of solar and internal gain). If the lower limit of comfort is T_L, then comfort can be maintained as long as the outdoor temperature does not fall below T_L - 0.5•dT. In order to allow for less than perfect heat transfers, we set the limiting value of outdoor temperature as

$To = T_L - 0.4 \bullet dT$ ... eq.3.3)

Summer:
The winter limit was measured downwards from the lower limit of the winter comfort zone. The summer limit will be measured upwards from the upper limit of the summer comfort zone. Otherwise the argument is the same as above. There is however a major difference: in the summer the solar radiation effects would seriously reduce the effectiveness of this mechanism, therefore the coefficient is substantially smaller than the above. Thus, if the upper comfort limit is T_U = Tn + 2, then the outdoor temperature limit will be taken as

$To = T_U + 0.25 \bullet dT$ ... eq.3.4)

With overnight ventilation the building fabric would cool down to near the minimum temperature of the day, thus the upper limit of outdoor temperature could be T_U + dT, but allowing for less than full equalisation of fabric temperatures, and the solar effects mentioned, the limit is set as

$To = T_U + 0.45 \bullet dT$ ... eq.3.5)

These limits of the mass effect CPZ will be marked on the 50% RH curve, and the corresponding new effective temperature (denoted ET*) line is the boundary of the CPZ. An example printout is shown in Fig.3.6.

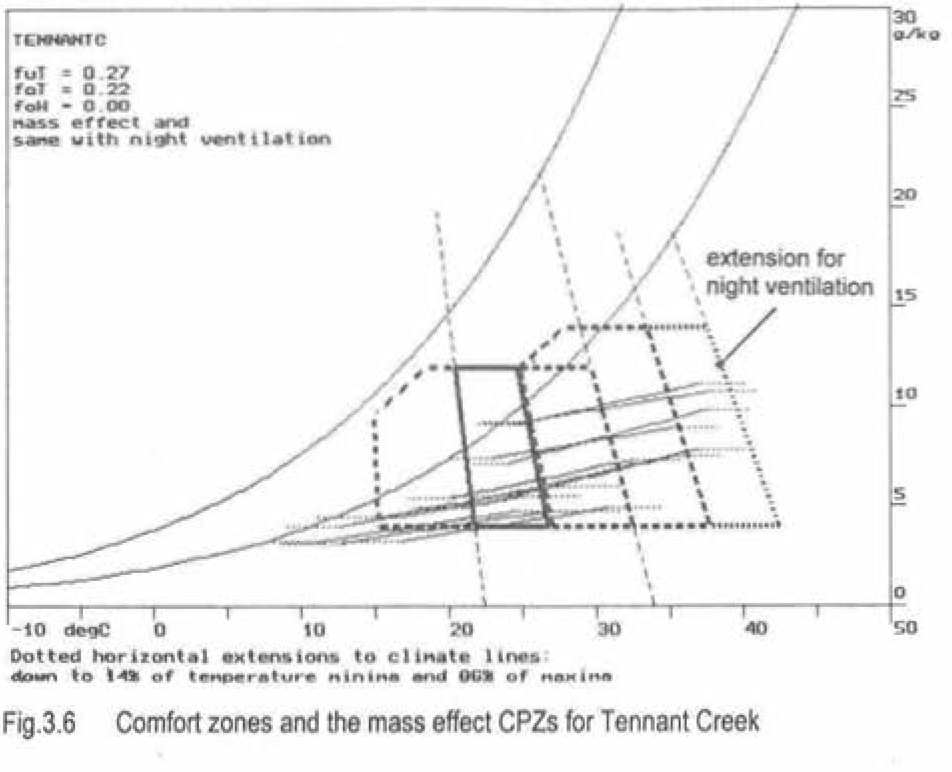


Fig.3.6 Comfort zones and the mass effect CPZs for Tennant Creek

3.2.3 air movement effect

Air movement at the body surface has a cooling effect even when the air is warmer than the skin (up to about 38°C), by accelerating the evaporation of perspiration or diffusing moisture. Many (some very complex) methods have been proposed for the calculation of this cooling effect, but the best simple approximation under average conditions is

$dT = 6 \bullet (v-0.2) - (v-0.2)^2$ for up to v=2 m/s ... eq.6)
where v is the air velocity in m/s (up to 0.2 m/s it is unnoticeable)

The practical limit is about 1.5 m/s as above this secondary, annoyance effects may occur. We look at the CPZ for at least two air velocities:
for 1 m/s: $dT_1 = 6 \bullet 0.8 - 0.8^2 = 4.2$ K
for 1.5 m/s: $dT_2 = 6 \bullet 1.3 - 1.3^2 = 6.1$ K

These dT values will be added to the upper comfort limit in terms of ET*, ie along the 50% RH curve. Upwards from this point the CPZ boundary follows the slope of the corresponding ET* line, but below this the slope is steeper: the x-axis intercept displacement is halved, as in dry air there is unhindered evaporation even without air movement, so the extra cooling due to this is not so pronounced.

For example, in Darwin the January To.av is 28.3°C thus
$Tn = 17.6 + 0.31 \bullet 28.3 = 26.4$°C
the upper comfort limit is 28.4°C
for 1 m/s: limiting ET* = 28.4 + 4.2 = 32.6°C
the AH at 50% RH at this temperature is 16 g/kg
intercept = $32.6 + 0.5 \bullet [0.023 \bullet (32.6-14) \bullet 16]$ = 36.0°C
for 1.5 m/s: limiting ET* = 28.4 + 6.1 = 34.5°C
the AH at 50% RH at this temperature is 18 g/kg
intercept = $34.5 + 0.5 \bullet [0.023 \bullet (34.5-14) \bullet 18]$ = 38.7°C
Fig.3.7 shows the CPZ boundaries for this example.

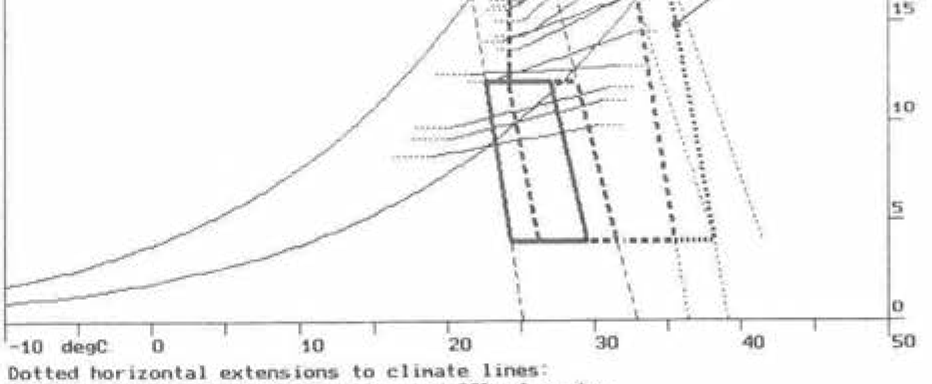


Fig.3.7 Comfort zones and the air movement CPZs for Darwin

3.2.4 evaporative cooling effect

The definition of the evaporative cooling CPZ is based on the following considerations:

Evaporation is an endothermic process, it absorbs heat from its surroundings, from the atmosphere. The DBT and the sensible heat content are reduced, but the addition of water vapour increases the latent heat content. In other words: adiabatic cooling converts sensible heat to latent heat. The "status point" will move upwards and to the left, along a WBT (wet bulb temperature) line.

It is then logical to follow this process backwards: if the resulting air condition is to be within the comfort zone, we can take the WBT lines tangential to diagonally opposite corners of the comfort zone as boundaries of the CPZ, embracing the air conditions to be cooled by the system.

The upper temperature limit, as measured from the thermal neutrality in DBT terms is determined by practical considerations, such as air flow rates and evaporation effectiveness. We adopt the limiting temperature as (Tn + 12)°C

3.2.5 indirect evaporative cooling

Direct evaporative cooling is very effective in a dry atmosphere. Higher humidities would limit the cooling potential and the addition of moisture would also result in unacceptably high humidities.

In the indirect system one fan-driven air stream (eg the exhaust air) is cooled evaporatively and this would cool the supply air stream indirectly, through a heat exchanger (either a rotary or a plate type), without mixing the two air streams and without adding moisture to the supply air.

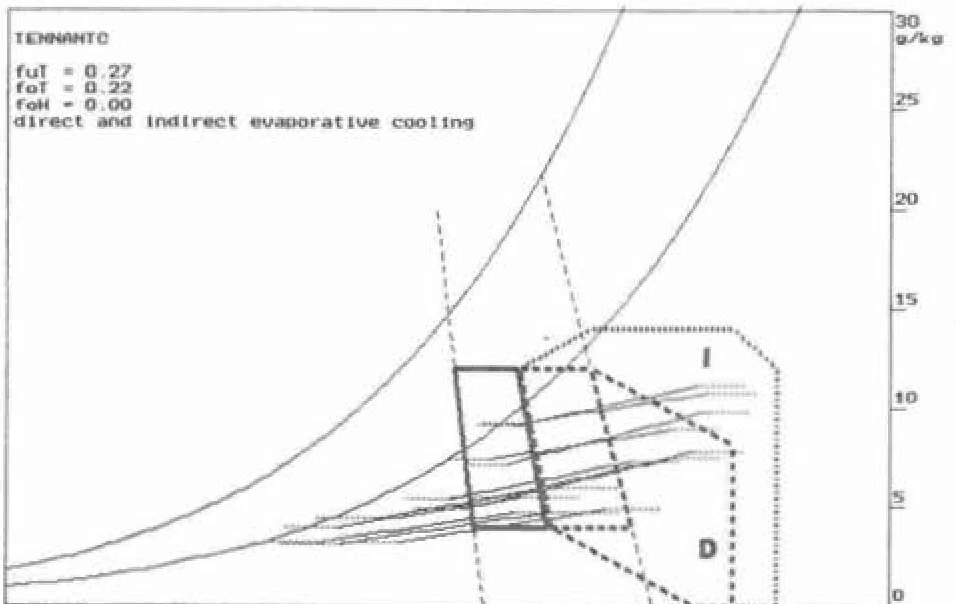


Fig.3.8 CPZs for direct (D) and indirect (I) evaporative cooling

Fig.3.9 shows a system diagram and Fig.3.10 is a cut-away view of a commercially available packaged unit.

The cooled (and then discarded) air stream can approach saturation, thus the sensible cooling is greater than with a direct system. The upper limit is set as (Tn + 15)°C. The upper humidity limit is set at 14 g/kg. The work of Wooldridge et al (1976) and Pescod (1976) suggests that the high humidity / high temperature corner should be rounded off, mainly for practical reasons.

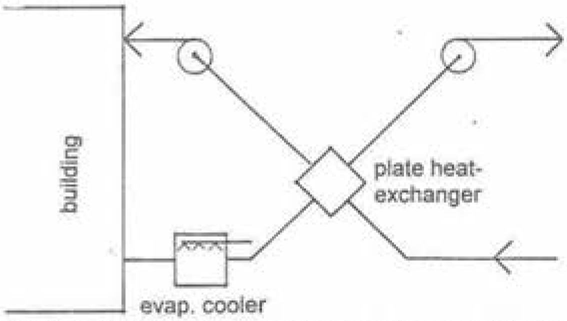


Fig.3.9 An indirect evaporative cooling system diagram

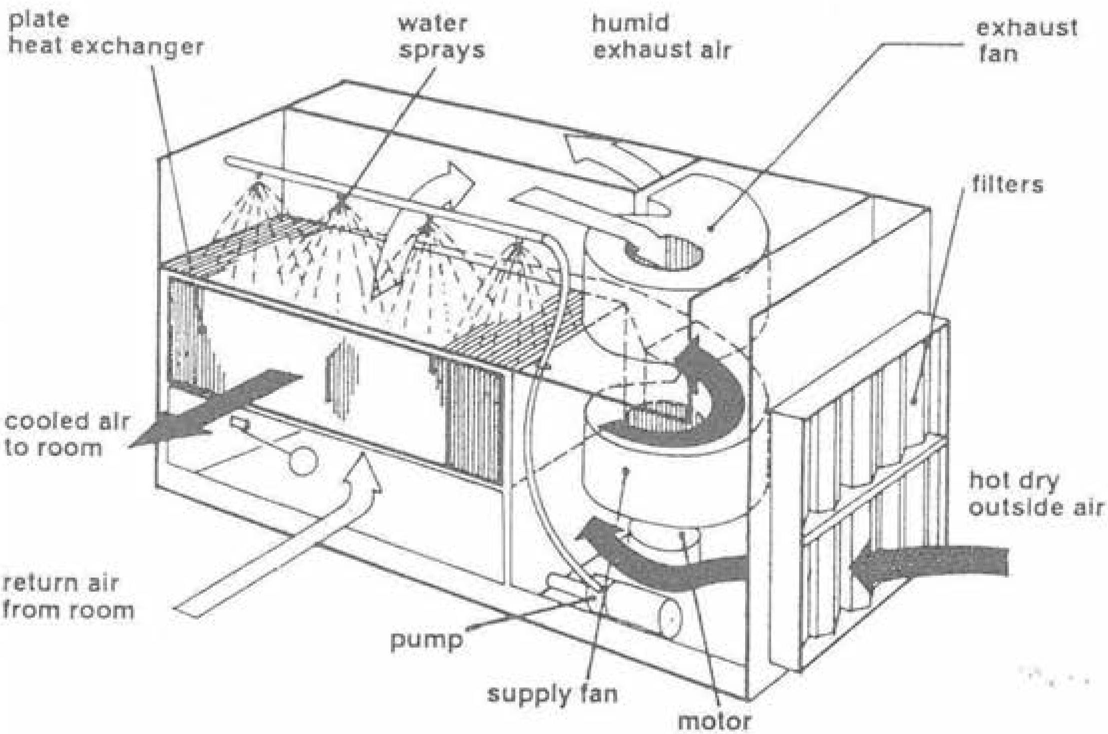


Fig.3.10 An indirect evaporative cooler packaged unit

3.3 Passive solar heating systems

If the previous section was about the selection of the design strategy most likely to succeed in a given climate, then the topic of the following sections is the tactics of climatic design, ie an examination of how the chosen strategy can be translated into an actual building.

In cold climates, or climates with a cold season the task is
1) to reduce heat losses
2) to make use of solar radiation for heating.

3.3.1 heat losses

Heat loss can be of two kinds:

- conduction through the enclosing elements of the building, ie the *envelope load*
- by ventilation, ie by the replacement of warm internal air by fresh cold air from the outside, ie the *ventilation load*; this would include both the deliberate ventilation (for fresh air supply, removal of odours and contaminants) and the incidental infiltration due to a "leaking" building.

This heat loss is – to some extent – counterbalanced by internal, incidental heat gains (heat output of human bodies, of the lighting system and of various appliances). A term used in air conditioning is *internal load*.

The thermal behaviour of residential buildings is normally dominated by the envelope load, but in offices, commercial buildings or in places of assembly the internal load is often dominant. In such cases, even in winter, the task may be to increase heat dissipation if overheating is to be avoided. The following discussion relates to envelope-load-dominated, especially residential buildings.

Envelope heat losses can be reduced by

1) minimising the envelope area, ie the surface of contact between the indoor space and the outdoor environment; this means the design of a compact building, the smallest possible surface-to-volume ratio, ideally the hemispherical Eskimo igloo.

2) thermal insulation of envelope elements, walls, roofs and floors (a subject discussed in PLEA Note No.2: *Thermal insulation*), the use of moveable (night-) insulation of windows, the use of double glazing or other innovative glazing systems. Windows are generally the weakest points of the envelope and, the colder the climate, the more attention should be paid to windows. Single glazing produces a heat loss some six times greater than a reasonable solid wall. Using a sealed double glazing unit, with a well-made frame would halve the heat loss, but modern window systems, with low-e (low emittance) coating, with evacuated double (or multiple) glazing and an insulated frame or one incorporating a thermal break can reach the same U-value as the average wall.

3) reduction of infiltration by

a) airtight envelope construction, with special attention to joints between dissimilar elements (eg window frame and wall)

b) providing air-lock type entries to avoid sudden blasts of cold air every time the door is opened

4) keeping ventilation to the lowest level required for health reasons (usually specified by regulations or standards).

3.3.2 passive solar heating design

Many books and publications are devoted to passive solar heating systems, with various classifications of such system types. In our view every house is a solar house, every window is a **direct gain system**, provided that it has the right orientation. One of the pioneers of climatic design said once that there are three important factors:
1) orientation, 2) orientation and 3) orientation.

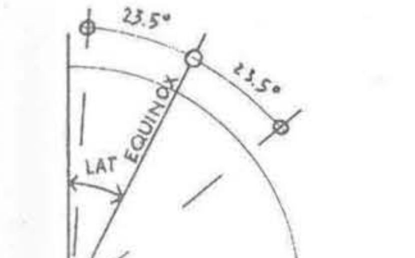


Fig.3.11 Equinox cut-off shading for a north-facing window (Brisbane, Lat: -27°)

Outside the tropics the best orientation is that facing the equator (ie north in the southern hemisphere and south in the northern half of the globe). The reason for this is two-fold:

- a surface with equatorial orientation receives the most solar radiation in winter (with low solar altitude angles) when this heat is most needed
- this is the only orientation where a simple fixed horizontal shading device (a canopy, or awning or just the overhanging eaves) would give an automatic seasonal adjustment (Fig.3.11). The example shown gives an equinox cut-off, ie all beam solar radiation is excluded for the summer six months, with solar input increasing towards the maximum at the winter solstice. For a colder climate the eaves may be reduced, to bias the system towards an increased solar input. For other orientations the appropriate shading is more difficult and solar radiation won't be utilised to its full potential. It is therefore suggested that all major windows should have an equatorial orientation.

Getting the solar radiation into the building is the first task, but equally important are its absorption (conversion to heat) and storage. Many authors suggest the use of a dark finish (eg dark quarry tiles) over a solid floor (eg a concrete slab) of significant thermal capacity in areas reached by the winter sun. This is good, but not as important as it seems. Any radiation reflected, eg by a light colour carpet, would be absorbed by other surfaces in the room. The essential requirement is the presence of adequate thermal mass for some surfaces in the room, otherwise the solar radiation entering would cause overheating, which would result in an increased heat loss and the heat would not be retained for the no-gain period (overnight).

It is suggested that for the 24-hour cycle the effective depth for heat storage and release is about 100 mm in concrete or brick elements. A thickness larger than this will have a role for longer term storage, eg over a number of days of inclement weather. For exterior walls it is advisable to have a thermal insulation layer outside of the storage layer, to prevent the loss of any stored heat. The area of internal surfaces of elements used for storage should be about six times the glazing area.

The glazing system together with the form and quantity of available thermal mass will determine the "utilisability" of the solar heat input (or the efficiency of the system), ie the fraction of solar radiation incident on the outer surface of the window that will actually contribute to the heating requirement. This is usually around 0.5 – 0.7 for a well-built system.

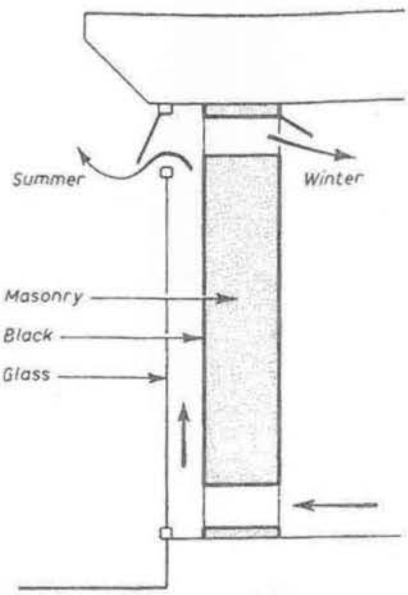


Fig.3.12 Principles of the Trombe-Michel wall

The second most popular passive system is the **mass wall** or Trombe-Michel wall. This is essentially an equatorially oriented solid masonry wall of 200 – 300 mm thickness, with a dark absorbent surface and a glass cover enclosing an air space of some 100 mm in front of the wall.

There are ventilator openings to the room behind it both at the top and near floor level (Fig.3.12). These will allow a buoyancy-force driven convective current to develop in the enclosed air space: the heated air rises and enters the room at the top and it is replaced by cooler air drawn in at floor level. (Sometimes it is referred to as the *circulating* Trombe-wall). This circulation gives an instantaneous heating effect (during the sunshine period), whilst the heat absorbed and stored by the mass wall will be transmitted to the room with a delay or *time-lag* of up to 10 hours.

Closing the vents would increase this delayed gain, but also increase the heat loss (as the heated wall surface is not cooled by an air current, its temperature will increase, heating the air in the cavity, increasing the back-loss through the glass). A top vent to the outside would assist the dissipation of heat in the summer, when it is unwanted.

The masonry wall may be replaced by water in containers of various kinds, in which case the system will be referred to as a **water wall**.

The overall 24-hour efficiency of these walls may be similar to that of direct gain systems, but the resulting indoor temperatures will be more even, with the indoor peak certainly and the indoor mean probably lower than with a direct gain system (due to back losses through the glass).

The use of transparent insulation over solid walls would serve a function similar to the (non-circulating) mass wall. The transparent (translucent) insulation (usually covered by a sheet of glass) transmits most of the solar radiation, which is then absorbed by and heats the solid wall surface. The insulation prevents the backward loss of heat, which is stored and transmitted by the solid wall with a time lag depending on the construction. Summer shading of such walls is essential, not just to prevent unwanted heat gain, but also to protect the fabric, especially the insulation itself, which may be damaged by overheating.

Finally the once very fashionable attached greenhouse or **sun-space systems** must be mentioned (Fig.3.13). The function of such a sun-space is essentially the same as of a mass-wall, except that the 100 mm air space is extended to 2 – 3 m. In sunshine this space can become quite hot and the hot air can be allowed to enter the room behind it. A facility for closing off this sun-space from the room behind it is essential. Without this the sun-space would become a net looser of energy over the 24-hour cycle because of the large heat loss through the extensive glazing during the no-sun period.

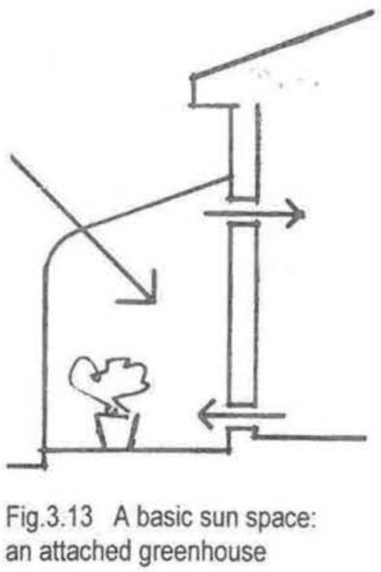


Fig.3.13 A basic sun space: an attached greenhouse

It will rarely be a significant contributor to the heating of the house itself, but its advantage is that it can become a very pleasant space to be in on a sunny winter day, serving as a passively heated wintergarden. The summer protection (shading) of such sun-spaces is important to prevent serious overheating.

3.4 Massive buildings

A cave remains cool in summer and warm in winter compared to outdoor temperatures. A very heavy massive building (in the absence of solar and internal gains) will have a constant temperature about the 24-hour average of the outdoors. This effect is the basis for the CPZ discussed in section 3.2.2, useful both in summer and in winter.

In warm climates, or the summer of temperate climates the task is
1) to prevent or reduce heat gain
2) to delay the heat gain to a time when it is not inconvenient
3) to dissipate as much heat as possible.

The first task is served by shading and thermal insulation, especially of the roof*. The second task is achievable by the mass-effect.

The realisation of this strategy would demand a heavy construction. A floor of concrete slab on ground would provide "earth coupling", ie utilising the very large thermal capacity of the ground below the slab. The walls should be heavy masonry, a minimum of 200, preferably 300 mm thickness. If hollow concrete blocks are used, the cavities should be filled with a weak concrete mix or just with sand. The archetypal example is the desert architecture of the Middle East and North Africa.

The roof should preferably be also heavy, a reinforced concrete slab, perhaps of precast elements with an in-situ topping, but if this is too expensive, a lightweight roof can be "neutralised" with very good insulation ($\approx$ R3 insulation or a U-value of no greater than 0.3 W/m^2K).

Once the thermal capacity is available, it can be made use of in several different ways, its performance can be biassed according to the climatic conditions. In a cold climate, or the winter of a temperate climate some solar heat input can be designed for. This would elevate the indoor mean well above the outdoor mean temperature.

In a hot climate (especially a hot-dry climate with large diurnal variations) night-time ventilation would assist the dissipation of stored heat (sometimes referred to as a "night flush"). This would reduce the internal mean to a level approaching the minimum of the outdoor temperatures. The operational requirement would be for the building to be closed during the day (as the indoor temperature is well below the outdoor, ventilation would cause a heat gain), but fully opened at night to promote heat dissipation by the incoming cool night air.

* in a low-latitude warm climate the roof receives the most solar radiation, through which the heat flow will be driven by the sol-air temperature (the combined effect of warm air and solar radiation); sunlit walls would show the same effect, but it is easier to shade walls than the roof.

The period of ventilation can be simply stated as "whenever the outdoor temperature is lower than the indoor". Fig.3.14 compares the outdoor and indoor temperature profiles of a moderately massive house and identifies the desirable ventilation period.

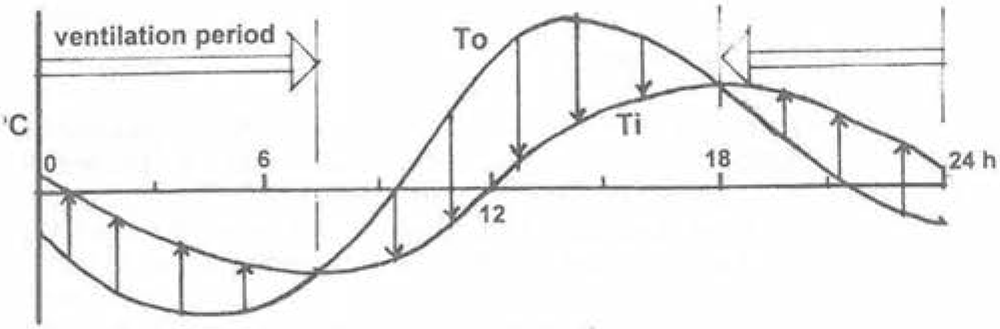


Fig.3.14 Outdoor and indoor temperature profiles: determining the period of night ventilation (arrows indicate the direction of heat flow, eg by ventilation)

3.5 Cross ventilation

The strategy of relying on the cooling effect of air movement, discussed in section 3.2.3 can be realised by cross ventilation. Natural ventilation can be generated by two possible mechanisms: stack effect or wind effects.

The **stack effect** is driven by the buoyancy force, the pressure difference between cool and warm air. It will be larger with an increased difference between the 'stack' temperature and the outdoor air and an increased stack height (ie difference between inlet and outlet openings). It will work only if the stack temperature is higher than the outdoor temperature.

The pressure difference is

$$\Delta p = h \bullet g \bullet (d_o - d_i) \qquad \text{eq. 1)}$$

where Δp= pressure difference (Pa)
h = height difference
g = gravity (9.81 m/s^2)
d = density of air (kg/m^3)

as the density of air at temperature T is

$$d_T = 1.293 \bullet 273/T \qquad \text{eq. 2)}$$

where T = absolute temperature (°K)

$$\Delta p = h \bullet 9.81 \bullet (1.293 \bullet 273/Ti - 1.293 \bullet 273/To) = h \bullet 3462 \bullet (1/Ti - 1/To)$$

and the volume flow rate is

$$vr = 0.827 \bullet A \bullet \sqrt{\Delta p} \qquad \text{eq. 3)}$$

In ventilating a room of a house the available height is unlikely to be more than 5 m. If Ti – 28 + 273 = 301°K and To = 20 + 273 = 293°K then

$$\Delta p = 5 \bullet 3462 \bullet (1/293 - 1/301) = 1.57 \text{ Pa}$$

and if we have a stack of 500 mm square, ie 0.25 m^2 then the volume flow rate is

$$vr = 0.827 \bullet 0.25 \bullet \sqrt{1.57} = 0.26 \text{ m}^3/\text{s}$$

This may be adequate for fresh air supply, but for physiological cooling the velocity is the important criterion and if this flow rate occurs through a 4 m^2 window opening, the velocity will only be $v = 0.26/4 = 0.06$ m/s Which is barely noticeable.

In warm climates the above assumed temperatures rarely occur, therefore the stack effect cannot be relied on to provide a sensible air velocity.

Wind is the only force that can provide adequate interior air movement. If a single open window is exposed to wind, there will be practically no ventilation and buffeting is likely to occur. As the name suggests, 'cross ventilation' requires both an inlet and an outlet opening. Air flow through the room (or building) is driven by the pressure difference between the windward and leeward sides.

The wind pressure can be estimated as

$$pw = 0.612 \bullet v^2 \qquad \text{eq. 4)}$$

On the windward side of a building the pressure may be 0.5 to 1 pw and on the leeward side the negative pressure will be –0.3 to –0.4 pw, both depending on the wind direction and on aerodynamic effects of the particular situation. Then the volume flow rate will be

$$vr = 0.827 \bullet A \bullet \sqrt{\Delta p} \qquad \text{eq. 5)}$$

If (say) we have a moderate wind speed of 7 m/s then
$pw = 0.612 \bullet 7^2 = 30$ Pa

and if the pressure difference is (say)
$\Delta p = 0.75\ pw - (-0.25\ pw) = 1\ pw$

and if both inlet and outlet openings are 4 m^2 the air flow will be
$vr = 0.827 \bullet 4 \bullet \sqrt{30} = 18.1\ m^3/s$

the velocity through the window will be
$v = vr/A = 18.1 / 4 = 4.5$ m/s, which is quite respectable.

If the inlet and outlet openings are unequal, the effective area can be calculated as

$$A = \frac{A_1 \bullet A_2}{\sqrt{A_1^{\ 2} \bullet A_1^{\ 2}}}$$

For physiological cooling the air velocity is important and this can vary from point to point within the room, depending on the size and position of openings and also on the conditions outside the inlet opening. The maximum volume flow rate will occur when the inlet and outlet openings are equally large, but maximum velocity is produced when the inlet opening is smaller and the outlet larger. This will occur only in certain parts of the room, depending on the inlet. The largest flow rate will occur with an oblique (up to 45°) wind incidence, but this would result in an asymmetrical velocity distribution within the room.

Useful cross ventilation can also be created even with 90° wind incidence (ie parallel to the wall considered) by the use of wing walls, to create positive and negative pressure zones outside the building (Fig.3.15). On a smaller scale an opening-out casement window or even vertical louvres can have a similar effect.

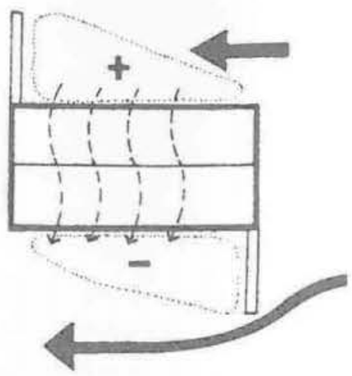


Fig.3.15 Wing walls to generate cross ventilation with 90° wind

For a building fully exposed to the wind or breeze, eg on the sea-shore or facing a large unobstructed space, the magnitude of cross-ventilation can be estimated reasonably well. However in a built up area or if the foreground is heavily vegetated, such estimates are very uncertain. There are too many external and unpredictable variables involved. Very often all the designer can do is to maximise the effect of even the slightest breezes (and hope for the best):

- position the building (if there is any freedom) to avoid obstructions
- possibly elevate the building on stilts to avoid low-level barriers and the much retarded air flow near the ground
- in planning allow for cross ventilation, preferably use a single row of rooms, otherwise less than full partitions
- provide large inlet and outlet openings
- choose the right window system: eg a sliding window can only have half of it opened, whilst a casement allows full opening
- if flyscreens are necessary, the smooth nylon net will give less restriction to air flow (approx 35%) than textile nets. A cotton net will result in a reduction of velocity by some 70%
- if a window or door faces a balcony or terrace, the flyscreen could be mounted at the outer edge of that balcony or terrace, over a much larger surface, so that the free opening area of the net is larger than the door or window opening.

The cooling effect of such air movement can be estimated as

$$dT = 6 \bullet (v-0.2) - (v-0.2)^2$$

where dT = temperature increment the air movement could compensate for
and v = air velocity (m/s) at the body surface.

However, even with the best designs there remains the uncertainty of a breeze occurring when it is most needed. One doesn't have to religiously adhere to passive principles, and we can see nothing wrong with the use of a low-powered ceiling fan to generate the desirable air movement in the room when there is no wind available.

3.6 Evaporative cooling systems

In evaporative cooling the latent heat of evaporation is taken from the environment (from the air) which results in a reduction of sensible heat, (sensible heat is converted into latent heat) thus its temperature is reduced. As the latent heat of evaporation of water at ambient temperatures is around 2400 kJ/kg, the evaporation of 1 L (1 kg) of water in one hour produces a cooling rate of 666 W.

The simplest evaporative cooler is a pond. Evaporation from a still free water surface can be estimated as

$$Ev = 0.003 \bullet (vp_s - vp_a) \bullet (1+0.38\ v)$$

where Ev = evaporation rate in mm (depth)/day or L/m^2day
vp_s = vapour pressure of water surface (saturation pressure)
vp_a = vapour pressure of the air (Pa)
v = air velocity over the surface

eg if water temperature is 25°C, thus vp_s = 3150 Pa
air is at 23°C and 50% RH, thus vp_a = 1400 Pa and v = 2 m/s

then

$$Ev = 0.003 \bullet (32150\text{-}1400) \bullet (1+0.38 \bullet 2)$$
$$= 0.003 \bullet 1750 \bullet 1.76$$
$$= 9.24\ L/m^2day$$

which, for a $3 \bullet 2$ m = 6 m^2 pool would result in $9.24 \bullet 6 = 55.4$ L/day corresponding to a cooling rate of $55.4/24 \bullet 666 = 1537$ W (assuming that the evaporation is fully effective).

The problem with such cooling is that it is quickly dissipated. If the pond is in an enclosed space or a courtyard, it may be useful, as the cooled air (being heavier) is retained, it would form a cool air pool. The effect can be enhanced by a fountain or water sprays. The modern high pressure atomisers ("micronisers") can produce a very fine mist with practically 100% evaporation of the sprayed water. The "life time" of individual droplets (before full evaporation) is between 2 and 5 seconds. This requires droplet sizes of 60 – 100 μm in a hot-dry atmosphere (RH≈10%) or 15 – 25 μm under humid conditions (RH≈90%). For general application 50 μm droplet size is recommended (Rodriguez et al. 1991). Systems based on such atomiser sprays have been used for the cooling of outdoor spaces (eg at the Sevilla Expo'92).

For the cooling of indoor spaces many evaporative coolers are commercially available and widely used, especially in hot-dry climates, eg. central Australia or Arizona. Such coolers use a fan (Fig.3.16) which forces air through wetted pads of some fibrous material before it is fed into the room or building.

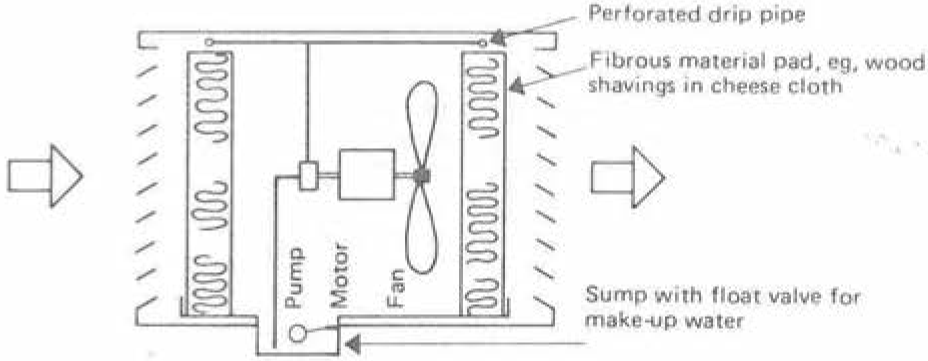


Fig.3.16 Schematic diagram of a packaged evaporative cooler

These can be considered as "semi-passive" systems: although a fan (most often a centrifugal fan) is used to drive the air flow, the work of cooling is performed by the "passive" evaporation of water.

In larger, especially single storey buildings the cooler is often mounted on the roof and feeds down to a ceiling diffuser.

In domestic scale buildings these coolers are usually placed at one end of the house and feed cooled air into the room (normally the living room) at a fairly high volume flow rate (1.5 – 2.5 m^3/s). This flow is directed at the occupants who benefit also from the air velocity cooling effect. It is all fresh air, no recirculation. Windows at the opposite end of the room (or house) are kept open, so there would be a steady flow of air through the house. The open window provides a contact with the outside, which appears to be psychologically more satisfying than the "sealed box" operation of refrigerated air conditioning.

As mentioned in section 3.2.5, the effect of such systems is rather limited in humid climates, where the use of indirect evaporative coolers (Fig.3.10) is more appropriate.

Dehumidification has been attempted by many experimental systems, which are collectively referred to as **open cycle systems** (as opposed to refrigeration systems where the evaporation/condensation or absorption/ desorption processes occur in a closed cycle). Fig.3.17 shows such a system based on silica gel, which is contained by wire mesh in a slowly rotating wheel. This takes up moisture from the supply air and is in turn dried by a solar heated air stream. The supply air is then cooled by an indirect evaporative cooler.

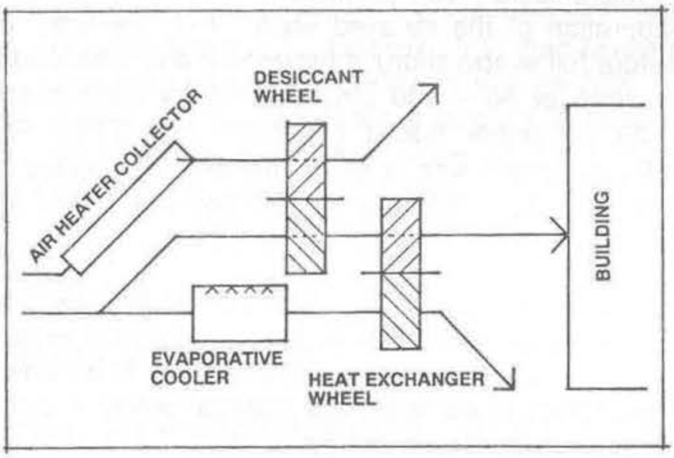


Fig.3.17 An open cycle cooling system based on a solid desiccant

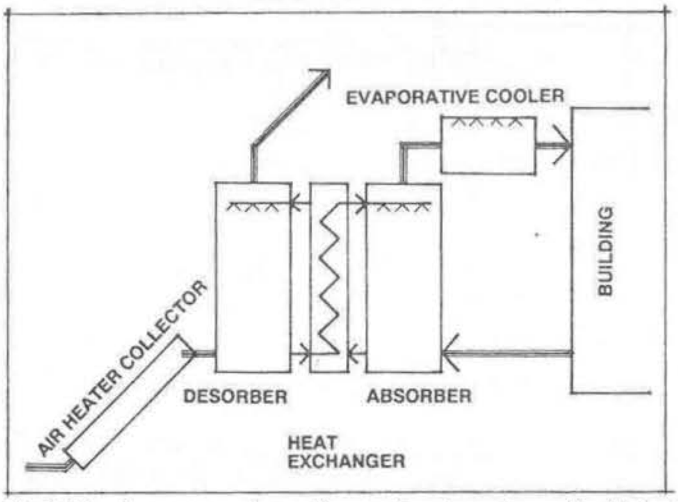


Fig.3.18 An open cycle cooling system based on a liquid desiccant

The system shown in Fig.3.18 uses glycol as the desiccant. This is sprayed into the desorber chamber where a counter-flow of solar heated air dries it. It is then sprayed into an air stream where it absorbs moisture, thus dries the air, which is then evaporatively cooled before it enters the building.

Many other permutations and refinements have been tested, but none are "clear winners" – yet. These are mechanical engineering systems (although rely on passive processes) but architects should be aware of the potential of such open cycle systems.

4 CONCLUSION

Having carried out a climate analysis and selected a thermal design strategy, the crucial step: the production of a sketch design follows. The theoretical approach is to be translated into a practical building. The main design decisions to affect the climatic performance of the building relate to shape, fabric, fenestration and ventilation. Consideration of these is summarised in the following sections.

4.1 Shape

1) **Surface-to-volume ratio**: as the magnitude of heat flow in and out of the building is proportional to the surface area, in severe climates it is advisable to present the least surface area to the outside. For this purpose the hemisphere is the most efficient shape, rarely practical, but at least a compact plan is always better than a fragmented or spread-out arrangement.

2) **Orientation**: if the plan is other than a circle (or square) orientation in relation to solar exposure will have a strong effect. The term *aspect ratio* is often used to denote the ratio of the longer east-west dimension of an oblong plan to the shorter north-south dimension. This can be optimised as a function of solar incidence on various surfaces, depending on whether heat gain is wanted or not.

4.2 Fabric

1) **Shading** of wall and roof surfaces can control the solar input. In extreme cases a *parasol roof* can be used over the roof itself, to provide shading, or an exposed western wall may be shaded to avoid the late afternoon (unwanted) solar heat input. If the plan shape is complex, *self-shading*, ie the shading of one surface by another part of the building should be considered, especially if solar gain is wanted.

2) **Surface qualities,** absorptance/reflectance will strongly influence the solar heat input: if it is to be reduced, reflective surfaces are preferred. A white surface may have the same reflectance as a shiny metal one, but white is a *selective surface*, with high emittance at normal temperatures, whilst the emittance of the shiny metal is negligible. Thus if heat dissipation is to be promoted, a white painted surface is better.

3) **Resistive insulation** controls the heat flow in both directions; it is particularly important in cold climates (heated buildings), or in hot climates (air conditioned buildings). In free-running (passive) buildings such insulation of the roof and elements exposed to solar radiation is necessary.

4) **Reflective insulation**: this is most effective if a foil is suspended in the middle of a cavity, so that both the high reflectance and low emittance are utilised. This is rarely practical or achievable. There is no difference in performance between the emittance and reflectance effects. Deterioration by eg dust deposits should be considered, therefore in a roof space the foil under the roof cover, with face down (low emittance) is better than one on the ceiling, face up (high reflectance).

5) **Capacitive insulation** (massive construction) provides a very powerful control of the timing of heat inputs.

4.3 Fenestration

1) **Size, position and orientation** of windows affect sun penetration, therefore the solar heat input, but these are also important from the point of view of ventilation, especially if cross-ventilation (physiological cooling effect) is desirable.

2) **Special glasses** (heat absorbing, reflective or 'heat rejecting' glasses) may be used to ameliorate an otherwise bad situation, by reducing the solar heat transmission. These should only be used as a last resort. Double or multiple glazing and low-e coating is desirable where heat transmission is critical (see 4.2 /3 above). In situations where the desirability of solar input is variable in time, photochromic or switchable glasses may be considered.

3) **Blinds and curtains** used internally can slightly reduce solar heat input. They certainly reduce direct (beam) radiation but they will absorb much of this and will be heated, thus causing convective gains and low temperature re-radiation.

4) **External shading devices** are the most positive tools for controlling solar input through windows. They may be fixed or adjustable. Their effect on wind (where cross ventilation is desirable), on daylighting and on views must be considered.

5) **Special features**: fenestration itself can form a 'direct gain' passive solar heating system (together with some massive constructional elements), but some special elements: a Trombe wall, water wall or sun-space (solar greenhouse) may be considered where underheating is the problem. A Trombe wall or water wall is particularly useful where –for some reason- the construction is lightweight.

4.3 Ventilation

1) **Air-tight construction** is important in a cold climate or in air conditioned buildings.

2) **Heat dissipation** is served by ventilation (beyond the provision of fresh air and removal of contaminants) when the indoor temperature is higher than the outdoor. These purposes are well served by opening a window or by the stack effect.

3) A **solar chimney** can enhance the stack effect in hot climates, where it would otherwise not work. This is a panel exposed to solar radiation, with an air space, where an upward current would be generated by solar heating, which may draw in ventilation air. This may be pre-cooled by evaporation.

4) **Cross-ventilation** would provide physiological cooling. For this the air velocity in the occupied zone is the important criterion, not the volume flow rate. Window size, position orientation and closing mechanism are important. This is practically the only passive control effective in warm humid climates.

5) **Evaporative cooling** may be passive (a pond or a spray) but the fan-driven supply air may be cooled evaporatively by a semi-passive system. Especially useful in hot-dry climates. Indirect evaporative coolers (see section 3.2.5) are effective in a broader range of climates.

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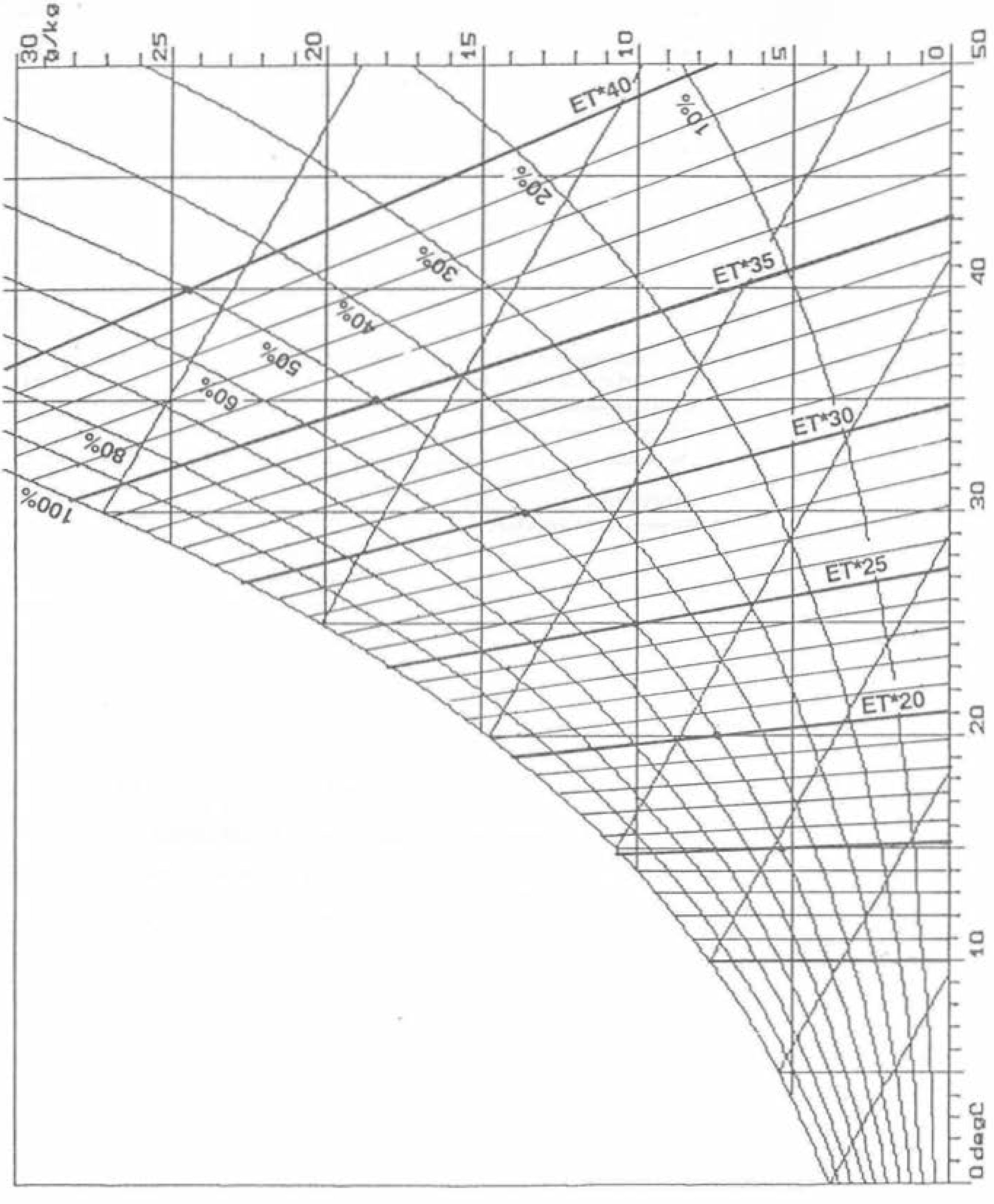
Appendix 1
The Beaufort wind force scale

force	observable effects	speed : m/s	km/h
0	Complete calm, smoke rises vertically, lake surface smooth	< 0.5	1.8
1	Slight movement, smoke slightly inclined	1.7	6.1
2	Slight breeze, leaves rustling	3.3	11.8
3	Slight wind, twigs moved, small ripples on water	5.2	18.7
4	Moderate wind, small branches moved	7.4	26.6
5	Strong wind, larger branches moved, booming noise, white crested waves	9.8	35.3
6	Very strong wind, leaves torn off, walking somewhat difficult	12.4	44.6
7	Storm, smaller tree trunks bent, twigs torn	15.2	55.4
8	Strong storm, branches may be torn, large branches bent	18.2	65.5
9	Very strong storm, smaller trees uprooted, roof tiles blown off, buildings damaged	21.5	77.4
10	Gale, havy building damage, trees broken or uprooted	25.1	90.4
11	Gale, buildings destroyed, whole woods uprooted, man and animals may be lifted and carried	29.0	104.4
12	Gale, as above, but more so	> 29.0	> 104.4

Appendix 2
Measures of comfort

symbol	name	factors considered
DBT	dry bulb temperature	air temperature
WBT	wet bulb temperature	air temperature, humidity
GT	globe temperature	air temperature, radiation
MRT	mean radiant temperature	radiation
EnvT	environmental temperature	air temperature, radiation
WCI	wind chill index	air temperature, air velocity
THI	temperature-humidity index	air temperature, humidity
ET	effective temperature	air temperature, humidity, later: air movement
CET	corrected effective temperature	air temperature, humidity, radiation, air movement
WBGT	wet bulb globe temperature	air temperature, humidity, radiation
OT	operative temperature	air temperature, radiation, also air movement
EqT	equivalent temperature	air temperature, radiation, air movement
RT	resultant temperature	air temperature, humidity, air movement
ECI	equatorial comfort index	air temperature, humidity, air movement
Tsi	tropical summer index	air temperature, humidity, air movement
TSI	thermal strain index	air temperature, humidity, metabolic rate, clothing
P4SR	predicted 4-hour sweat rate	air temperature, humidity, radiation, air movement
HSI	heat stress index	air temp, humidity, radiation, air movmt, metabolic rate
RSI	relative strain index	air temp, humidity, radiation, metabolic rate
ITS	index of thermal stress	air temp,humidity,radiation, air movmt, met.rate, clothg
PMV	predicted mean vote	air temp,humidity,radiation, air movmt, met.rate, clothg
ET*	new effective temperature	air temperature, humidity, others indirectly
SET	standard effective temperature	air temperature, humidity, others indirectly
ST	subjective temperature	air temperature, radiation, air movmt, met.rate, clothg
TS	thermal sensation (index)	air temp,humidity,radiation, air movmt, met.rate, clothg
DISC	discomfort (index)	air temp,humidity,radiation, air movmt, met.rate, clothg



Appendix 3
Psychrometric chart with ET* lines superimposed

Appendix 4
Psychrometric algorithms

The basis of all psychrometric calculations is to find the saturation-point vapour pressure (pvs) for any given temperature T (either DBT or WBT).
Four such equations are in general use :

The Ferrel equation

pvs = exp[19.013 - 5325/(273+T)] (kPa) ... eq. 1)

The Antonine equation

pvs = 0.133322 * exp[18.6686 - 4030.183/(235+T)] (kPa) ... eq. 2)

Keenan-Keyes equation[1]

$K = 673.4 - 1.8 * T$

$A = 3.2437814 + 0.00326014 * K + 2.00658 * 10^{-9} * K^3$

$B = (1165.09 - K) * (1 + 0.00121547 * K)$

pvs = 22105.8416 / exp(2.302585*K*A/B) (kPa) ... eq. 3)

ASHRAE thermodynamic solution[2]

$K = 273.15 + T$

$C = 1.3914993 - (5800.2206/K) - 0.048640239 * K + {} +(0.41764768 * 10^{-4} * K^2) - (0.14452093 * 10^{-7} * K^3) + 6.5459673 * \ln(K)$

pvs = exp(C)/1000 (kPa) ... eq. 4)

Saturation humidity

SH = 622 * pvs / (pt - pvs) (g/kg) ... eq. 5)
where pt = 101.325 kPa, the total pressure of a "standard atmosphere"

Relative humidity

RH = (AH/SH)*100 = (pv/pvs)*100 (%) ... eq. 6)

Wet bulb temperature

WBT = 7.5 + 0.9*(DBT-10) + (RH-70)/30*[2.75+0.1*(DBT-10)] ... eq. 7)

From psycrometer measurement (DBT and WBT measured)
find $\mathbf{pvs_W}$ at the WBT and $\mathbf{pvs_D}$ at the DBT (from one of eq. 1 - 4)
then the vapour pressure is

$pv = pvs_W - coeff * (DBT - WBT)$ (kPa) ... eq. 8)

(valid for WBT > 0°C)
for fully aspirated psychrometers ($v \approx 3.5$ m/s) coeff = 0.0666
for screen type psychrometers (v = 1 to 2 m/s) coeff = 0.0799
(valid for atmospheric pressure pt between 95 and 105 kPa)

then **absolute humidity**[3]

AH = 622 * pv / (pt - pv) (g/kg) ... eq. 9)
where pt = 101.325 kPa, the total pressure of a "standard atmosphere"

$RH = (pv / pvs_D) * 100$ (%)

---

[1] Keenan, J & Keyes, F G (1936): Thermodynamic properties of steam. Wiley, New York

[2] AHRAE Handbook of Fundamentals (1985), SI edition, The Society, Atlanta

[3] meteorologists make the following distinctions:
a) humidity ratio: non-dimensional: g/g or kg/kg (vapour per dry air)
b) absolute humidity: g of water vapour per m^3 volume of moist air (air/vapour mixture)
c) moisture content: g of water vapour per kg mass of moist air (air/vapour mixture)
d) in general use, here adopted: absolute humidity means g of vapour per kg of dry air

Appendix 5
Solar irradiation on a vertical, equator-facing surface

based on S Klein in *Solar Energy*, 19:325-329 (1977)

Data requirement: H_h, daily horizontal irradiation (Wh/m^2) and
Hd_h and Hb_h, its diffuse and beam components
LAT, geographical latitude (south negative)

Then the equator-facing vertical surface receives

$$\boxed{H_v = R \bullet Hbh + Hd_h/2 + ref \bullet H_h/2} \quad \text{... eq.1)}$$

where

ref = reflectance of foreground — normally taken as 0.2

$$R = \frac{\cos DIF \bullet \cos DEC \bullet \sin SSP + SSP \bullet \sin DIF \bullet \sin DEC}{\cos LAT \bullet \cos DEC \bullet \sin SSH + SSH \bullet \sin LAT \bullet \sin DEC} \quad \text{... eq.2)}$$

where

if LAT > 0 then DIF = LAT - 90
if LAT < 0 then DIF = LAT + 90
SSH = arcos(-tanLAT•tanDEC) — sunset hour angle
SSP = arcos(-tanDIF•tanDEC) — same for the vertical plane
but if SSP>SSH then SSP=SSH
DEC = 23.45 • sin[0.986•(284+NDY) — declination
NDY = number of day of year (1-365) — for the selected date

For solar radiation the 'average' day of the month is not the 15th, but the dates given in Table 5.1

Table 5.1
Average day of month

Month	date	NDY	DEC
Jan	17	17	-20.9
Feb	16	47	-13.0
Mar	16	75	-2.4
Apr	15	105	9.4
May	15	135	18.8
Jun	11	162	23.1
Jul	17	198	21.2
Aug	16	228	13.5
Sep	15	258	2.2
Oct	15	288	-9.6
Nov	14	318	-18.9
Dec	10	344	-23

Appendix 6
The variable-base degree-hour method

(refer to section 1.4.2, p.16 and section 3.2.1, p.32)

Thermally the building may be characterised by its conductance (or building heat loss coefficient) (q) in W/K, ie its heat loss per unit temperature difference.
where
q = qc + qv ie envelope conductance + ventilation conductance
qc = Σ(A • U)
qv = 0.33 • N • V
A = area of each envelope element (m^2)
U = the transmittance of each element (W/m^2K)
N = number of air changes per hour
V = volume of the building (m^3)
and 0.33 Wh/m^3K is the volumetric specific heat of air

The heating requirement for any period will be the product of this building conductance and the number of degree-(Kelvin-) hours for that period.
H = q • deg.h in units of W/K • Kh = Wh
The outdoor temperature (To) at which the q•(Ti-To) product equals the solar and internal heat gains is taken as the "balance-point" or base temperature (Tb). The number of degree-hours for the month to any given Tb can be calculated by the following algorithm:

Data requirement: the value of Tb as found above
mean temperature of the month (To_{av})
standard deviation of daily mean temperatures (sd)

If the sd is not known, it can be estimated if the 14th and 86th %-ile values of the daily men minima and maxima are given (as in Australia):

$$sd_{max} = (T_{max86} - T_{max14}) / 2.16$$
$$sd_{min} = (T_{min86} - T_{min14}) / 2.16$$

then

$$sd = 0.5 \bullet (sd_{max}^2 + sd_{min}^2 + 2 \bullet r \bullet sd_{max} \bullet sd_{min})$$

where r is an empirical correlation coefficient between daily minima and maxima, given by Walsh & Spencer(1980) as 0.4

Degree-days (Kelvin-days):

$$\boxed{Kd = N \bullet (\Phi \bullet dT + sd \bullet \phi)} \qquad \text{... eq.1)}$$

where N = number of days in month
Φ = fraction of the unit area distribution curve below Tb
ϕ = value of the probability density function at Tb
$dT = Tb - To_{av}$

dT is expressed as a multiple of sd: $dT = z \bullet sd$, from which $z = dT / sd$

$$\boxed{\phi = 0.3989 \bullet \exp(-z^2 / 2)} \qquad \text{... eq.2)}$$

where $0.3989 = \dfrac{1}{\sqrt{\pi}}$

The tail area (AT) is found by a numerical approximation of the integral:
(Abramowitz & Stegun, 1965)
if $t = 1 / (1+0.33267 \bullet z)$ then

$$\boxed{AT = \phi \bullet (0.43618 \bullet t - 0.12016 \bullet t^2 + 0.93729 \bullet t^3} \qquad \text{... eq.3)}$$

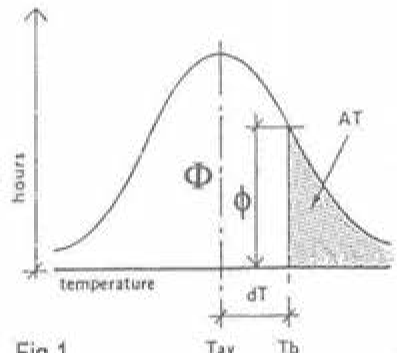


Fig.1
Normal distribution of temperatures

With reference to Fig.1 it can be seen that Φ will be
if $dT < 0$ then $\Phi = AT$
if $dT = 0$ then $\Phi = 0.5$
if $dT > 0$ then $\Phi = 1-AT$

Degree-hours (Kelvin-hours) are often taken as 24 • degree-days, but Walsh (1987) suggested two adjustments

$Kh = 24 \bullet Kd + ad1 + ad2$
if $T_{mean.max} > Tb > To_{av}$ then $ad1 = 12 \bullet N \bullet (T_{mean.max} - Tb)$, else $ad1 = 0$
if $T_{mean.min} < Tb < To_{av}$ then $ad2 = 12 \bullet N \bullet (Tb - T_{mean.min})$, else $ad2 = 0$

Abramovitz, M & Stegun, I A (1965): *Handbook of mathematical functions.* Dover, New York

Walsh, P J & Spencer, J W (1980): *Heating degree-days for Australian localities.* CSIRO Div.Bldg.Res. Techn.Paper (second ser.) No.35

Walsh, P J (1987) private communication

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