THERMAL COMFORT STUDY ON TERRACED HOUSE OVERSEEING THE EFFECT ON RAINWATER HARVESTING SYSTEM

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ABSTRACT

The tropical climate in Malaysia that is hot and humid with average temperatures between 23.7^{o}C to 31.3^{o}C throughout a day with the highest maximum recorded as 36.9^{o}C and the average relative humidity between 67% to 95% and this may have an adverse impact on occupant comfort indoor. With this kind of climate thermal comfort can become a problem to occupants of many residential buildings especially when they are not equipped with air-conditioning system. With the cost living in the city increased higher, the needs to promote the energy saving are needed. This paper presents outcomes of an ongoing research work to investigate thermal comfort by using rainwater harvesting system on terraced houses. Temperature data as an ongoing research through the month and to be compare with cooling load temperature difference (CLTD) method that normally practice inthe design of the air conditioning system for a certain building. The data will be compared to prove the rainwater harvesting system cannot be neglected or overseeing that can help in reducing temperature closed to thermal comfort on the terraced houses.

ABSTRAK

Iklim tropika di Malaysia yang senantiasa panas dan lembab dengan perbezaan suhu antara 23.7^{o}C hingga 31.3^{o}C sepanjang hari dengan bacaan tertinggi yang pernah dicatat sehingga 36.9^{o}C dengan perbezaan kelembapan bandingan antara 67% hingga 95% member impak yang buruk kepada pengguna. Dengan keadaan iklim seperti ini terma keselesaan akan menjadi suatu masalah kepada pengguna di kawasan perumahan terutama sekiranya rumah tersebut tidak memiliki unit penghawa dingin. Peningkatan kos sara hidup di kawasan bandar, memaksa pengguna untuk lebih berjimat dalam penggunaan tenaga elektrik. Kajian ini merupakan kajian yang berterusan untuk merungkai keberkesanan sistem penakungan air hujan dalam memberi kesan terma keselesaan kepada pengguna di kawasan perumahan teres. Data suhu merupakan kajian yang berterusan sepanjang bulan dan dibandingkan dengan data pengiraan perbezaan suhu beban haba penyejukan (CLTD) yang biasa di praktik dalam merekabentuk sistem penyamanan udara bagi sesebuah bangunan. Data yang dikumpul dari sistem penakungan air tadi akan dibuktikan bahawa sistem penakungan air hujan di tidak boleh diabaikan atau terlepas pandang akan kepentingannya yang mampu menurun suhu sehingga mencapai kesan tahap terma keselesaan di kawasan perumahan teres.

TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

LIST OF CHARTS

LIST OF APPENDICES

Appendix No

CHAPTER 1

INTRODUCTION

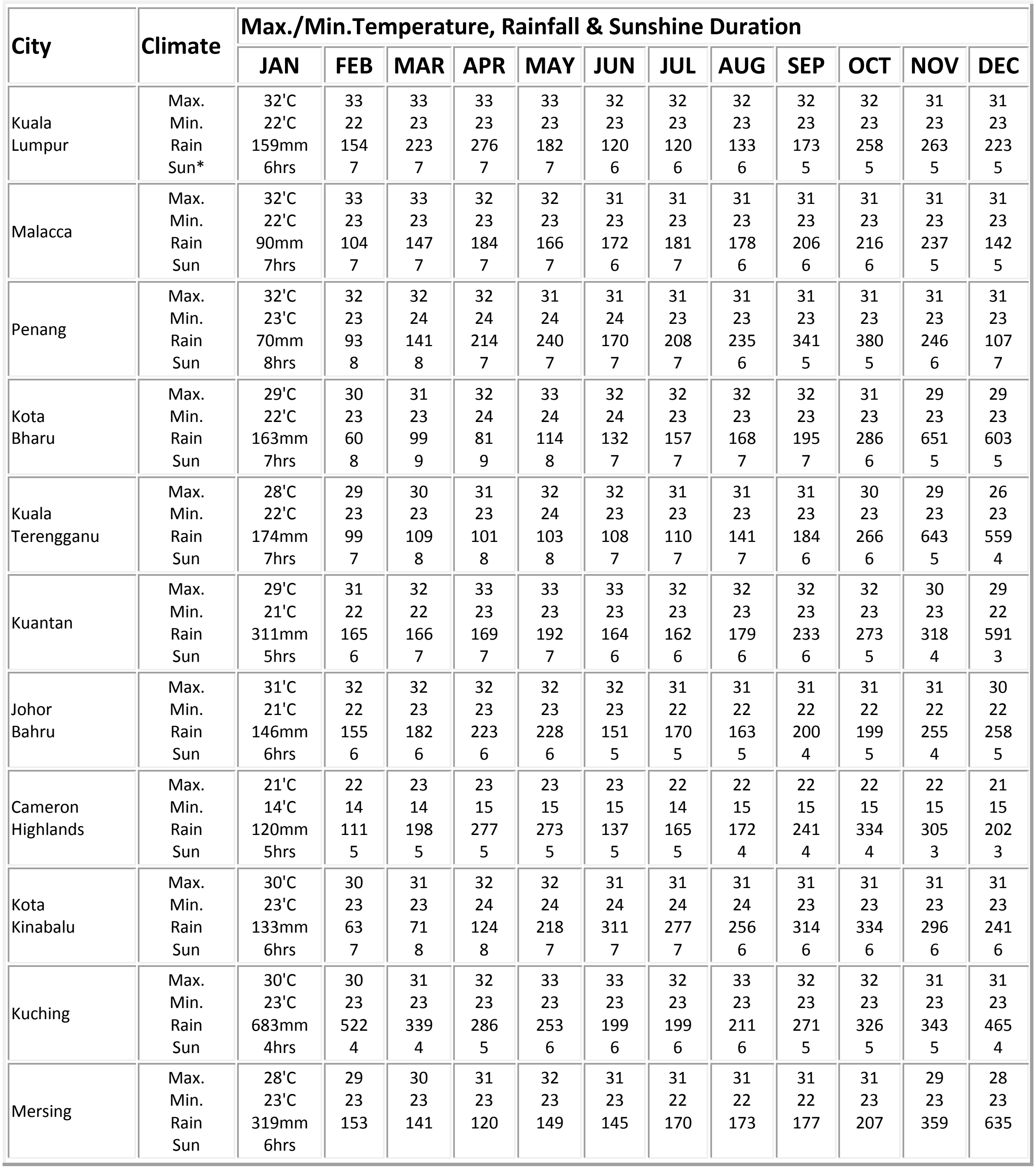
1.1 Introduction

In hot and humid climates thermal comfort can become a problem to the occupants of many residential buildings especially when they are not equipped with air-conditioning system. Malaysia is one of the tropical country which very much like most of the conutry that have the temperature can be hot throughout the year and there is a large amount of rainfall.

In Malaysia there is no considerable difference between seasons, like summer and winter. Days are warm and usually humid but the nights are quite cool. The temperature also varies in different locations. At Penang, the temperatures stay close to 82^{o}F (28^{o}C) and at Labuan the average temperature is 80^{o}F (27^{o}C). The temperature in areas located above sea level is considerably cooler. The Cameron Highlands which are about 5000 feet (1500m) above sea level has a temperature of 64^{o}F (18^{o}C) which is very much a good thing for foreigners [1,7,8].

The main raining season runs between November and February, while August is considered the most humid and wettest period on the West Coast (Terengganu, Kelantan and Pahang). Sabah and Sarawak have heavy rains during November to February. Rainfall, however, is heavy all year round in the country. Rainfall is heavy in the mountain areas. In the Cameroon highlands, the total annual rainfallis over 100 inches (2540 mm). No single month has less than 5 inches or 125 mm of rainfall[7,8].

With those kind of climate and temperature, special attention must be given to not overseeing the affectiveness rainwater harvesting system. Moreover, it is the most cost efficient and energy saving system.



City	Climate	Max./Min.Temperature, Rainfall & Sunshine Duration											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Kuala Lumpur	Max.	32'C	33	33	33	33	32	32	32	32	32	31	31
	Min.	22'C	22	23	23	23	23	23	23	23	23	23	23
	Rain	159mm	154	223	276	182	120	120	133	173	258	263	223
	Sun*	6hrs	7	7	7	7	6	6	6	5	5	5	5
Malacca	Max.	32'C	33	33	32	32	31	31	31	31	31	31	31
	Min.	22'C	23	23	23	23	23	23	23	23	23	23	23
	Rain	90mm	104	147	184	166	172	181	178	206	216	237	142
	Sun	7hrs	7	7	7	7	6	7	6	6	6	5	5
Penang	Max.	32'C	32	32	32	31	31	31	31	31	31	31	31
	Min.	23'C	23	24	24	24	24	23	23	23	23	23	23
	Rain	70mm	93	141	214	240	170	208	235	341	380	246	107
	Sun	8hrs	8	8	7	7	7	7	6	5	5	6	7
Kota Bharu	Max.	29'C	30	31	32	33	32	32	32	32	31	29	29
	Min.	22'C	23	23	24	24	24	23	23	23	23	23	23
	Rain	163mm	60	99	81	114	132	157	168	195	286	651	603
	Sun	7hrs	8	9	9	8	7	7	7	7	6	5	5
Kuala Terengganu	Max.	28'C	29	30	31	32	32	31	31	31	30	29	26
	Min.	22'C	23	23	23	24	23	23	23	23	23	23	23
	Rain	174mm	99	109	101	103	108	110	141	184	266	643	559
	Sun	7hrs	7	8	8	8	7	7	7	6	6	5	4
Kuantan	Max.	29'C	31	32	33	33	33	32	32	32	32	30	29
	Min.	21'C	22	22	23	23	23	23	23	23	23	23	22
	Rain	311mm	165	166	169	192	164	162	179	233	273	318	591
	Sun	5hrs	6	7	7	7	6	6	6	6	5	4	3
Johor Bahru	Max.	31'C	32	32	32	32	32	31	31	31	31	31	30
	Min.	21'C	22	23	23	23	23	22	22	22	22	22	22
	Rain	146mm	155	182	223	228	151	170	163	200	199	255	258
	Sun	6hrs	6	6	6	6	5	5	5	4	5	4	5
Cameron Highlands	Max.	21'C	22	23	23	23	23	22	22	22	22	22	21
	Min.	14'C	14	14	15	15	15	14	15	15	15	15	15
	Rain	120mm	111	198	277	273	137	165	172	241	334	305	202
	Sun	5hrs	5	5	5	5	5	5	4	4	4	3	3
Kota Kinabalu	Max.	30'C	30	31	32	32	31	31	31	31	31	31	31
	Min.	23'C	23	23	24	24	24	24	24	23	23	23	23
	Rain	133mm	63	71	124	218	311	277	256	314	334	296	241
	Sun	6hrs	7	8	8	7	7	7	6	6	6	6	6
Kuching	Max.	30'C	30	31	32	33	33	32	33	32	32	31	31
	Min.	23'C	23	23	23	23	23	23	23	23	23	23	23
	Rain	683mm	522	339	286	253	199	199	211	271	326	343	465
	Sun	4hrs	4	4	5	6	6	6	6	5	5	5	4
Mersing	Max.	28'C	29	30	31	32	31	31	31	31	31	29	28
	Min.	23'C	23	23	23	23	23	22	22	22	23	23	23
	Rain	319mm	153	141	120	149	145	170	173	177	207	359	635
	Sun	6hrs											

Table 1.1:Monthly Temperature for Malaysia.

* Average sunshine duration.
1) Mean daily sunshine hour
2) Temperatures - Mean Maximum/Minimum.
3) Rainfall - Mean Monthly ForPeriods As Specified.

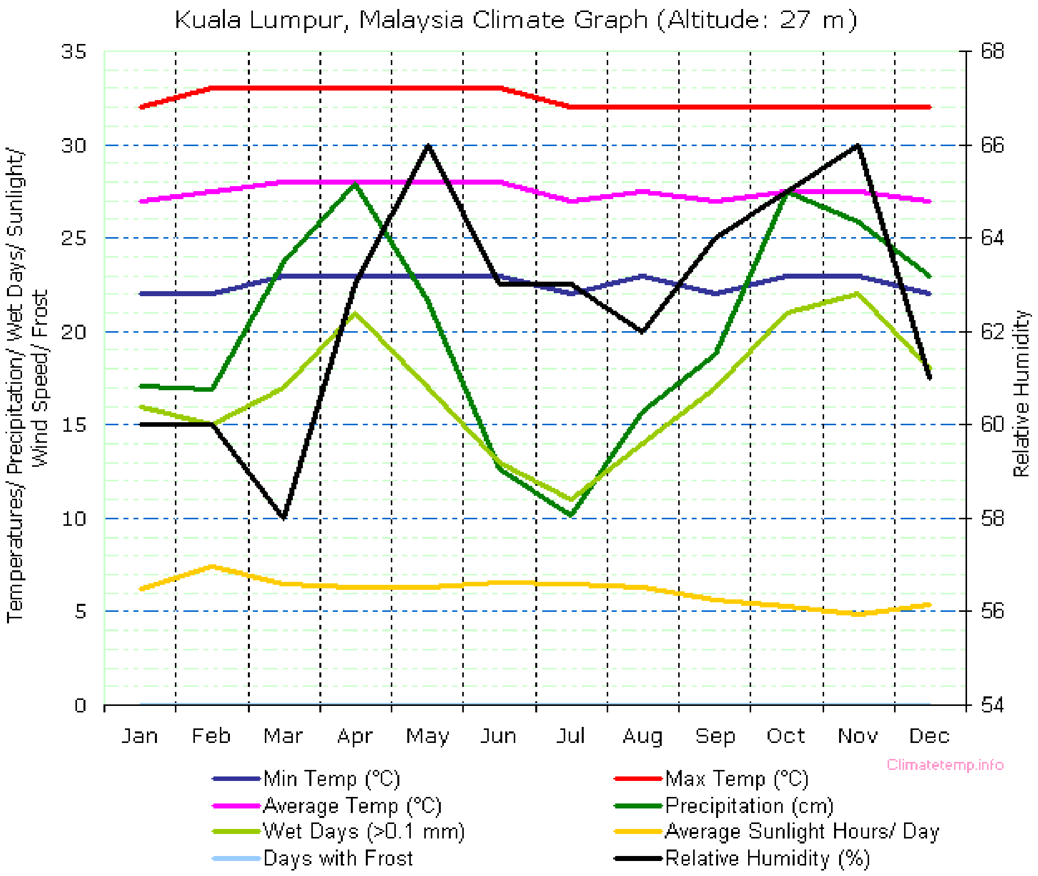


Chart 1.1:Malaysia Weather Chart

Month	Mean Temperature ^{o}C		Mean Total Rainfall (mm)	Mean Number of Rain Days
	Daily Minimum	Daily Maximum		
Jan	22.9	29.8	684.1	22
Feb	23.0	30.2	473.3	17
Mar	23.2	31.3	338.6	16
Apr	23.4	32.3	272.9	17
May	23.6	32.7	241.8	15
Jun	23.3	32.7	220.3	14
Jul	23.0	32.4	185.6	13
Aug	23.0	32.4	229.6	14
Sep	22.9	32.0	262.3	16
Oct	22.9	31.9	338.6	19
Nov	22.9	31.6	371.5	22
Dec	22.9	30.6	498.1	22

Table 1.2: Mean Temperature and Monthly Rain Fall in Kuching

1.2 Theoretical Background

Studies of the condition that effect human comfort have lead to the development of recommended indoor air conditions comfort, published in ASHRAE Standard 55-1992, *Thermal Envonmental Conditions for Human Occupancy*. [1]

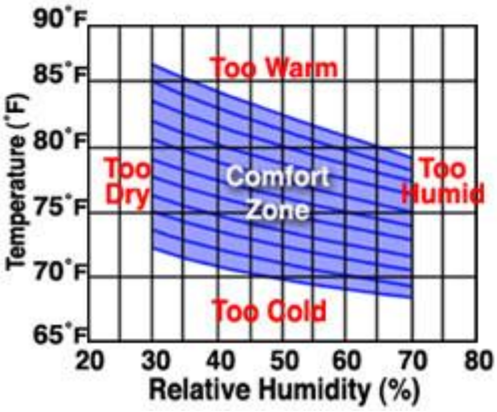


Chart 1.1: Comfort zone of indoor air temperature ans relative humidity. These zones apply to person clothed in typical summer or winter clothing engaged in sedentary activity.

Some of the results of these studies are shown in Chart 1.1. The shaded regions in Chart 1.1are called the comfort zones. They show the regions of air temperature and relative humidity where at least 80% of the occupants will find the environment comfortable. The use of Chart 1.1 valid only for the following conditions:

1. The comfort zones apply only to sedentary or slightly active person.
2. The comfort zones apply only to summer clothing of light slack and a short sleeve shirt, or equivalent 0.5 clothing insulation (0.5clo) and winter clothing of heavy slack, long sleeve shirt and sweater of jacket, or equivalent (0.9clo)[2].
3. The comfort zones apply to air motion in the occupied zone not exceeding 30feet per minute (FPM) in winter and 50FPM in summer[2].
4. The comfort zones apply only under certain condition of thermal radiation between the occupantand the surroundings. For example, an individual receiving direct solar radiation through a window in summer might feet uncomfortably warm even though the rrom air temperature and humidity are within the comforrt zone.

1.3 Problem Statement

As Malaysia strives for the status of developed nation, it propels associated environmental and energy security issues commonly encountered by other developed countries. Subsequently, Malaysia and the rest of the world are faced with challenges to seek equilibrium between environmental sustainability and intensifying development. Many studies showed that residential sector accounts for 30 percent of the total world’s energy demand. Per capita residential electricity demands projected to more than double on 2030 as more households are able to afford most modern electrical appliances, including air conditioning, to improve their lifestyles.

Anybody that has regularly tuned into the news over the last decade or so has probably become tired of all of the green initiatives that the government seem to conjure up. Most of these ideas have revolved around solar technology and insulation improvements although in the midst of all of this, many of the approaches seem to forget about rainwater harvesting as solution to bring near to thermal comfort and saving energy.

Kuching was one of the wettest places in Malaysia with an average rainfall of 4,128 mm (162.5 in) with 247 days of rain a year. With the roof is open to approximately 85,000 litres of water every year it will all going to waste. Therefore, a rainwater harvesting system will collect this water in a butt before supplying it to the house when it required. Unfortunately, this harvesting water cannot be used as drinking water, although it can be used for any sort of washing which doesn’t require pure water. In fact, people overseeing that rainwater harvesting can be used to reduce the energy in the house especially in terraced houses.

1.4 Objective of the Study

The mainobjective of this research is to investigate and compare the effectiveness of rainwater harvesting system to bring thermal comfort condition especially on the terraced house because it a waste for overseeing rainwater harvesting as a medium that can bring comfort condition of mind that expresses satisfaction to an user. This project has aimed some objectives regarding thermal comfort on the building as listed below;

a) Not to neglected the effectiveness of rainwater harvesting system that can bring thermal comfort to the user.

b) To bring near to thermal comfort level to the occupants that not only satisfied the occupants but also to efficient energy consumption.

c) To apply Cooling Load Temperature Difference (CLTD) method in approach of mathematical calculation to calculate the total heat load (energy) in the building and how the rainwater harvesting system can meet the requirement to thermal comfort of the building.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Located near the equator, Malaysia's climate is categorized as equatorial, being hot and humid throughout the year. The average rainfall is 250 centimeter's (98 in) a year[3] and the average temperature is 27 °C (80.6 °F).[4]

Malaysia faces two monsoon winds seasons, the Southwest Monsoon from late May to September, and the Northeast Monsoon from November to March. The Northeast Monsoon brings in more rainfall compared to the Southwest Monsoon,[7] originating in China and the north Pacific. The southwest monsoon originates from the deserts of Australia. March and October form transitions between the two 6 monsoons.[3]

The highest temperature was recorded at Chuping, Perlis on 9 April 1998 at 40.1 °C (104.2 °F). The lowest temperature was recorded at Cameron Highlands on 1 February 1978 at 7.8 °C (46.0 °F). The highest rainfall recorded in a day was 608 mm (23.9 in) in Kota Bharu, Kelantan on 6 January 1967. The highest rainfall recorded in a year was 5,687 mm (223.9 in) at Sandakan, Sabah in 2006. Meanwhile, the lowest rainfall recorded in a year was 1,151 mm (45.3 in) at Tawau, Sabah in 1997.[8] The wettest place in Malaysia is Kuching, Sarawak with an average rainfall of 4,128 mm (162.5 in) with 247 days of rain a year. The driest place in Malaysia is in Chuping, Perlis with average rainfall of only 1,746 mm (68.7 in) a year.[8]

With the climate recorded data, Kuching was the wettest place in Malaysia and most people overseeing the effect of rainwater harvesting system as a medium to bring thermal comfort to the residences.

Rainwater collection is certainly nothing new to humans because have been doing it for thousands of years. However, with the advent of cheap, potable water delivered right to your doorstep, those who harvest rain have become somewhat of an anomaly where in can be an eco-friendly water supply.

Nevertheless it can be used as an energy reduction solution rather using air conditioning system which used more energy consumption.

2.2 Rudoy and Duran (1975) – work lead to GRP to comfort in the modern society

The current Cooling Load Temperature Difference (CLTD) method delineated in ASHRAE GRP 158 (1979) is based on work done by Rudy and Duran (1975). The cooling load due to external heat gain (roofs, walls and fenestrations) and internal heat gains lights, people and equipment) are calculated separately and added to heat gain due to infiltration to obtain the total zone cooling load.

2.2.1 Walls and roofs

[48].The Transfer Function Method (TFM) was used to compute cooling loads for 36 types of roofs and 96 different wall constructions. These cooling loads correspond to the heat gain caused by outdoor air temperature and solar radiation under the following standard conditions.

40deg.	North Latitude
95^{o}F	Maximum outdoor design dry bulb temperature
21^{o}F	Daily temperature range
75^{o}F	Inside design dry bulb temperature
3.0Btu/hr-ft^{2}-^{o}F	Outside heat transfer coefficient
1.46Btu/hr-ft^{2}-^{o}F	Inside transfer coefficient

Hourly cooling for a 24 hour period were converted to Cooling Load Temperature Difference (CLTD) values by dividing the roof or wall area and the overall heat transfer coefficient so that the cooling load could be calculated for any wall or roof by the following relation:

$$q = U \times A \times CLTD \qquad (1)$$

Where,

q = Cooling load, BTU/hr.

U = Overall heat transfer coefficient, BTU/hr-ft^2-^{o}F

A = Area, ft^2.

CLTD = Equivalent temperature difference, ^{o}F.

CLTDs were calculated for 96 types of walls for a medium type of zone construction. The CLTDs were analyzed for similarity in profile as well as the absolute value. Walls were then grouped in 7 different categories and CLTDs were calculated for 8 facing directions.

CLTDs were calculated for 36 types of roofs. The normalized profiles of these roof CLTDs were found to be quite similar. In the paper (1975), Rudoy suggested listing only the peak value, the hour of its occurrence and the range of values for each roofs into 13 categories with suspended ceilings, and 13 without suspended ceiling making 26 categories in all. It appears that the same technique was eventually applied to roofs as to walls. Both wall and roof CLTDs were published for the month of July only. The following equation was given to adjust for other latitudes and months and other indoor and outdoor design temperatures.

$$CLTD_{corr} = (CLTD + LM) \times K + (78 - T_R) \times (T_0 - 85) \qquad (2)$$

Where,

LM = Latitude moth correction factor, found in a table

K = Color adjustment factor, applied after latitude moth correction

T_R = Room temperature, ^{o}F

T_0 = Outdoor temperature, ^{o}F

It is not clear from either the paper or GRP 158 manual how this equation was derived.

The drawbacks with the CLTD method for walls and roofs are;

1. The wall and roof groups don’t cover the range of possible constructions well.
2. Complicated and questionable adjustment are required if a wall of roof does not match one of the group listed. (e.g. for each 7 increase in R-value above that of the wall structure in the listed group, move on one group if insulation is on interior of structure and two groups if on exterior.
3. The inaccuracy of correcting for other months and latitudes can be significant.

2.2.2 Fenestration/ Opening

To find the cooling load due to fenestration the heat gain was divided into radiant and conductive portions. The Cooling load due to conduction was calculated using the same relation used for roof and walls, Eq. 1.

CLTDs for windows (which can also be applied to doors) were listed for standard condition and relation was provided to correct for outdoor daily average temperature other than 85^{o}F and indoor temperature other than 78^{o}F. The CLTDs are calculated for 40 deg. N. latitude which causes some error for other latitudes, but the conduction load from fenestration is such a small portion of the overall load that this was deemed negligible.

To find the radiant portion of the cooling load the solar heat gain for each hour through a reference glazing material (double strength (1/8 in.) sheet glass) was calculated for different fenestration orientation using the ASHRAE clear sky model. The heat gain was converted to cooling load using the room transfer function equation. Cooling loads corresponding to theses heat gain were calculated for light, medium and heavy zone construction without interior shading and for zones with interior shading. A cooling Load Factor (CLF) was derived for each hour of the day so that the cooling load for that hour could be found by multiplying the maximum solar heat gain for the day by the hourly CLF as follows:

$$q_r = SHGF_{\max} \times CLF \tag{3}$$

Where,

q_r = cooling load for reference glazing system, BTU/hr

$SHGF_{max}$ = Maximum solar heat gain factor BTU/hr

CLP = Cooling load factor, ratio cooling load to maximum solar heat gain

To account for glazing system other than the reference system a shading coefficient was developed.

$$SC = \frac{\text{Solar heat gain of fenestration system}}{\text{Solar heat gain of reference glass}} \tag{4}$$

So that the cooling load for a particular glazing system would be:

$$q = SHGF_{\max} \times SC \times CLF \tag{5}$$

CLFs were listed for July 21 at 40 deg north latitude. These CLFs were considered to be representative of all summer months (May through September) at all northen latitudes. The maximum solar heat gain ($SHGF_{max}$) was listed foe all directions, months and northen latitudes from 0 to 60 deg in 4 deg intervals. The cooling load at a particular latitude by the CLF calculated for July at 40deg north. This was the worst problem with the old manual since CLFs calculated for the month of July could be significantly different from those for other months and CLFs calculated at 40 deg north latitude could be significantly different from those corresponding to other latitudes. These error could well be additive when calculating cooling loads for other months and latitudes.

2.2.3 People

An energy balance for the human body was developed for the following range of conditions:

1. The skin temperature was varied between 100^{o}F and 80^{o}F.
2. The clothing type was varied from typical business suit to light summer clothing.
3. The temperature of the outer surface of the clothed body was varied between skin temperature and air temperature.
4. The average height of the people was varied from 5.33 ft to 6 ft.

The room temperature was held constant at 75^{o}F. The result of the energy balance yielded a convective fraction ranging from 24.58% to 33.58% with a mean average value of 29.65%.

Based on the previous calculations a convective fraction was of 30% was deemed to be a reasonable representative value. CLFs were derived for a medium weight zone for each hour of the day. These CLFs were derived by calculating the cooling load corresponding to a unit heat gain, in this zone type, using the room transfer function equation. The CLFs were tabulated for various occupancy profiles. The cooling load due to people is then calculated as follows:

$$q = N(q_S \times CLF + q_l) \tag{6}$$

Where,

q = Cooling load, BTU/hr

N = Number of people

q_S = Sensible heat gain per person, BTU/hr

q_l = Latent heat gain per person, BTU/hr

2.2.4 Equipment

An energy balance was developed for many common appliances with several simplifying assumptions applied. The energy balances yielded convective fractions between 32% and 46% for the equipment. A convective fraction of 40% was deemed to be appropriate and the room transfer functions were applied to the heat gain to derive cooling loads corresponding to the appliance heat gain. CLFs were derived analogously to those for people. As with people, the latent portion was assumed to become instantaneous cooling load. The cooling load due to appliances then becomes:

$$q = q_S \times CLF + q_l \tag{7}$$

Where,

q = Cooling load, BTU/hr

q_S = Sensible heat gain per person, BTU/hr

q_l = Latent heat gain per person, BTU/hr

CLF = Cooling load factor, ratio

One table was published to cover all zone constructions; this does not allow for variations in zone construction which somewhat limits accuracy in the case of extremely light or heavy zones.

2.2.5 Light

Mitalas (1973) described the cooling load corresponding to heat gain from lights by a transfer function of the following form:

$$q_t = a_1 W_{t-1} + a_2 W_{t-2} + b q_{t-1} \tag{8}$$

Where,

q_t = Cooling load from light at time = t

W_t = Power input to lights at time = t

a_l = Coefficient dependant on light ficture and ventilation arrangements

b = Coefficient dependant on circulation, type of return and floor weight

a_2 = $1 - b - a_1$

Cooling loads for lights, corresponding to unit heat gains or power inputs were calculated for lights on for 8 to 16 hours duration in two hour increment using this equation. These hourly cooling loads were calculated for a 24 hour period. The cooling load induced by a unit heat gain is defined as the Cooling Load Factor (CLF). These CLFs were grouped into 4 groups depending on the permutations of a_1 and b coefficients tables were supplied to determine these coefficients for a given light system. The cooling load due to lights was then found with the following equation:

$$q_S = 3.41 \times q_i \times F_u \times F_S \times CLF \tag{9}$$

Where,

q_s = Sensible cooling load, BTU/hr

3.41 = Conversion factor BTU/hr per watt

q_i = Total lamp wattage, W

F_u = Fraction of q_i in use

F_S = Ballast allowance factor for fluorescent fixtures

CLF = Cooling load factor

2.3 Harris and McQuiston (1988) – methods for grouping walls and roofs

To use the CLTD method for walls and roofs, one had to determine which wall or roof type a particular surface matched. To do this the overall conductance and the product of mass time specific heat was determined for the surface in question. If a surface did not exactly match a wall or roof listed, a complicated set of instructions were followed to pick the best match. This method was tendicious to apply and its accuracy was questionable under certain conditions.

Harris and McQuiston (1988) performed a study to devise a method for grouping walls and roofs with similar transient heat transfer characteristics, in order to obtain a compact set of conduction heat transfer which would cover a broad range of constructions.

The walls and roofs were classified on the basis of their thermal lag and amplitude characteristics. The thermal or time lag is defined as the time between peak input and peak output heat gains while the amplitude ratio is defined as the ratio of peak output to peak input heat gains. The reference heat input is defined as follows.

$$Q_{ref} = Ah_oT_e \tag{10}$$

Where,

A = area

h_o = Outside coefficient of heat transfer

T_e = Sol air temperature

The output heat gain is found with the conduction heat function equation as follows:

$$q_{i-j} = A\left[\sum_{n=0} b_n(t_{e-j-n}) - \sum_{n-1} d_n(q_{i-j-n}/A) - t_i\sum_{n=0} C_n\right] \tag{11}$$

Where,

q_{i-j} = Heat gain inside the zone, Btu/hr

A = Area, ft^2

$b_nd_nC_n$ = Conduction heat transfer coefficients

t_e = Outside temperature, ^oF

t_i = Inside temperature, ^oF

The amplitude ratios and time lags were studied for 2,600 walls and 500roofs. The walls and roofs were grouped on the basis of these thermal characteristics in 41 groups of walls and 42 groups of roofs. The normalized amplitude ratios in each group were within +0% and 20% and the thermal lag within ± one hour in each group.

Correlation methods were used to find correlation between the amplitude ratio and time lag and the wall or roofs physical properties or geometry. Important grouping parameters for walls were found to be:

1. Principal wall material (the most massive material in the wall)
2. The material the principal material is combined with (such as gypsum etc.)
3. The R value of the wall
4. Mass placement with respect to insulation (mass in, mass out or integral mass).

Important grouping parameters for roofs were found to be:

1. Principal roof material (the most massive material in the roof)
2. The R value of the roof
3. Mass placement or absence of a suspended ceiling

Using these parameters one can determine into which of the 40 plus groups a particular wall or roof will fall. Each group was assigned a unique set of conduction heat transfer coefficients so as to produce conservative results. These conduction heat transfer coefficient are to be used in the conduction transfer function equation to calculate a representative heat gain for any wall or roof in that particular group.

2.4 Sowell (1988a,b&c) – zone classification & weighting factor development

It has been found that the weighting factors developed by Mitalas and used by Rudoy in GRP 158 are not applicable to all zones. The problem is that these weighting factors do not reflect the effects of many design parameters now known to be important. Thus to insure accurate cooling load calculations for a wide range of zones further research became necessary.

Three papers published by Sowell detail the methods used to classify and group 200,640 parametric zones. The first paper (Sowell 1988a) defines the objectives of ASHRAE research project 472(RP-472) to be:

1. Validate the methodology for calculation of zone dynamic thermal responses to several heat gain components, and
2. To classify zones according to dynamic thermal response characteristics, accounting for full ranges of variation of: floor plan, zone height, number of exterior walls, per cent glass, partition type, interior shading, zone location, slab type, mid-floor construction, wall construction, roof construction, floor covering, ceiling type, and furnishings.

Weighting factors are used to calculate the zone cooling load at time t, $Q_t$based on past loads and current and past heat gains using the relation:

$$Q_t = V_0 q_t + V_1 q_{t-1} + V_2 q_{t-2} - W_1 Q_{t-1} - W_2 Q_{t-2} \tag{12}$$

Where,

Q_t = cooling load at time t
V_i and w_i = weighting factors
Q_t = heat gain at time t

Previous cooling loads and heat gains are initially assumed to be zero and calculation are performed in an iterative manner until the results for a 24 hour cycle converage.

The weghting factors reported in RP-472 were normalized by dividing the V_i by a factor:

$$F_c = (V_0 + V_l + V_2)/(1 + W_l + W_2) \tag{13}$$

This has the effect of "insulting" the zone so that no input heat gain can conduct back to the outside air. To normalize the V_i should be multiplied by the F_c appropriate for the zone being analyzed.

2.5 Thermal comfort

Thermal comfort is complex and partly subjective. It depends on many factors, of which air temperature, humidity, air movement, thermal radiation, the metabolic rate and the level of clothing are fundamental. The impacts of these factors on the thermal balance of the human body irrespective of adaptation to the local climate form the basis on which theoretical comfort models/ standards, such as Fanger's PMV [11], its derivative ISO 7730 and most versions of ASHRAE Standard 55, were developed. However, adaptive models, such as those developed by Auliciems[12], Humphreys [13] and Szokolay[14], also consider acclimatization an important factor in comfort sensation. This difference leads to the adaptivemodels predicting comfort zones which vary according to the prevalent local climates, while the theoretical models predict comfort zones which are independent of local thermal conditions. Results from a large number of field studies have indicated that theoretical models which neglect the impact of acclimatization can significantly underestimate the thermal and humidity tolerance of the occupants of free running buildings in hot humid climates [15]. For example, while ASHRAE Standard 55-1992 Addenda 1995 [24] suggests that the summertime comfort zone ranges from about 23.5^{o}C at 25% relative humidity (RH) to about 26$_{o}$C at 60% RH, comfort is experienced at a temperature as high as 32$_{o}$C at over 85% RH in Bangladesh [19], and within higher ranges of temperatures and relative humidity's of 25-31.5$_{o}$C and 62.2-90% RH in Thailand [15]. Adaptive models, however, usually predict comfort zones which are closer to the field study results. This tolerance to relatively high temperatures and humidity's is likely to be a result of adaptive activities, such as opening windows and removing clothes, which form part of the daily life in hot humid climates [25], as well as the homoeothermic mechanisms of the body. Indeed, the degree of adaptive opportunity can influence thermal comfort expectation: people tend toaccept warmer environments more readily in their homes than in offices, as they have more control over their environments and activities in the former situation[25]. Such impact of acclimatization in extending the comfort zone suggests that passive design probably has greater potential to provide thermal comfort in hot humid climates than is generally believed. Also, theoretical comfort standards which neglect acclimatization, such as ISO 7730: 2005 [26], are likely to be inappropriate for free-running buildings in hot humid climates. The impact of acclimatization observed in the above field studies has also led to the modification of existing comfort standards/models. A key example is the work by de Dear and Brager[23] that contributes to the introduction of an adaptive comfort model for naturally conditioned spaces for the first time in ASHRAE Standard 55, in its 2004 version [27]. Other examples include the work by Srivajana[20] that adjusts the Standard Effective Temperature (SET) comfort scale originally defined by Gagge et al. [27] to accommodate prediction of thermal sensation under higher air velocities and lower clo values commonly found in hot humid climates. Jitkhajornwanich[17] modifies Olgyay's bioclimatic chart [29] to take into account the acceptance of higher temperatures and humilities in hot humid climates (Figure 1). And Khedari et al. [18] put forward a ventilation comfort chart for a higher range of indoor air velocities often encountered in the climates. As attempts to identify the appropriate comfort zones for different local conditions continue, the impact of humans' acclimatization to global warming on their thermal tolerance and preference should perhaps also be taken into consideration. To observe and understand this impact, research which involves long-term monitoring is probably required. Moreover, as the economies of certain parts in hot humid regions grow peoples' tolerance to higher temperatures and humilities may diminish due to increased expectations [22]. The impact of economic and social factors on thermal sensation is another area which offers opportunity for research.

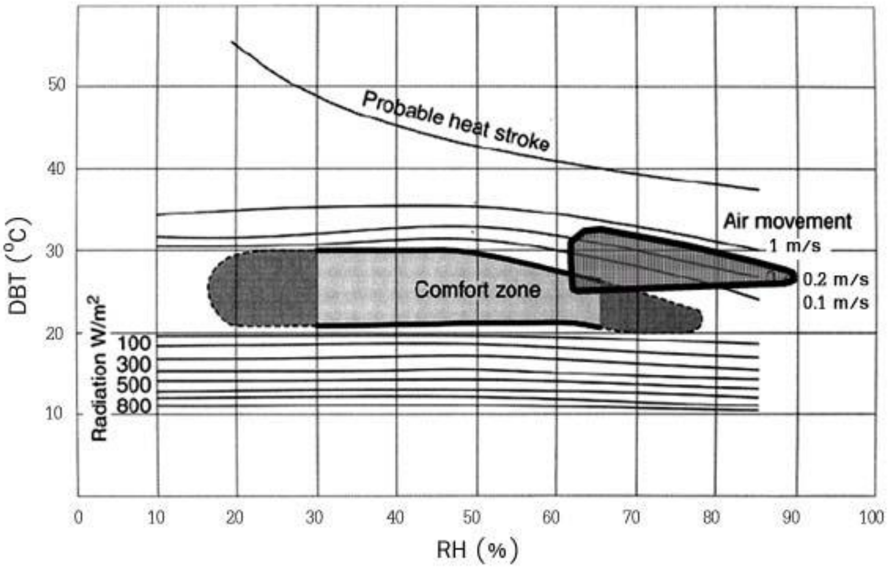


Figure 1.1: Bioclimatic chart modified for hot humid climates (adapted from Olgyay[30] followingJitkhajornwanich[15]). The new comfort zone is shown on the right of the original one.

2.6 Design for Minimizing Cooling Requirement

In hot humid climates, a significant amount of energy can be saved if cooling needs can be minimized. In general, to achieve this, solar and conductive heat gains should be contained,and natural ventilation promoted for cooling and humidity removal. Some of the key strategies for minimizing cooling needs involve appropriate orientation and spatial organization, shading, and appropriate use of materials, colors, textures and vegetation.

2.6.1 Orientation and Spatial Organization

Orientation and spatial organization affect the ability of a building to ventilate and receivesolar radiation. To minimize solar gain and maximize ventilation, traditional buildings in hothumid climates usually employ spread-out plans and permeable internal organization (Figure 1.1)

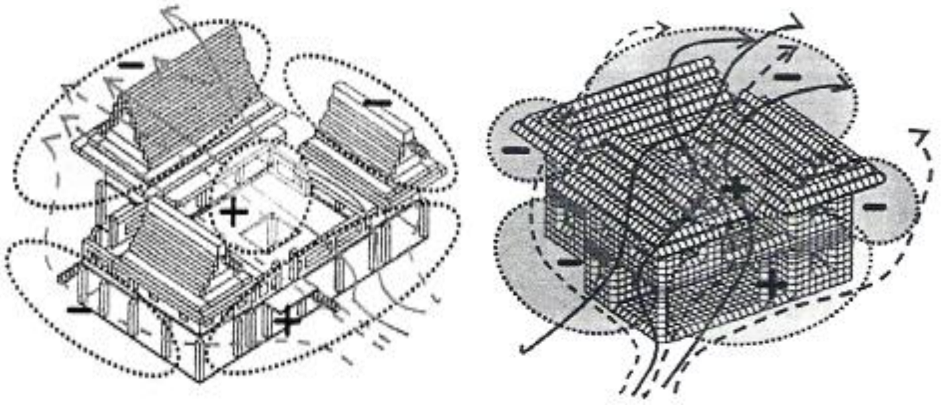


Figure 1.2:The orientation and spatial organization of a traditional Thai house [30].

By orientating the longer sides of the buildings to intercept prevailing winds and theshorter sides to face the direction of the strongest solar radiation, effective ventilation can beachieved, while thermal impact from solar radiation is minimized [31]. Such strategy can also be applied effectively to modern buildings, both in smaller scales, such as houses [30,32] and larger scales, such as residential blocks [35,37] and campuses[38]. However, work is still required to overcome the challenge of applying such orientation and spatial organization to commercial buildings in high density areas, such as high-rise offices, so that a balance is struck between comfort, energy use and commercial feasibility.

2.6.2 Shading

Solar gain through windows is often a major component of the heat gains of a building. Also, solar radiation on the opaque parts of the building envelope raises the surface temperatureof the envelope and contributes to the heating of the interior environment. A number of investigations highlight the importance of providing effective shading as part of the overall strategy for preventing overheating in hot humid climates [36,39]. Of these, some also present results which suggest that shading opaque areas, such as walls and roofs, is probably of no less importance than shading glass areas [39,41]. Figure 1.2Examples of modern buildings which employ spread-out plans and permeable spatial organization to achieve good ventilation: a modern house (a [30]), a residential block (b [35]), and a campus (c [38]). The bottom diagram in shows the age of air among the residential units as simulated by a computer programs the prevalence of lighter tones signifies good overall ventilation. Figure 1.2 shows air movement among the campus buildings as **(c)** simulated by a flow visualization table.

Effective shading can be provided by various means, including dedicated shading devices, nearby structures, vegetation and special glasses. Generally, external shading devices are considered the most effective, since they intercept solar radiation before it passes through the building envelope into the interior space. An appropriately orientated high-pitched roof which affords self-shading and allows only one side of itself to received direct solar radiation at a time is another possible shading technique [46]. A key issue which should be considered in shading design is its tendency to conflict with day lighting. Reduced daylight penetration due to inappropriate shading design can increase the demand for artificial lighting, which then offsets the energy savings from reduced heat gains [47]. Such a conflict can be lessened, for example, by using interior surfaces of high reflectance values, such as those in light colors, or using light shelves to reflect daylight into the deeper part of the interior [47]. Movable shading devices, such as louvers, which allow the occupants to adjust their local lighting and thermal environment, are another solution. When shading is provided by a special glass, the choice of glass is essential for balancing the benefit of heat gain reductionwith that of day lighting. Work is still required to identify the appropriate types of glass for free running buildings in hot humid climates, although some suggestions have been made with regard to their air-conditioned counterparts. Overall, research opportunity is still open for developing quantitative principles of shading that will balance thermal and energy benefits with day lighting quality. Shading as provided by vegetation is discussed in Section 3.4.

2.6.3 Material, Color and Texture

In hot climates, materials for building envelopes and the surrounding surfaces, such as walkways and terraces, should help minimize heat gains into the buildings. A survey [31] shows that many traditional buildings in hot humid climates use lightweight materials along with relatively permeable constructions, such as wooden walls with ventilation gaps and woven bamboo strip flooring, to allow the interiors to cool rapidly in the evening following the outside air temperature, and achieve a relatively comfortable environment during sleeping hours. Such materials often provide poor thermal insulation, and so to reduce heat gains shading is given for the buildings and the surrounding areas in the form of projected roofs, shutters and vegetation, for example. However, such uses of traditional materials may no longer be appropriate today, particularly in urban areas, due to increased pollution levels andpopulation densities, along with the diminished availability of traditional materials, among other things. For many regions in hot humid climates, modern materials produced using technologies imported from colder and drier climates, such as plasterboards, lightweight concrete blocks and insulations have become prevalent. As more new materials enter the market, effort has been made to identify their properties, notably their thermal conductivities and water absorptions, in order to develop a database which will be useful for low-energy building design. However, information is still lacking with regard to the thermal capacities of many of these materials. To minimize thermal impact from solar radiation, multiple layers of materials may be required to make up a building envelope (Figure 1.3). A layer of insulation, such as foam or glass fiber, is probably required to cut effectively conductive heat transfer through opaque surfaces which receive strong solar radiation. In addition, a ventilation gap may be beneficially provided between the different layers of the envelope materials to vent excessive heat accumulated within. Such a gap may also be internallylined with a reflective material, such as aluminum foil, to help block radiated heattransfer. Furthermore, double-glazing with low-emissivity coating, more commonly found in colder climates, may be used to reduce appreciably the ingress of heat building up on the external glass surface. Thermal mass materials are probably appropriate for spaces used during daytime as they delay heat transfer into the interiors during working hours, whereas lightweight materials are more appropriate for spaces used at night, as they allow the interiors to cool down quickly during sleeping hours [43]. To prevent heat accumulation at night in well insulated, high-mass buildings with multi-layered glazing, effective ventilation of the buildings structures should be provided. Also, the color and texture of the building envelopes and the surrounding surfaces are important. In general, lighter colors and smoother surfaces lead to lower surface temperatures, and therefore are desirable from the thermal comfort point of view. Indeed, it has been shown that in hot humid climates a white roof can

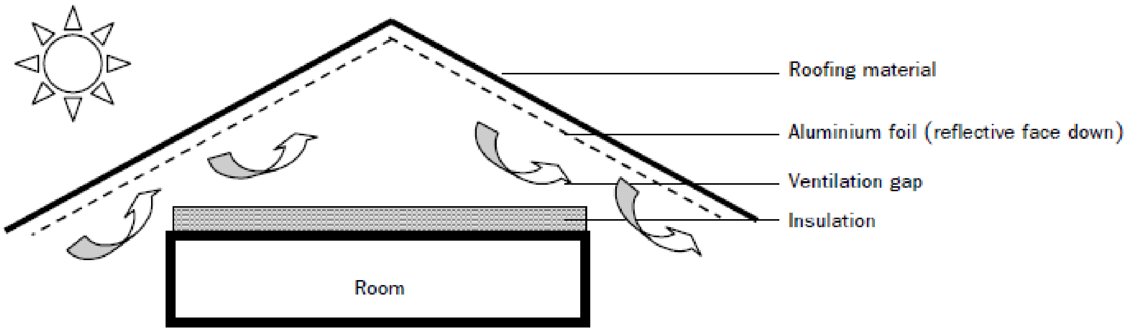


Figure 1.3 A schematic of a roof section showing an example of a combined use of insulation, a ventilation space and reflective lining to minimize thermal impact from solar radiation on the interior environment.

have an average diurnal temperature which is a few degrees lower than that of the outside air, owing to its 24-hour long-wave radiant loss being greater than the net solar energy it absorbs. In addition to the use of traditional and imported materials, a number of new materials have been developed in hot humid climatesusually from local raw materials, such as agricultural wastes. Examples include particleboards from a mixture of rice straw and rice husks, and veliger grass; insulation boards from cassava and corncobs; a composite concrete from a combination of durian peel, coconut fiberand coconut coir; a brick from a combination of soil and coconut coir; a cement board from coconut coir; a concrete block from oil palm fibers and bagasseand sandwich walls from rice straw and rice husks. Some of these materials, such as the cement board from coconut coir, have lower thermal conductivities than those of conventional materials such as bricks and concrete, and in this regard are more appropriate for construction in hot climates. Work is required to identify more of such high-potential materials and develop them for wider commercial use. Attention should be given in particular to the ability of the materials to absorb and release accumulated moisture, given the high levels of humidity in hot humid climates.

2.6.4 Vegetation

Vegetation can be an effective means of moderating the temperature around a building andreducing the building’s cooling requirement. Vegetation in the form of trees, climbers, highshrubs and pergolas, for example, can provide effective shading for the building’s walls andwindows. Ground cover by plants also reduces the reflected solar radiation and long-wave radiation emitted towards the building, thus reducing solar and long-wave heat gains. The evaporate inspiration process also cools the ambient air and nearby surfaces. Furthermore, climbers over the walls can reduce the wind speed next to the wall surfaces and provide thermal insulation when the exterior air temperature is greater than that of the walls. Fieldwork in hot humid climates has reported the ability of plants to lower the ambient temperature appreciably, with areas such as urban parks often found to be a few degrees Celsius cooler than the surrounding built-up areas. Also, the average temperature of buildings’ walls which are shaded by plants can be 5-15$_{o}$C less than that of unshaded ones, depending on the local climates and planting details [39]. Likewise, a roof garden can attain a temperature 10-30$_{o}$C below that of an exposed roof surface, depending on the roof construction, planting details and surrounding conditions. To complement such field studies, quantitative planting principles should be developed which will help optimize the cooling effect of vegetation, especially when it is used in conjunction with/in place of conventional shading devices and insulation. Attention should be given to balancing the benefits from temperature reduction with the adverse effects from increased humidity due to the evaporate inspiration process, especially when plants are grown near ventilation inlets. Optimization of the use of local plants should also be explored.

2.7 Cooling Techniques

Even with the best effort to reduce heat gains, cooling requirement may not be eliminated. In such cases, a range of passive cooling techniques may be employed to help achieve thermalcomfort. Key cooling techniques for hot humid climates involve appropriate utilization of natural ventilation, thermal mass and heat dissipation by radiation and evaporation.

2.7.1 Ventilated Cooling

Ventilation provides cooling by enabling convective heat transfer from a warm building's interior to a cool exterior. Also, sufficiently high indoor air velocities give the occupants direct physiological cooling. In a natural system, ventilation can be accomplished by either wind, buoyancy or a combination of wind and buoyancy.

a) Ventilated Cooling by Wind

This technique relies on wind force to produce pressure differences between the interior and exterior of a building, which in turn lead to internal air movement and heat removal from theinterior. Sufficiently high indoor air velocities can also increase appreciably convective heat transfer from the occupants' skins and clothing and the rate of skin evaporation, the net effect of which is physiological cooling. With an indoor air speed of around 1.5-2.0 m/s, ventilation can provide comfort in regions and seasons when the maximum outdoor air temperature does not exceed about 28-32$_{o}$C, depending on the humidity level and the acclimatization of the population [80]. Such climatic conditions are common in hot humid climates, and work in the regions shows that thermal comfort can be brought about for an appreciable part of the year (of order 20% according to Tantasavasdi et al. [32-34] and Tantakitti and Jaturonglumlert) by allowing wind to induce sufficient indoor air movement. However, an indoor air velocity above 0.9 m/s may be considered excessive for a working environment [20], due to it being able to disturb loose paper [9]. Several investigations [32-34] agree that, in general, to achieve effective ventilation in hot humid climates at least two large operable windows should be provided on different walls, preferably one opposite the other, with one of them intercepting the prevailing wind (Figure1.6a). When the windows cannot be orientated to face the wind, wind deflectors, which may be in the form of appropriately placed internal partitions, can be employed to channel air through the occupied zone (Figure 1.6b)[33-34]. Obstruction of the air path should be minimized (Figure 1.6c) [33-34]. Furthermore, windows should be at the body level (Figure 1.4).Examples of opening design to encourage interior air movement [34]. to increase potential for physiological cooling. To complement these qualitative guidelines, quantitative design principles for maximizing the cooling effect of wind in hot humid climates should be developed.

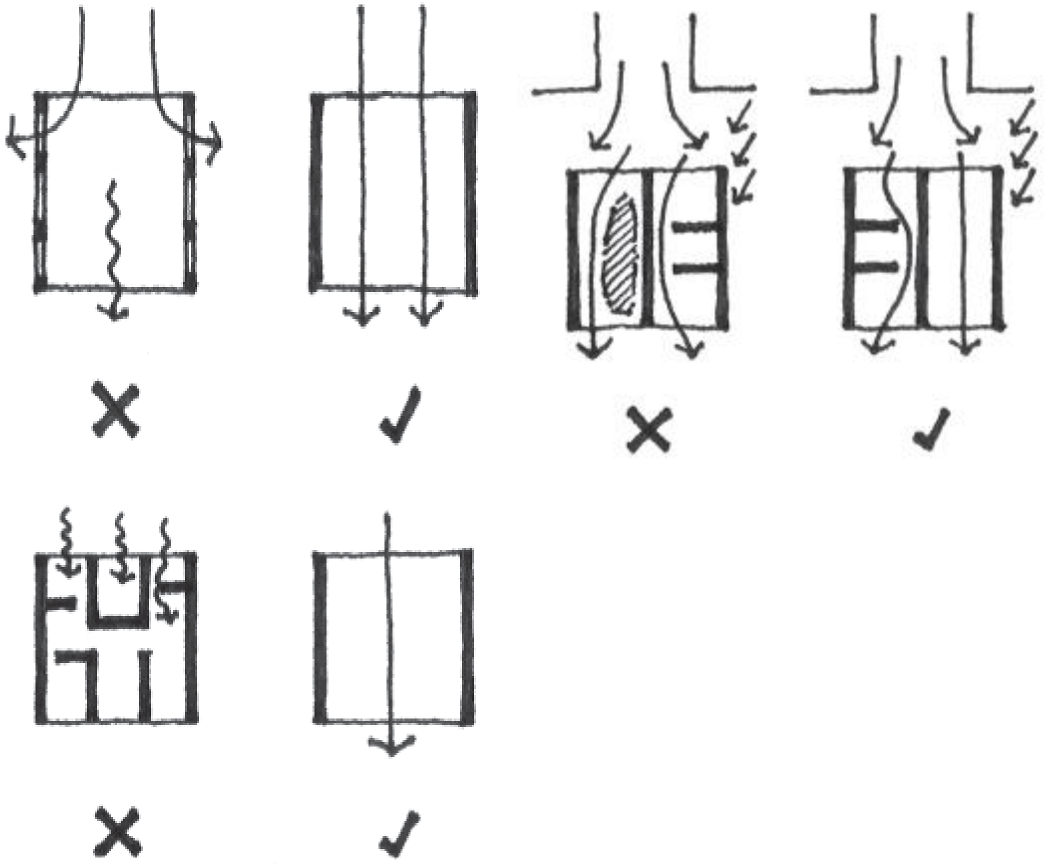


Figure 1.4: Examples of opening design to encourageinterior air movement [34].

b) Ventilated Cooling by Buoyancy

This technique relies on temperature differences between the interior and exterior of a building to produce pressure gradients across the vents and drive the ventilation. Such temperature differences are usually a result of the heating by the occupants, lighting and other internal heat sources. While buoyancy-driven ventilation may be used to keep the interior temperature from rising excessively above the exterior and supply sufficient fresh air, the movement of indoor air achieved by this technique is usually insufficient to provide physiological cooling: computer simulations have shown houses fitted with ventilation chimneys being able to achieve a maximum indoor air velocity of only about 0.1 m/s, for instance [33-34].In general, to maximize the heat removal potential of buoyancy-driven ventilation, the vent area should be maximized, along with the vertical distance between the inlet and outlet. Additional buoyancy can be provided to increase the heat removal rate without raising the interior temperature by using solar radiation to heat a part of the ventilation path that is sufficiently separated from the occupied space. Such techniques may be implemented in the form of the so-called solar chimney (Figure 1.5), for example, which appears to have potential in hot humid climates where solar radiation is strong. Work on the solar chimney shows that the optimum width of a chimney is independent of solar intensity, but is dependent on the height of the chimney itself, the size of the room inlet and the size of the chimney inlet [89]. Furthermore, greater flow rates can be achieved when the chimney is inclined appropriately according to the latitude in which it is used or made of a low-emissivity material to minimize radiateheat loss through its walls.

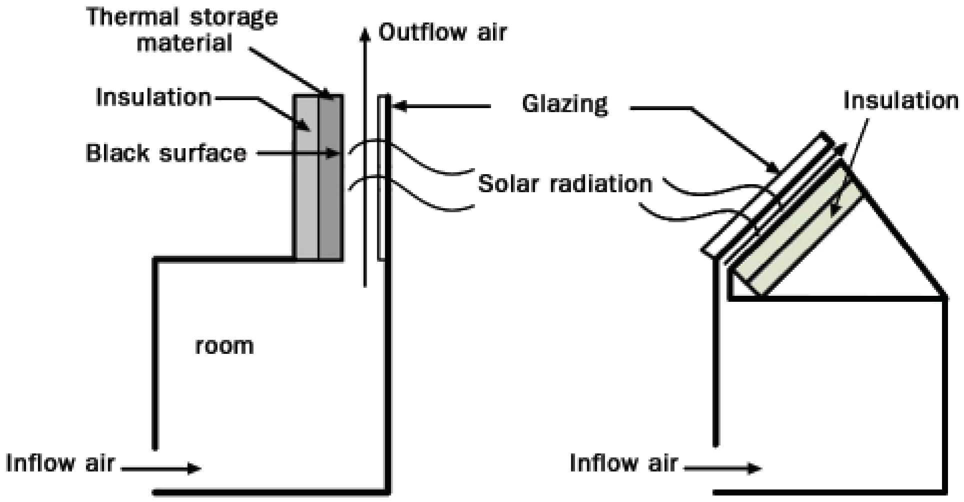


Figure1.5:Examples of solar chimney configurations: vertical (a) and inclined (b)

Driven ventilation can be enhanced further by pre-cooling intake air, by means of thermal mass or a low-energy groundwater heat exchanger, for example. This will allow the interior to be cooled below the exterior, and achieve thermal comfort when the exterior temperature is uncomfortably high. Chenvidyakarn and Woods described the fluid mechanics of this technique; more work is required to develop the idea for use in hot humid climates. In addition, strategies should be explored to maximize the cooling potential of buoyancydrivensystems which exploit complex combinations of sources of heating and cooling often available in modern buildings, such as occupants, ingress solar radiation, heated envelopes, thermal mass, lighting and machinery. Attention should be given in particular to the resultant interior temperature structures which hold the key to the control of flow patterns and thermal comfort. Wind could also be introduced to a buoyancy-driven system to promote heat removal and physiological cooling; this is discussed in Section 4.1c below.

c) Ventilated Cooling by Combined Wind and Buoyancy

The presence of wind can reduce or enhance the cooling potential of buoyancy-driven flows. Wind will assist buoyancy when the inlet is located on a windward side and the outlet is located on a leeward side (Figure 1.6a). The result is a greater indoor air velocity and greater cooling. In contrast, wind will oppose buoyancy if the inlet is placed on a leeward side while the outlet is on a windward side. In this case, if the magnitude of the wind-produced velocity is smaller than the buoyancy-produced velocity, the net flow will be reduced along with the cooling effect (Figure 1.6b).

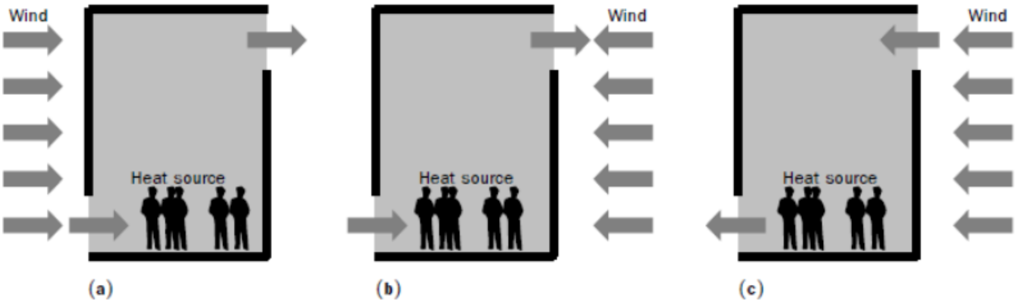


Figure 1.6: Wind-assisted ventilation (a); buoyancy dominated, wind-opposed ventilation (b); and wind dominated, wind-opposed ventilation (c).

However, if the wind-produced velocity exceeds the buoyancy-produced velocity, the net flow will be greater, although the flow regime will be reversed following the direction of the wind (Figure 1.6c). Greater cooling may be expected as a consequence. Such interaction between wind and buoyancy highlights the need for locating the ventilation inlet and outlet appropriately to optimize the cooling potential of natural ventilation. This may be achieved by placing them according to the prevailing wind direction, for example. Alternative solutions include using ventilation terminals that incorporate weather vanes to allow automatic orientation of the inlet/outlet according to the wind direction, or ventilation terminals that have openings on all sides. Relatively little work has been done inhot humid climates to explore the cooling potential of ventilation driven by combined wind and buoyancy. Indeed, more investigation is required to develop generic design principles which will help optimize the cooling potential of this technique and complement the knowledge gained from specific case studies. Special attention should be given to the impact of the interaction between wind and buoyancy on the interior temperature structure and thermal comfort. Insights could be drawn from relevant fluid mechanics work.

2.8 Thermal Mass

Thermal mass can be defined as a material that absorbs or releases heat from or to an interior space. It can delay heat transfer through the envelope of a building, and help keep the interior cool during the day when the outside temperature is high. Moreover, when thermal mass is exposed to the interior, it absorbs heat from internal sources and dampens the amplitude of the interior temperature swing. Thermal mass can be utilized in several ways. The mass may be integral to the building envelope to provide direct cooling, or it can be remote, such as the earth under or around a building, through which fresh air is passed and cooled before entering the occupied space. Traditionally, thermal mass is used in hot humid climates predominantly in public buildings of social/religious importance, such as temples, whose heavy masonry envelopes also satisfy the need for durability. Appreciable reduction of the indoor temperature can be achieved in such buildings, with indoor air maxima about $3_{\circ}$C below outdoor air maxima having been observed in some cases. For modern buildings in hot humid climates, small-scale experiments and computer modeling[36, 43] suggest that thermal mass can make an appropriate envelope material for spaces used primarily during the day, e.g. living rooms, since it can help keep the interior cool during the occupied period. However, thermal mass is inappropriate for spaces used mainly at night, e.g. bedrooms, as the mass usually releases heat to the interior during that period and may warm the space to an uncomfortable temperature. To optimize the daytime cooling capacity of thermal mass, the mass should be ventilated at night to allow relatively cool night air to remove heat absorbed in the mass during the day. Such use of nocturnal ventilation in conjunction with thermal mass is more common in hot dry climates, which have relatively high diurnal temperature swings and low minimum night-time temperatures. Nevertheless, computer simulations suggest that this technique may also have potential in hot humid climates where night-time temperatures are generally higher and diurnal temperature swings smaller. A reduction in the indoor temperature of about 3-6$_{o}$C below the exterior air may be achievable, depending on the local climate, the amount of mass, its distribution and the ventilation details. More field and theoretical work are required to develop strategies to optimize the use of thermal mass and night ventilation in hot humid climates, particularly in institutional and commercial buildings which are occupied mainly during the day. Attention should also be given to the control of condensation in the structure or of the air that comes into contact with cool mass, given relatively high dew point temperatures in these climates.

2.8.1 Radiant Cooling

When two surfaces of different temperatures face one another, radiate heat exchange will occur between them. Radiant cooling relies on this mechanism to dissipate heat from a building or an occupant’s body. One of the more common radiant cooling systems uses the roof of a building as a radiator to dissipate heat to the night sky. This process cools the roof, which in turn serves as a heat sink for the occupied space underneath. The effectiveness of such a system depends chiefly on the details of the roof and the local climate. It will work well in hot humid climates only when the skies are predominantly clear: in such conditions, ambient night air passing near the roof could be cooled by about 2-3$_{o}$C, which could then be channeled into the building to provide additional cooling (Figure 1.7). To enhance the performance of such a system further, a desiccant bed can be incorporated in the roof structure to dehumidify the passing air. More work is still required to optimize the cooling potential of this technique in hot humid climates. To aid this, experience may be drawn from other climates, particularly hot arid, in which nocturnal radiant cooling is more widely used, thanks to their predominantly clear skies.

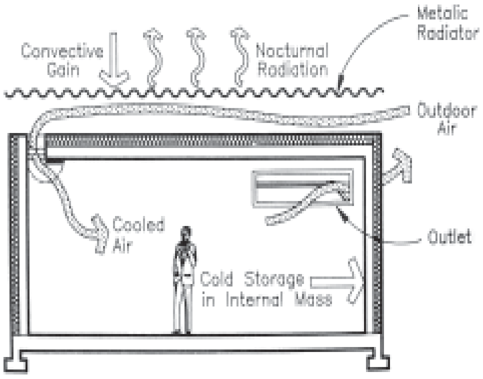


Figure 1.7: A schematic of a radiant cooling system which involves cooling the roof by nocturnal radiation and introducing cooled night air into the occupied space.

Another radiant cooling technique which has been tested in hot humid climates is one that circulates cool water behind panels attached to the envelope of a building and uses them as aheat sink for the interior space. A small system has been tested in Thailand which shows a promising performance (Figure 1.8). More field-testing is required on such a system, along with the development of generic design and control principles to optimize its performance.

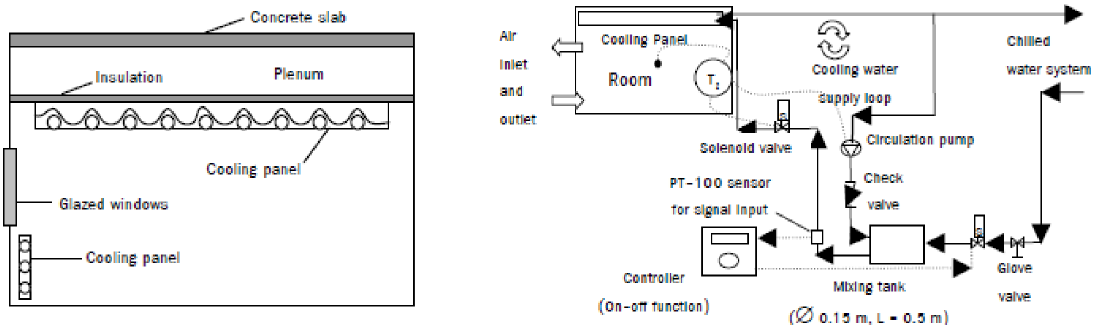


Figure 1.8: A schematic of the cool radiant panel system tested in Thailand.

2.8.2 Indirect Evaporative Cooling

Water left on a surface of a building has a natural tendency to evaporate in order to achievephase equilibrium with the water vapor in the surrounding air. As it evaporates, every grams of water extracts about 2550 J of heat from its environment. Indirect evaporative cooling uses this principle to provide cooling, while keeping the evaporation process outside the building to avoid elevating the indoor humidity level. Indirect evaporative cooling can be achieved by several means, notably a roof pond, a spray of water over a roof surface and a roof garden. (This paper does not review direct evaporative cooling because the technique increases the indoor humidity level, and so is generally inappropriate for hot humid climates.)

a) Roof Pond

This system collects water on the roof of a building and lets it evaporate. The evaporation cools the roof which then serves as a heat sink for the interior. A roof pond system has been tested in the hot humid climate of Mexico, which has an insulation floating on the water surface to shield it from solar radiation during the day, and which circulates the water over the insulation at night to remove heat absorbed in the water by convection, evaporation and radiation (Figure 1.7). The performance of this so-called ‘cool roof’ is significant: it can cool the interior air by as much as 10-13^{o}C below the outside air, depending on the ambient wet bulb temperature. To develop the roof pond technique in hot humid climates further, more work is required to test different types of pond, such as that which has embedded insulation or that which allows ventilation above the water surface. Furthermore, principles should be acquired for optimizing the design of the pond’s components, such as its depth and the roof’s mass, in order to maximize its cooling potential under different climatic and occupancy conditions. Insights could be drawn from work carried out in drier climates, in which a number of systems have been tested.

b) Roof Spray

Where collection of water on the roof is not possible, for structural reasons for instance, water may be sprayed onto the roof surface as an alternative to the roof pond. Case studies show that this technique has some potential in hot humid climates, with a reduction in the indoor air temperature of about 1-4^{o}C being possible. Research opportunity is still open for developing the design and control principles of this technique, both qualitative and quantitative, that will help maximize its potential.

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