THERMAL PERFORMANCE OF FREE-RUNNING THREE-STOREY HOUSES: AN ASSESSMENT THROUGH COMPUTER SIMULATIONS

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ABSTRACT

Sri Lanka is presently facing a serious energy crisis due to continuous increase in energy demand annually. One of the solutions for this is energy conservation for which houses are a good candidate. The need for using active means such as fans and air-conditioning can be minimized by planning the houses with desirable passive features. In order to determine the passive performance, computer simulations were carried out for two houses with and without passive elements. A comparison of similar volumes in these two houses indicated that it is possible for the indoor temperature of certain type of volumes to rise about 5°C above the maximum outdoor temperature when passive elements are ignored.

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Sri Lanka is presently facing a serious energy crisis due to continuous increase in energy demand annually. One of the solutions for this is energy conservation for which houses are a good candidate. The need for using active means such as fans and air-conditioning can be minimized by planning the houses with desirable passive features. In order to determine the passive performance, computer simulations were carried out for two houses with and without passive elements. A comparison of similar volumes in these two houses indicated that it is possible for the indoor temperature of certain type of volumes to rise about 5^0C above the maximum outdoor temperature when passive elements are ignored.

INTRODUCTION

Sri Lanka is a country experiencing warm humid climatic conditions at low altitudes (i.e., below 300m). Therefore, many houses could be thermally uncomfortable during the day time. This could encourage the occupants to use active means such as fans and air conditioners for achievement of thermal comfort. This is not a desirable situation because Sri Lanka is presently facing a power crisis triggered mainly due to the annual increase in electricity demand, which is around 10% (Statistical Digest, 1999). However, attempts to develop new power plants have been confronted with stiff resistance from the general public on environmental grounds. Two such recent examples are the proposed Upper Kotmale hydropower plant and Norochcholai coal power plant.

Of the total electricity sales in Sri Lanka in the year 1998, the domestic sector accounted for around 40% (including the bulk supply sales by the Ceylon Electricity Board, most of which is resold to houses) (Central Bank of Sri Lanka, 1999). Electrical energy usage in a typical house mainly consists of energy used for lighting and thermal comfort. Since lighting is an essential need, the energy used for thermal comfort becomes a good candidate for energy conservation in houses.

Building design is the first "line of defence" against the stress of the outside climate. The building envelope, which consists of external walls, openings and the roof, is the device through which heat exchange between the exterior and the interior environment is controlled. Climatic design can be adopted to control this heat transfer in a favourable manner, creating a thermally comfortable interior microclimatic zone (Watson & Labs, 1983).

For warm humid climatic conditions, as experienced in Sri Lanka, extensive research has been carried out round the world on passive approaches for achievement of indoor thermal comfort. De Waal (1993) reports that compact multi-storey buildings perform substantially better than low-rise buildings. This could be attributed to the undesirable effect of the roof in the latter case. De Waal (1993) also recommends that large building facades should orient north or south for high sun heights, as is the case in Sri Lanka. Another feature recommended is the shading of openings (Jayasinghe & Attalage, 1999b). Therefore, for openings as well, north or south orientation is more desirable because overhangs cannot effectively shade east or west facing openings due to the low solar altitudes in the morning and in the evening, respectively. The colour of the outside surface of a building is expected influence the indoor thermal comfort as it determines the amount of solar radiation absorbed and, therefore, its inward transmission. Light colours have been found to be desirable (Givoni, 1976).

Therefore, qualitatively, the following could be suggested: the reduction of roof area per floor area by way of three-storey construction; provision of openings facing north or south; and application of light colours to the walls and, if possible, to the roof as well. Also recommended is roof for balconies for protection from the sun. It is possible to provide two sheltered floors in three-storey houses, which would have better thermal performance, as described by Jayasinghe & Jayawardena (2001). It is useful to quantify the effect of the passive elements on indoor thermal comfort of such houses. This study investigates the effect of the roof, the orientation of openings, shading of openings and surface colour on indoor thermal comfort of three-storey houses. It also explores the combinations that could achieve desired indoor thermal comfort levels.

OBJECTIVES

The main objectives of this research are the following:

1. Identification of passive elements applicable to warm humid climates.
2. Quantification of their effects of indoor thermal comfort of houses.
3. Development of guidelines for integration of various passive elements.

METHODOLOGY

The following methodology was used to achieve the above objectives:

1. Two houses were planned, one including and the other disregarding the passive elements that can be suggested for Sri Lanka. These suggestions were based on qualitative reasoning.
2. These houses were modeled using the DEROB-LTH computer program and the thermal performance was compared for selected volumes.
3. The desirable passive features that can be included were determined on the basis of the results of the computer analysis.

THERMAL COMFORT AND PASSIVE ELEMENTS

Thermal comfort is a sensation of complete physical and mental well being; it is a subjective quantity resulting from internal environmental variables such as dry bulb temperature, mean radiative temperature, humidity and air velocity. It is also affected by personal variables such as activity level and clothing level of the occupants. Thermal comfort could be achieved for several combinations of the environmental and personal parameters. These combinations of parameters form the basis of a "comfort zone" on the psychrometric chart given in Figure 1 (ANSI/ASHRAE, 1981).

The word "psychrometry" refers to the study of air and water vapour mixtures and their changes. As shown in Figure 1, the psychrometric chart has two main axes: Dry Bulb Temperature or DBT (i.e. air temperature) and Humidity ratio (i.e. kg of moisture per kg of dry air). Saturation Humidity refers to the maximum amount of moisture that air can support at any given temperature. Plot of this against DBT forms the basis of the psychrometric chart. In the psychrometric chart, the curved lines give the Relative Humidity, which is an expression of the moisture content of a given atmosphere as a percentage of the saturation humidity at the same temperature. The sloping lines refer to the Wet Bulb Temperature, which can be used to determine the relative humidity when the corresponding DBT is known (Szokolay, 1991).

On this psychrometric chart, it is possible to mark a zone within which a majority of the people will be thermally comfortable. The center point of the comfort zone is the Neutral Temperature, i.e. preferred temperature. It is shown by Humprey (1978) that annual mean outdoor temperature of a particular region could be related to its neutral temperature. This relationship as well as the equations for the determination of the boundaries of the comfort zone are given in Szokolay (1991).

The thermally comfortable conditions for Sri Lankans involved in sedentary activities such as desk work can be presented as shown in Figure 1 for various internal air velocities (Jayasinghe & Attalage, 1999a). The boundaries of the comfort zone and its extensions were determined using the equations given in Szokolay (1991). It can be seen that Sri Lankans can be thermally comfortable at elevated temperatures like 30°C, when sufficient air movement is available. This is a very important finding since it gives a definite goal for the building designer. That is, the need to maintain the indoor temperature of the house below 30°C irrespective of the outdoor temperature. The means for achieving thermally comfortable conditions for low altitudes of Sri Lanka are qualitatively given in Jayasinghe & Attalage (1999b). However, there is a need to quantify the various effects of the passive features in detail.

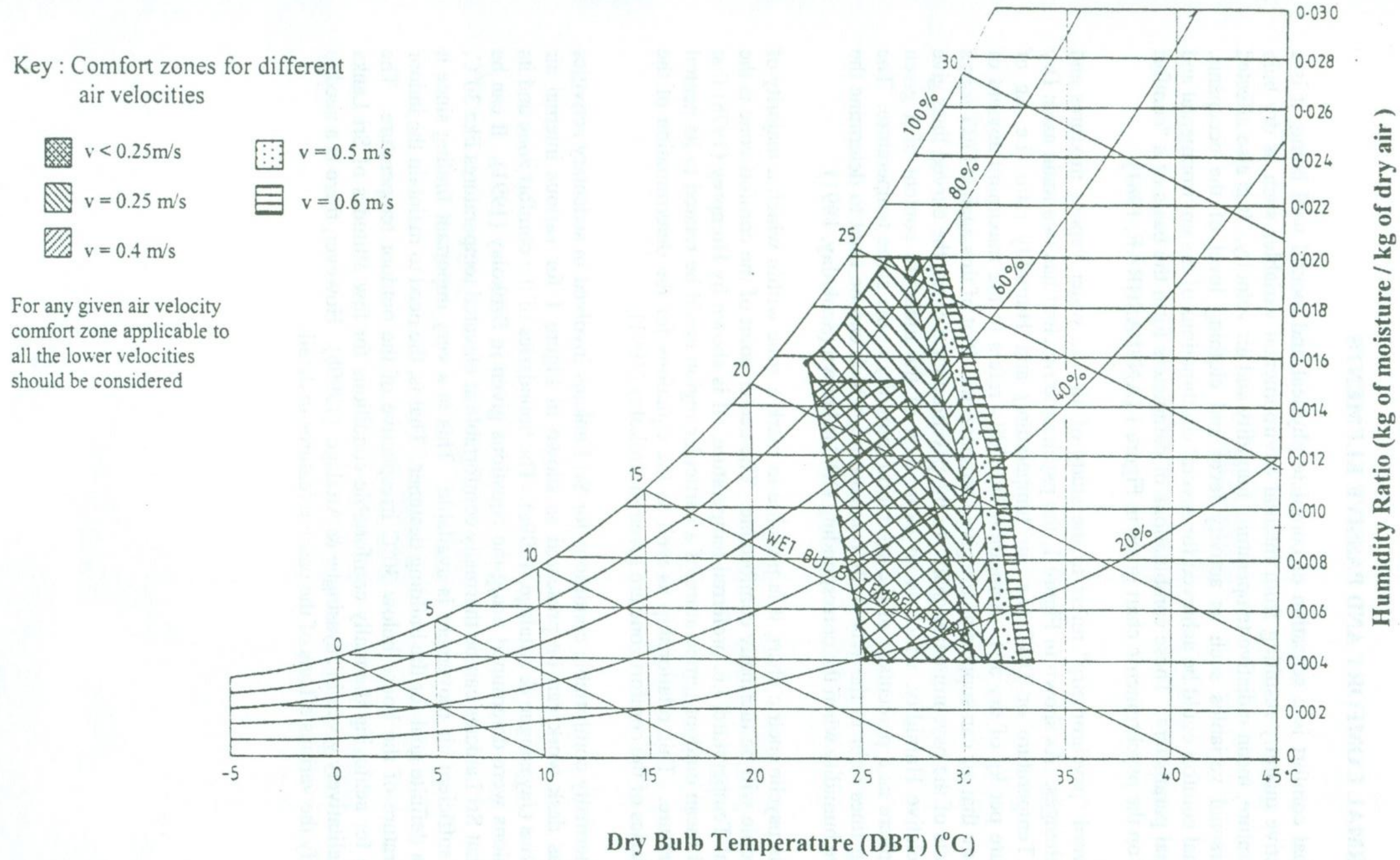


Figure 1: Psychrometric chart giving modified comfort zones taking physiological effects of cooling into consideration

COMPUTER SIMULATION OF HOUSES

The Simulation Software

For the computer simulation, the Dynamic Energy Response of Buildings (DEROB-LTH) program was used. It was originally developed at the Numerical Simulation Laboratory, School of Architecture, University of Texas. Later, it was further enhanced at the Department of Building Science, Lund Institute of Technology (LTH), Sweden.

DEROB-LTH is a versatile simulation tool that facilitates the creation of models of actual buildings with a relatively high level of accuracy. It handles energy transmission across the building envelope by taking account of thermal properties of building materials. In addition to the thermal loads from direct and diffuse solar radiation, it considers solar radiation reflected from the ground and shading devices. It takes account of infiltration and forced ventilation. It can also take account of static pressure driven air exchanges between volumes, that take place across openings at different levels (advection connection). It can also calculate the air-conditioning loads and required plant capacities (DEROB-LTH, 1999).

The Simulation Model

Two houses of the same layout (Figure 2) assumed to be located in Colombo were considered for simulations.

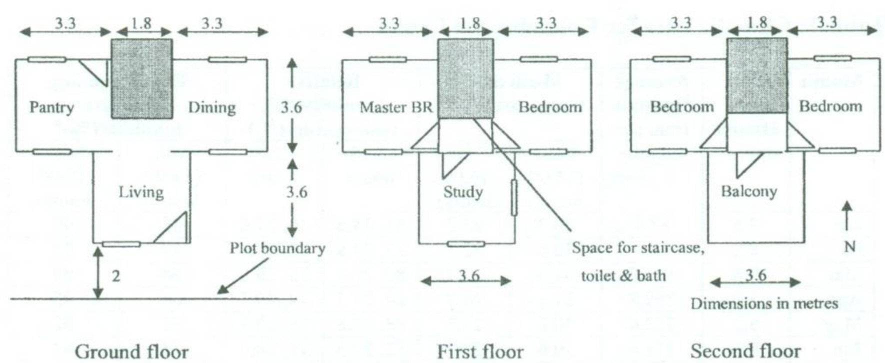


Figure 2: Ground floor, first floor and second floor plans of the modeled house

House 1 has shaded openings with proper orientation (i.e. north or south facing). House 2 has the same layout but is designed without any regard to shading and proper orientation of openings (non-shaded windows are provided facing west for Master bedroom, study room and bedroom at top floor) and its balcony is roofless. Therefore, House 1 can be considered as a passive house and House 2 can be considered as "unpassive".

In both cases, only three volumes were modeled. Master bedroom (MBR) at first floor represents a typical sheltered volume, and the bedroom (BR) above it represents an equivalent unsheltered volume and the study room allows the determination of the effects of the balcony with or without a roof (Figure 3).

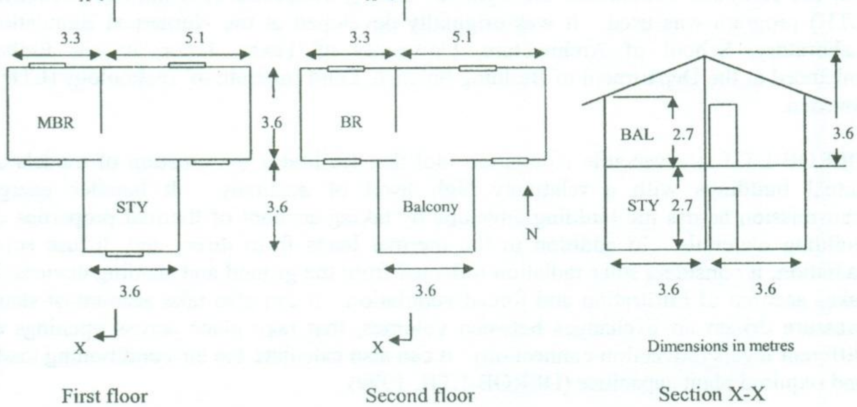


Figure 3: First floor and second floor plans, and Section X-X of the model used for simulations for the house given in Figure 2.

The Climatic Data for Colombo

Table 1: Climatic data for Colombo, Sri Lanka

Month	Sun shine Hours/ day	Average Rainfall (mm per month)	Mean daily temperature(°C)		Relative humidity(%), temperature(°C)		Corresponding relative humidity(%)*	
			Max (14.00 hours)	Min (6.00 hours)	8.30 hours	17.30 hours	Min (14.00 hours)	Max (6.00 hours)
Jan	7.5	87.9	30.3	22.2	81, 24.5	70, 27.6	58	90
Feb	8.2	96.0	30.6	22.3	82, 24.9	72, 28.1	59	92
Mar	8.8	117.6	31.0	23.3	83, 26.4	72, 28.8	64	94
Apr	7.9	259.8	31.1	24.3	84, 27.3	74, 29.1	68	95
May	6.2	352.6	30.6	25.3	83, 27.8	78, 28.7	72	92
Jun	6.6	211.6	29.6	25.2	82, 27.5	78, 28.0	73	93
Jul	6.1	139.7	29.3	24.9	82, 26.9	78, 27.6	70	90
Aug	6.5	123.7	29.4	25.0	81, 27.1	77, 27.6	65	90
Sep	6.4	153.4	29.6	24.7	81, 26.9	77, 27.5	67	91
Oct	6.2	354.1	29.4	23.8	83, 26.5	78, 27.2	70	92
Nov	6.8	324.4	29.6	22.9	83, 26.8	77, 27.1	67	93
Dec	6.9	174.8	29.8	22.4	81, 26.1	74, 27.1	61	91

* These are calculated using the psychrometric chart assuming that the moisture content remains the same. Minimum relative humidity corresponds to maximum temperature and maximum relative humidity corresponds to minimum relative humidity.

Both houses (House 1 & 2) were simulated for the 21st day of the month of March. With respect to thermal comfort, March can be considered as the most undesirable month for Colombo. The sun is directly above the equator; the number of sunshine hours is the highest and the rainfall is relatively low. Climatic data for Colombo are given in Table 1.

The Cases Considered for the Simulations

To determine the effect of the surface colour, various colours were considered. The colours and the absorptance values are given in Table 2.

Table 2: Variables used for simulation of surface colour

Building element	Surface colour	Notation	Absorptance for shortwave radiation
Wall/floor	Off-white (e.g. very light green etc)	WA	35% (Walls)
			50% (Floor)
	Green, blue, red etc.	WB	70% (Walls)
			70% (Floor)
Roof	Light grey (new cement fibre sheets)	RA	50%
	Blackish grey (old cement fibre sheets)	RB	85%

A set of three cases was considered for each house, representing the following practical situations:

1. The series of WARA cases represents light colour walls and floors, and light colour roof. Therefore, it is the most desirable series. This represents new cement fibre sheets.

2. The series of WARB cases represents light colour walls and floors, and dark colour roof. Under tropical climatic conditions, cement fibre sheets turn to blackish grey with time. This series represents such a roof along with light colour walls and floors.

3. The series of WBRB cases represents dark colour walls and floors, and dark colour roof. Therefore, it is the most undesirable series. This situation occurs when the walls and floors are of colours like green, blue and red, and the roof is left unpainted for a long time.

The different cases used for the simulations are given in Table 3.

Table 3: Different cases used for computer simulations.

Month	House	Wall & floor surface colour (W)	Roof surface colour (R)	Case
March	No. 1 (Passive)	Light (A)	Light (A)	M1WARA
		Light (A)	Dark (B)	M1WARB
		Dark (B)	Dark (B)	M1WBRB
	No. 2 ("Unpassive")	Light (A)	Light (A)	M2WARA
		Light (A)	Dark (B)	M2WARB
		Dark (B)	Dark (B)	M2WBRB

The Composition of Building Elements

The constituent materials and thicknesses of walls, floors and roofs used for the simulation are given in Table 4. The details of the materials are given in Table 5. The contents of both tables are based on BRE (1984) and Evans (1980).

Table 4: Constituent materials and thicknesses for the walls, floors and roofs

	Constituent materials from front to back as defined for DEROB-LTH	Dynamic attenuation	Time lag (hrs)
Adiabatic floor	1000mm mineral wool, 60mm reinforced concrete, 20mm cement plaster	0.02	0.79
Reinforced concrete floor	20 mm cement plaster, 115 mm reinforced concrete, 15mm cement plaster	0.91	2.27
External or internal wall	15 mm cement plaster, 210 mm thick wall, 15 mm cement plaster	0.59	6.05
Cement fibre roof with cement fibre ceiling	8 mm thick cement fibre sheets, 200 mm air gap, 6 mm thick cement fibre sheets	0.99	0.216

Table 5: Properties of the materials used for the simulations

Material type	Conductivity (W/mK)	Specific heat (Wh/kgK)	Density (kg/m^3)
Reinforced concrete	2.0	0.25	2400
Hand moulded bricks	0.75	0.24	1800
Cement plaster	1.4	0.28	2000
Timber	0.15	0.76	800
Cement fibre sheets	0.22	0.25	1600
Air space	0.24	0.28	1.201

The Internal Loads

For each case, the same internal loads were considered (Table 6). They are calculated on the basis of 75 W for a person who is asleep and 100 W for a person occupying the space engaged in activities such as studying, reading etc. The contribution from electric appliances such as bulbs is considered at an appropriate value such as 60 W per bulb. This value can be reduced much further in reality by using energy efficient compact fluorescent lamps.

Table 6: The internal loads for various periods of a day

Volume	Internal load (Watts)	Reason
Master Bedroom (MBR)	1 to 6 hours, 150 W 7 to 21 hrs, 0 W 22 to 24 hrs, 150 W	Two persons are asleep No persons Two persons are asleep
Study (STY)	1 to 15 hrs, 0 W 16 to 18 hrs, 200 W 19 to 20 hrs, 250 W 21 to 24 hrs, 0 W	No persons Two persons are present Two persons are present; a light is on No persons
Bedroom (BR)	1 to 6 hrs, 150 W 7 to 21 hrs, 0 W 22 to 24 hrs, 150 W	Two persons are asleep Bedroom is vacant Two persons are asleep

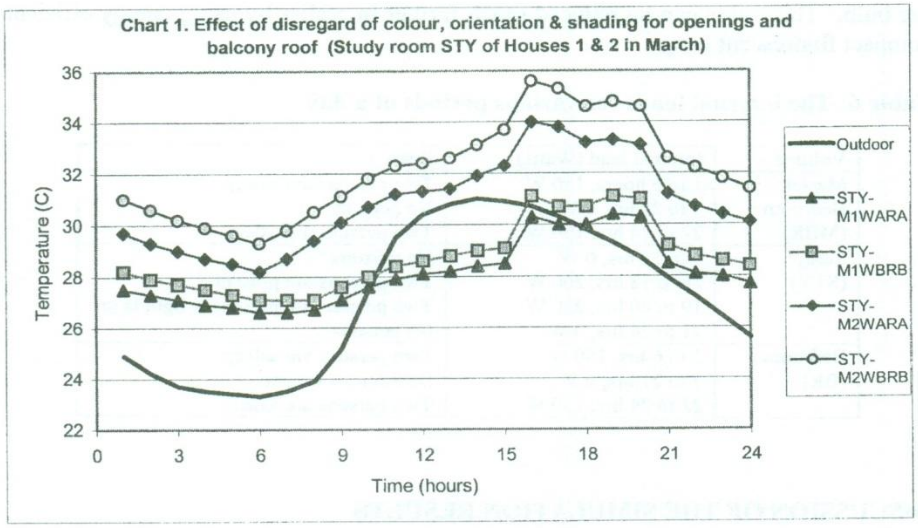
DISCUSSION OF THE SIMULATION RESULTS

For comparison of the thermal performance of different volumes, the indoor temperature around 14.00 hours can be employed as a good indicator because the outdoor temperature becomes a maximum around this time. The peak that occurs around 20.00 to 22.00 hours is ignored as its occurrence can be directly attributed to the internal gains.

Effects of Balcony Roof on the Volume Below (i.e. Study Room)

In House 1 the balcony is provided with a roof. The Study room (STY) below the balcony has two openings: one south-facing and the other east-facing. The latter though not the best is not so undesirable as an equivalent west-facing opening. As shown in Chart 1, when the surfaces are of light colour, the indoor temperature of the study room of House 1 rises in March to slightly above 30°C from 16.00 to 20.00 hours, especially due to the influence of the internal loads. Dark colour surfaces further increase the indoor temperature by 1°C; however, not in excess of 31°C, which is the maximum outdoor temperature in March.

On the other hand, House 2 (i.e. "unpassive" house) contains several undesirable features such as lack of shading devices for openings, west-facing openings and a balcony without a roof. All these cause an increase in the maximum indoor temperature by 4°C over the corresponding case of the passive house. The resulting indoor temperature of 34°C is highly undesirable, and achievement of reasonable levels of thermal comfort is highly unlikely even by using forced ventilation. Resorting to dark colour surfaces will further aggravate the thermal situation in the study room as the indoor temperature reaches a staggering 36°C when the maximum outdoor temperature is only 31°C.

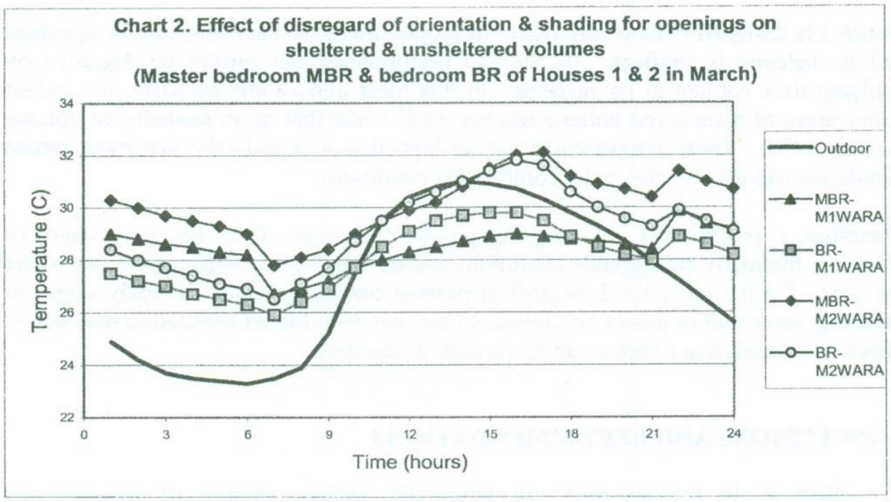


Therefore, by providing the balcony with a roof, the volume below can be maintained within 30°C provided its surfaces are of light colour and the openings are properly oriented and shaded. Neglect of all those aspects may cause the indoor temperature to rise to as much as 36°C, which is highly undesirable.

Effects of Disregard of Orientation and Shading on Sheltered and Unsheltered Volumes

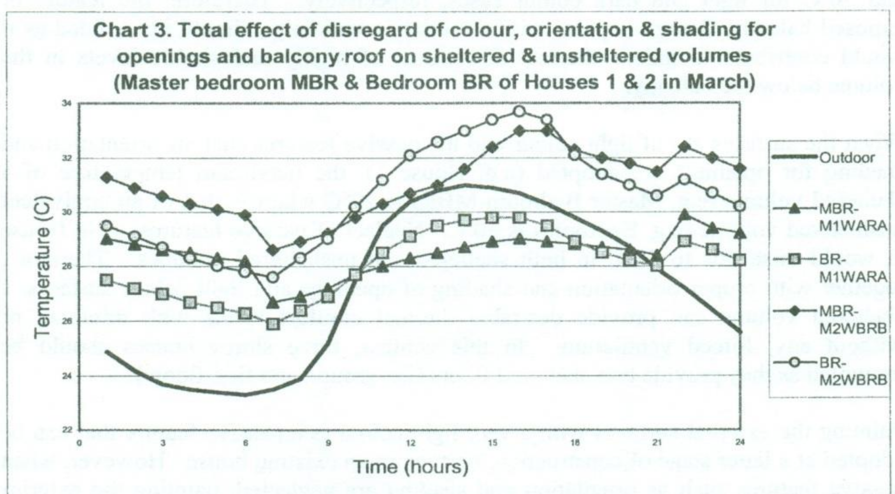
In this comparison, both houses are light-coloured. As shown in Chart 2, the indoor temperature of a sheltered volume (Master bedroom MBR at first floor level) could be maintained within 29°C in March even though the outdoor temperature reaches a maximum of 31°C, if basic passive features such as proper orientation and shading for openings and balcony roof are adopted. Using light colours, the indoor temperature of an unsheltered volume (Bedroom BR) can also be maintained within 30°C in March. However, the Master bedroom MBR of the "unpassive" house, where orientation of openings and shading aspects are ignored and the balcony is roofless, experiences a maximum indoor temperature of about 32°C although the surface colour is light. As can be expected, the maximum temperature of the unsheltered volume (i.e. Bedroom BR) is even higher, but marginally.

This case yields two important findings. Firstly, passive concepts should be adopted at the planning stage so that features such as sheltered volumes and properly oriented openings can be effectively incorporated. Neglect of these aspects during the initial stages cannot be effectively rectified by painting the surfaces with light colours. Secondly, although, in a passive house, a sheltered volume thermally performs better than an equivalent unsheltered volume, both types of volumes are apparently the same in a light colour "unpassive" house like House 2.



Effects of Passive Elements: Extreme Cases

Chart 3 compares the extreme effects of passive elements of sheltered and unsheltered volumes. House 1 is a properly designed passive house with shaded openings with proper orientation. Its passive performance can be further enhanced by adopting light colour surfaces for roof, walls and floors. In this most desirable scenario, a sheltered volume like MBR can be maintained within 29°C and an unsheltered volume like BR within 30°C in March when the maximum outdoor temperature reaches 31°C.



House 2 is designed without any regard to proper orientation and shading for openings and its balcony is roofless. Its thermal performance can further be degraded by applying dark colours to its surfaces. In this most undesirable scenario, the indoor temperature of a sheltered volume reaches 33°C while that of an unsheltered volume reaches 34°C. These temperatures are so high that it is unlikely that even forced ventilation can achieve thermally comfortable conditions.

Therefore, it is clear that, by adopting passive techniques from the early stages of planning, thermally comfortable conditions can be achieved throughout the day round the year. On the other hand, neglect of passive concepts, during the early stages of planning, can result in indoor conditions so hot that even forced ventilation may not be effective in inhibition of the resulting thermal discomfort.

CONCLUSIONS AND RECOMMENDATIONS

The effect of the balcony roof, orientation of openings, shading of openings and surface colour on the indoor thermal comfort was investigated in this study through computer simulations using the DEROB-LTH computer program. Based on the results, the following conclusions can be drawn and recommendations can be given.

When passive features such as orientation and shading of openings and a balcony with a roof are adopted (as in the case with House 1), the indoor temperature of the volume below the balcony can be maintained within 30°C for the light colour surface case and 31°C for the dark colour surface case. When the above passive features are neglected (as is the case with House 2), the corresponding maximum indoor temperatures are 34 and 36°C for light and dark colour cases, respectively. Therefore, the feature of exposed balcony, though popular with the urban community, should be avoided as it would contribute to indoor thermal discomfort of highly undesirable levels in the volume below the balcony.

When the surfaces are of light colour and the passive features such as orientation and shading for openings are adopted (e.g. House 1), the maximum temperature of a sheltered volume (e.g. Master Bedroom MBR) is 29°C whereas that of an equivalent unsheltered volume (e.g. Bedroom) is 30°C. Neglect of passive features, as in House 2, would raise this to 32°C in both sheltered and unsheltered volumes. Therefore, together with proper orientation and shading of openings and light colour surfaces, a sheltered volume can provide desirable thermal comfort levels with minimal, or without any, forced ventilation. In this context, three storey houses should be promoted as they provide two sheltered floors (i.e. ground and first floors).

Painting the external surfaces with a very light colour is a passive feature that can be adopted at a latter stage of construction, or even in an existing house. However, when passive features such as orientation and shading are neglected, painting the exterior surfaces with a light colour would still be unable to reduce the maximum temperature below 32°C, even in a sheltered volume. This clearly shows that passive features such as orientation and sheltered volume concept are more influential than passive features such as light colour surfaces. In fact, the neglect of features such as orientation cannot be compensated at a latter stage by way of light colours. Therefore, the initial sketch design itself should be based on passive concepts.

ACKNOWLEDGEMENT

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