Approaches to tropical house design

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1 Introduction

The archetypes of hot-dry and warm humid climate houses are well known. The ideal for the former is the inward-looking, courtyard type house, of heavy masonry construction, with extensive use of water in the courtyards, developed in the Middle-East, brought to the Iberian peninsula by the Arabs and exported to much of Latin-America with great skill and good success.

The warm-humid climate archetype is the lightweight house, elevated on stilts, designed for full cross-ventilation, preferably with a single row of rooms, each room having openings on opposite sides. All openings are fully shaded and the windows are often glass louvres with metal louvres for the spandrels, down to floor level (Fig.1).

Fig.1 A standard house design for Darwin (Northern Territory, Australia)

2 Background

Warm-humid is the most problematic climate. The main control strategy relied on is the physiological cooling effect of air movement. This can be estimated as

$dT = 6\,(v-0.2) - (v-0.2)^2$ or more conservatively as $dT = 5.2\,(v-0.2) - (v-0.2)^2$

where v is the air velocity at the body surface (in m/s).

Both expressions are valid up to about 3 m/s, but the limit of acceptability is usually taken as 1.5 m/s. With this the former expression would give a maximum of $dT_{max} = 6$ K and the latter $dT_{max} = 5$ K. It is then a separate question how such air movement is generated, whether it is by “catching the breeze” or by a low-powered ceiling fan.

A typical warm month in such a climate would have a mean temperature of over 29°C (with a mean maximum of some 32°C). Thus the thermal neutrality can be taken as

$Tn = 17.6 + 0.31 \cdot 29 = 26.5°C$

giving an upper limit of comfort as 26.5 + 2.5 = 29°C

The above mentioned physiological cooling effect would extend this to 34 or 35°C with a 1.5 m/s air velocity.

Such temperatures are often exceeded, therefore comfort cannot be ensured at all times. Some people will install an air conditioner, which will operate in an extremely inefficient way as the house is not designed to be air conditioned, it leaks like a sieve.

The research work of one of my PhD students (Rosangela Tenorio from Recife) is aimed at optimising a house design for such climates, for dual operation: relying on passive controls (nb. cross ventilation) as far as practicable, but would also be suitable for subsequent air conditioning.

3 The lightweight / heavyweight dichotomy

An earlier study showed that even in Cairns a heavyweight building performs much better than a lightweight one. However, some interesting results emerged from my later study for Cairns (reported at PLEA'96). This is a sizeable town on the shores of the Coral Sea, in northern Queensland, at latitude 17°S. In this parametric study I examined the performance of over 2200 constructional variants of a simple house. Using the indoor overheating (K.h above the upper comfort limit, taken here as 29°C) in the warmest month as the criterion, the variant that produced the best result (the least overheating) was of a fairly heavy-weight construction:

- concrete slab-on-ground floor
- insulated tiled roof of a light colour
- reverse brick-veneer walls (105 brick inside of a timber load-bearing frame, with 50 mm glass wool insulation and a fibrous-cement cladding)

it had large windows facing north and south, no windows east and west, and a reasonable ventilation rate of 10 air changes per hour (ac/h).

This was not unexpected, but it was surprising that a lightweight building, with timber framed walls (sheeted with fibrous cement outside and plasterboard inside) can be nearly as good as the above. This would indicate that the building mass is not the critical factor. Four dominant factors emerged:

1. **Floor**: concrete slab-on-ground (without carpet) is always better than the elevated timber floor
2. **Fenestration**: the best solution is to have large windows (some 40% of the wall area) facing the equator, with smaller ones on the opposite side, with no windows east and west and all windows fully shaded (although medium size windows on both north and south were almost as good)
3. **Roof**: the roofing material makes little difference (whether it is metal sheeting, fibrous cement or terracotta tiles) but it should always be insulated, at least to R 1.5 (in m^2K/W) and should be of a light surface colour (a = 0.2)
4. **Ventilation**: 10 ac/h is always better than 1 ac/h.

It is however worth noting that the “thermal Gestalt” of the house, the interaction of variables is the most important. Just to give a few examples:

1. the addition of 50 mm insulation to the roof will **increase** the overheating if the windows are not shaded, or even with the best (fully shaded) fenestration, if the ventilation is inadequate (1 ac/h)
2. the roof absorptance (0.2 or 0.8) is most important in the absence of insulation, but it makes little difference if the roof is insulated
3. if walls are sufficiently massive (at least a 105 mm brick inner skin) and insulated on the outside of this mass layer, with the correct fenestration but inadequate ventilation the timber floor is marginally better than the concrete slab-on-ground.

Regarding the wall construction what has emerged is that – all other factors at their best – the mass will make very little difference (but if the floor is timber, then a massive wall is much better than the lightweight). Reverse insulated brick-veneer was the best wall, giving 1560 K.h overheating in January, but the similarly insulated timber-framed, fibro sheeted wall was not much behind, with 1568 K.h (both with concrete floor, optimised fenestration and 1 ac/h), although with ventilation increased to 10 ac/h the difference increased whilst the overheating was reduced, to 682 and 826 K.h respectively.

4 Present day knowledge

Some years ago the traditional archetype was challenged by proponents of massive construction, but from the above study the conclusion can be drawn that lightweight construction may be just as good as the heavyweight one.

Opponents of heavyweight construction would argue that it may moderate daytime indoor temperatures, but it would start releasing heat in the evening, at the worst time for people who want to go to sleep. The lightweight house would cool down quickly, it would ensure that the indoor cools down parallel with the outdoors.

Protagonists of heavyweight construction argue that the available thermal storage capacity makes it possible for the users to manipulate the thermal response of the building. The only passive method for keeping the inside cooler than the outside is to rely on the thermal storage effect of massive construction: closing all openings for the day-time (when $T_o > T_i$) and opening up the house at night as much as possible. This is a very effective control-strategy in climates with a diurnal variation greater than 10 K, or even only 8 K. When the house is closed during the day, air movement (for physiological cooling) can still be created by fans.

In warm-humid climates such as Cairns, where the January diurnal variation is around 7 K, this technique may reduce the indoor peak temperature by 2 - 2.5 K and the indoor average by a little less than this.

However, humans are not thermostats. There is anecdotal evidence (and personal experience) suggesting that people in warm-humid climates prefer an open-air life style, even if this means a few degrees higher indoor temperatures.

5 Ventilation

It is taken as axiomatic that in the absence of solar and internal heat gains the indoor mean temperature over the 24-hour cycle will be the same as the outdoor mean. However, there will always be some solar or internal gain, therefore T_i must become higher than T_o. This extra heat can be removed by ventilation, but ventilation can never make the indoor temperature lower than the outdoor.

Most textbooks are clear about this, but there is still much confusion in the minds of architects about ventilation. The word comes from the Latin *ventus*, meaning wind. It may be an unfortunate term, as it means three different things in architecture alone (let alone other disciplines):

1. **Air exchange:** removal of 'used' air and contaminants, the supply of fresh air. This need not be more than 4 L/s (0.004 m^3/s) per person
2. **Heat transport:** esp. removal of warmer indoor air, replacing it with cooler outdoor air. The rate of heat transport (in W) will be Q = 1200·vfr·DT where vfr is volume flow rate in m^3/s and DT is the temperature difference T_o-T_i. Quite small values of vfr can produce significant cooling effects, if the DT is large. Cooling (a negative Q) will occur only when the T_i is greater than the T_o.
3. **Physiological cooling** effect: for this the critical quantity is not the volume flow rate, but the velocity of air stream past the body surface. To obtain a 1.5 m/s velocity near a window of (say) $4m^{2,}$ the volume flow rate would need to be 6 m^3.

There appears to be an order of magnitude difference in air flow required between 1 and 2 and again between 2 and 3.

Natural ventilation may be produced by two forces: buoyancy force, creating a stack effect and wind pressure, creating cross ventilation. Stack effect could satisfy the first purpose, possibly give noticeable results for the second, but would never get near to providing a sensible air velocity for the third purpose (except perhaps in a staircase or lift shaft of a multistorey building). Far too often one can see architectural drawings with a small ventilating shaft, intended to create a physiological cooling effect. A colleague of mine gave a paper at a conference with the title *The air can't read the arrows*, making fun of architects who show beautiful arrows indicating an expected air flow. He showed that in most cases these express only a wish, not a probable occurrence.

For a quick comparison take the following everyday situations:

A) STACK EFFECT

if h = 4 m (from centre of window to a roof outlet)

with neutral pressure level at mid-height

T_o = 28°C (301°K) density of air at this T is 1.293 · 273/301 = 1.17 kg/m^3

T_i = 32°C (305°K) density of air at this T is 1.293 · 273/305 = 1.15 kg/m^3

A = 0.5 m^2 (cross section of shaft)

then the pressure difference is

$Dp = 2 \cdot 9.81 \cdot (1.17 – 1.15) = 0.39$ Pa

where 9.81 m/s^2 is the gravitational acceleration

$vfr = 0.827 \cdot 0.5 \cdot = 0.26\ m^3/s$

B) WIND EFFECT

if $v = 3$ m/s

$A = 3\ m^2$

then $p = 0.5 \cdot 1.17 \cdot 3^2 = 5.26$ Pa

windward $p_W = 0.9 \cdot 5.26 = 4.73$

leeward $p_L = -0.4 \cdot 5.26 = -2.1$ total $Dp = 4.73 – (-2.1) = 6.83$ Pa

$vfr = 0.827 \cdot 3 \cdot = 6.48\ m^3/s$

Prediction of wind-induced cross ventilation is fraught with difficulties. Any wind data from meteorological stations, typically at airports, is from measurements at 10 m level in an open field. What velocity can be expected at a particular building site?

Several research workers (notably Arens et al. 1985) examined the relationship of site climate to meteorological data and produced appropriate correction factors. For wind such factors would depend on site proximity, terrain roughness, height, topography and obstructions. Site location in relation to the measuring station and the wind direction would be of a strong influence. Such a correction factor would translate the meteorological wind data to the site, as affecting the outside surface of the building considered. From this the relevant pressure coefficients may be estimated.

Air flow through the building can best be predicted by using computational fluid dynamics (CFD). This is a sophisticated technique, with a big demand on computing power, but only as reliable as the specification of boundary conditions.

If the air flow through the house is divided or branching (through doors in partitions creating alternative flow-paths) then a network flow analysis may be necessary. However, as empirical correction factors were used to get from the meteorological station to the site, a comparable and adequate accuracy may be achieved by a simple orifice method. The volume flow rate through an inlet opening can be estimated as

$vfr = v \cdot A \cdot h$ (in m^3/s)

where v is velocity (m/s)

A opening area (m^2)

h is effectiveness, eg 0.5 – 0.6 for normal wind incidence

and 0.25 – 0.35 for oblique (diagonal) incidence.

This assumes a free flow through the space, with an outlet of comparable size.

Another set of empirical correction terms can allow for the building configuration. One method suggests a set of ‘W’ (window) factors:

W0 = 0 if the room has only one opening

W6 = 1 if there is free flow through the room (or building)

with factors W1 to W5 (between the above limits) depending on

- window type (opening sashes, flyscreens, etc)
- any eaves, wing-walls or return wings)
- internal openings and their alignment with inlet an outlet.

6 Suggested approach

As two radically different design strategies may be equally successful, a choice must be made at the outset. Clearly, the thermal performance cannot be a choice criterion. If the design is to be produced for a known client, then he/she must be consulted, pointing out the differences in the resulting life-styles, establishing his/her preferences. For housing projects (whether housing authorities or speculative project builders) a mixture is advisable. This would allow the choice of well-exposed sites for the lightweight, cross ventilated types, as the heavyweight ones are much less dependent on wind exposure. People’s preferences (or the market success of each type) would allow a subsequent adjustment of the ratio of the two types.

Certain attributes will be identical for both:

1. Orientation of major windows should be N and S, preferably no window on E and W
2. All windows should be shaded all year round, but avoid overshading as this would unnecessarily reduce daylighting
3. The roof should be of a light colour and should be well insulated. If there is an attic space, an economical solution is to insert an aluminium foil laminate under the roof cover, with face down. The roof cover can become very hot and the dominant downward heat transfer mechanism is radiation, so the low emittance surface will be very effective. Resistive insulation (eg of some 50 mm glass wool bats) is still advisable on top of the ceiling. Attic ventilation is always useful, but it is essential if the ceiling is not insulated.
4. A ceiling fan should be installed in every room to provide indoor air movement when there is no breeze, or even when the building is closed.

Heavyweight version

1. The floor should be a concrete slab-on-ground, with a hard finish (eg. tiles or screed)
2. The walls should have at least a 105 mm brick or 150 concrete block (solid or filled) inner skin, with at least 50 mm resistive insulation on the outer side of this, and some external protective layer. This can be fibrous cement sheeting or another skin of brick. The latter would thus become as 270 mm cavity brick wall, with insulating cavity fill.
3. Windows need not be large, but ample night ventilation must be facilitated. If – as in many such climates – there is hardly any breeze at night, a substantial ventilation shaft up to the roof ridge level may provide a sufficient stack effect to create around 10 ac/h or more. This would work well when the outside cools and the indoor temperature is higher. Alternatively a centrally located “whole house” (or attic-) fan can be installed in the ceiling, which would draw outside cool air through all rooms and force out the attic air. It is important to provide air intake openings in all rooms, preferably near the floor level.

Good intentions are not enough: careful calculations for the sizing of openings and of the fan are just as important as the sizing of a possible ventilation stack.

Lightweight version

1. If the site is exposed, it may not be necessary to elevate the building on stilts and a concrete slab-on-ground floor can be used. If local obstructions, shrubs etc. warrant it, it should be elevated. The undercroft so created is a much appreciated space, not only as a carport or storage area, but also for sitting out, socialising. The elevated floor can be timber, but preferably a concrete slab and in both cases it should be insulated on the under-side.
2. If the floor is concrete, the walls may be timber or metal framed, with plasterboard inside lining and fibrous cement, weatherboard or other sheeting onthe outside and in any case insulated with at least 50 mm glass wool, or similar. With timber floor some wall mass would be desirable, such as an inner skin of brick (if the structural support problem can be solved) or an at least 50 mm plaster plank inner lining. Insulation and outside lining as above.
3. A plan arrangement with a single row of rooms is preferable, so that every room can have windows in both N and S walls. If partitions are unavoidable, these should not be full height. The free passage of air through the house must be ensured. Windows should be fairly large (around 50% of wall area) and either casement or awning type (not sliders, as these can only have a maximum of 50% opened), or glass louvres. Flyscreens can reduce air flow (especially at low velocities) to less than half. For this reason it may be preferable to have the insect barrier (flyscreen) at the outer edge of a balcony or verandah, where the aperture area is at least twice the window area.

7 References

Arens E, Lee E S, Bauman, F and Flyn L (1985): Siteclimate: a program to create hourly site-specific weather data. *Proc. ASHRAE/DOE/BTECC Conf*. Dec.2-5

Szokolay, S V (1996): Thermal design of houses for warm climates. *Building and urban renewal.* Proc. PLEA'96, Louvain la Neuve.