Adaptive buildings' facades for thermal comfort in hot-humid climates

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ABSTRACT

Passive design and low energy strategies have been researched, developed and effectively put into practice in buildings and the effectiveness of these strategies is closely linked to the specific climate in which they are used. Mid-latitude or temperate climates tend to benefit the most from passive design and significant energy savings are possible.

In hot and humid climates, for those that can afford it, air conditioning is a standard requirement and designers generally intend their buildings to include some sort of mechanical cooling system. However, providing thermal comfort in naturally ventilated buildings in this climate is a big challenge. The dominant factor affecting thermal comfort is the relative humidity; even an increase in air movement might not significantly improve the body’s ability to lose heat to the atmosphere if the air is saturated or close to saturation. This paper highlights the issues surrounding thermal comfort in hot and humid climates, the limitations of current practices and introduces a new and adaptive facade system aimed at reducing the moisture content in indoor air to improve comfort conditions, taking Mumbai as a case study.

Key words: adaptive facades, hot-humid climates, thermal comfort, natural ventilation, passive design

1. INTRODUCTION

1.1 Conflicts in Facade Design

Building facades are now no longer seen as just a barrier separating the interior building environment from the external one. The building façade acts as a ‘skin’ that wraps around the building and affects the internal environment as it interacts with the external one. A façade may satisfy the design and functional requirements (e.g. aesthetics and structure), but once the building user enters the building, he or she ceases to be overly concerned with the façade materials, its colour or form and is more concerned with physical and physiological issues:

- Thermal comfort
- Aural comfort
- Visual comfort
- Air quality

Mechanical systems (HVAC) have traditionally been used to satisfy these comfort criteria. A proper façade design should reduce the need for these systems and hence the energy they
consume. To optimise energy reduction, facades need to take into account each of these issues and attempt to address them all as efficiently as possible; it is in this process that conflicts in facade design arise. A conflict exists where a facade system may adequately deal with one issue but in that process aggravate another one. For example, maximising daylight by increasing the glazing ratio on a building can reduce energy loads for artificial lighting but at the same time increase the potential for solar gain which will not always be desirable.

A number of conflicts can be identified:
- Shading – View out
- Shading – Daylighting
- Natural ventilation – Shading
- Natural ventilation – Temperature control (warm or cold weather)
- Natural ventilation – Humidity control (warm climates)
- Natural ventilation – Acoustic comfort

Shading is generally used to reduce the heating loads in buildings due to solar gains and to reduce the incidence of glare. The conflicts with shading arise because the shading system can obstruct the natural views from windows and also reduce the amount of daylight entering the building space. When daylight is limited, the only option is to increase the use of artificial lighting, thereby making use of extra energy for lighting when the original aim was to reduce energy use altogether. This occurs in any region where there are cooling loads for all or some part of the year.

Natural ventilation is the low energy alternative to produce thermally acceptable and improved air quality spaces within buildings. The need for natural ventilation clashes with other significant building issues: shading devices can obstruct the flow of air in and around a building and thereby reduce the effectiveness of a natural ventilation strategy. The free flow of air in and out of the building makes it much harder to keep indoor temperatures close to a prescribed “comfort temperature”.

1.2 Thermal Comfort

The alternative to the air-tight, sealed box building are buildings that can be opened and interact with their environment and provide better comfort conditions while reducing the dependence on energy intensive HVAC systems. The issue of providing thermal comfort in buildings has been always a major issue in building design. Before the cost of energy became an important factor, building design was carried out with little attention to the energy consumed in running the building and meeting the thermal comfort and air quality needs of the occupants. This gave rise to problems like Sick Building Syndrome and reduced employee productivity (Wargocki 2002). Increased understanding of the impact that the internal thermal environment has on its occupants has led to studies being carried out and standards being produced to address the subject matter.

ASHRAE(2004) defines thermal comfort as ‘that condition of mind which expresses satisfaction with the thermal environment’. The aim of a good designer is to provide a space that will ‘produce thermal environmental conditions acceptable to a majority of the occupants within the space.’ (ASHRAE 2004). An even higher ideal is to produce this sort of environment while using less energy than the current standard. Banham (1984) comments that if energy were limitless it would be theoretically possible to have thermal comfort even without buildings!
Thermal comfort in any environment is determined by a number of environmental and individual factors. The environmental factors are air temperature, radiant temperature, relative humidity and air speed while the individual factors are clothing and metabolic rate. The interactions of these six factors determine define a thermal boundary in which an individual feels comfortable. This boundary is also subjective and therefore it is quite complex to define what combinations of these factors will produce a feeling of ‘thermal neutrality’, where the building occupant is neither too hot nor too cold i.e. comfortable.

2. THERMAL COMFORT IN HOT- HUMID CLIMATES

In certain climates, there is a limit to the level of thermal comfort that can be achieved solely by passive measures and hot-humid climates are the most difficult to manage by passive design (Givoni 1998). A very important parameter in hot-humid climates is, of course, relative humidity. Relative humidity (RH) refers to the amount of moisture in the air as compared to the maximum amount of moisture the air can hold at a particular temperature. It gives an indication of how much moisture the air can take up from, say, a person’s skin through perspiration, and thus is indicative of thermal comfort. Givoni also explains the mechanisms of achieving comfort under hot-humid conditions: once the skin temperature exceeds that of the body’s core temperature due to a high external temperature, the skin secretes sweat which aids the body in losing heat. High relative humidity can inhibit the loss of moisture from the skin due the level of air saturation making it more difficult for the body to reduce its temperature which leads to the uncomfortable ‘sticky’, hot feeling that is experienced in a hot-humid climate.

2.1 Defining Thermal Comfort in Hot-Humid Climates

ASHRAE (2004) presents a standard for defining thermal comfort based on the PMV-PPD indices which take into account the six factors for determining thermal comfort and the satisfaction with thermal sensations experienced by individuals under varying thermal conditions. A comfort zone is a range of operative temperatures and relative humidity values that only 10% of individuals would be dissatisfied with. This zone is also defined by the level of clothing and metabolic rate of the individuals.

The adaptive thermal comfort model includes the concept of outdoor temperatures determining internal comfort temperatures by considering how people adapt themselves, psychologically and physiologically, to reach a thermally neutral state. However, international standards like ASHRAE 55-2004 and ISO 7730 have been found to inaccurately predict thermal comfort in hot-humid climates because wind speeds and temperatures that define the upper limit in these standards have been considered comfortable in field studies in hot-humid climates (Nicol 2004).

Several studies have been carried out to determine what constitutes thermal comfort in this climate: Mallick (1996); Cheong et al (2006); Liping (2007); Karyono (2002); Wong et al (2002). Nicol (2004) suggests how the adaptive comfort model can be used to specify comfort criteria in hot-humid climates. He showed that the relative humidity, however, has a marginal effect on comfort temperatures in naturally ventilated buildings for outdoor temperatures between 20°C and 30°C.
Figure 1: The effect of average outdoor relative humidity on comfort temperature at different values of outdoor mean temperature (Source Nicol 2004)

Figure 1 shows that for a given outdoor temperature a lower relative humidity allows for a higher comfort temperature, but the overall difference over the range of relative humidity figures is only about 1°C. However, the temperature within the building can quickly exceed the comfort temperature; therefore the temperature and/or the relative humidity will need to be reduced. Nicol’s paper tends to specify a comfort temperature, but a comfort relative humidity can be inferred from Fig 1. The relative humidity range that has the highest comfort temperatures is <63% RH; hence to achieve thermal comfort over a larger range of high outdoor temperatures, the relative humidity should ideally be kept below 63%. Between 64% and 75% RH there is a slight reduction in the range of comfort temperatures and the average (71% RH) can be used as an upper limit in defining the thermal comfort.

2.2 Hot-Humid Climate Analysis – Mumbai, India.

According to the Koppen Climate Classification, types A and C are considered warm/hot-humid. The Type A climate experiences high temperatures all year and periods of high rainfall. Type C is characterised by warm, humid summers and the winters are cool and wet.

An analysis of four different climates was carried out – Athens and Hong Kong (Type C) and Singapore and Mumbai (Type A). The data analysed was the average dry bulb temperature and relative humidity over 24 hours for each month of the year. This gives a picture of what a typical day in any month would look like. The combination of temperature and relative humidity, in terms of thermal comfort, is described by the Heat Index. This index is an apparent temperature that considers the human biometeorological effects of temperature and relative humidity (Steadman 1979). The highest temperatures during the year for each climate were noted and the corresponding relative humidity values were the inputs for the heat index calculation. Mumbai (in May) was found to have the highest heat index of the four and was selected for further investigation.

2.3 Limitations in Current Practice

Passive and low energy strategies are well developed, especially for temperate climates, and have achieved significant energy reduction in buildings. An example of this is the PassivHaus

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<th>Tile</th>
<th>RH%</th>
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<td>3</td>
<td>&gt;75</td>
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1 The dry bulb temperature is the temperature of air as measured by a standard thermometer and does not take into account the effects of evaporative cooling.
building design; when properly designed and constructed, the house can use much less energy than a commensurate building but performs optimally in temperate to cold climates. PassivHaus technology was developed in 1996 in Germany and to date around 30,000 have been built; their energy demands are up to 45% less than a standard house of similar proportions and use in the same climate (Promotion of European Passive Houses 2006). The PassivHaus standard has been proved effective in several European, which have temperate or more extreme climates; but not in hotter climates.

It is also evident that advanced facade technologies have been developed for high performance, high-end building projects (Haase 2009). For instance, double skin facades are widely used in Europe and are now beginning to be used in the USA; the system is designed to make highly glazed facades a better moderator of the external environment with respect to the inner one. The air buffer between the ‘skins’ can act as thermal mass, a thermal flue and even an acoustic barrier. However, in hot-humid climates, the air within the double skin facade cavity will be too hot and too humid to be passed into the building, and would have to be mechanically cooled and dehumidified.

In building design in hot and humid climates, a standard design addition is an air conditioning unit. Energy issues aside, air conditioning is the most effective way of providing thermal comfort in this climate. Air conditioning achieves two main purposes: reduction in temperature and relative humidity. There is a strong link between the two, both as psychrometric parameters and in terms of thermal comfort. High relative humidity can cause high temperatures to feel even higher because the body is less able to lose heat by evaporative cooling (through sweating) to the surrounding air. Air conditioning successfully controls two of the four variables that determine thermal comfort. Also, the inlet grills or louvres push out air into the building, increasing air velocity which, under the right conditions, improves the body’s ability to lose heat.

A main limitation of air conditioning is the amount of energy required to run it, especially in climates where it is very hot for most months of the year. Not all households or even commercial building owners can afford these systems. Energy Efficiency in Buildings (CIBSE 2004) shows the energy consumption in buildings using HVAC and those that do not. The Energy Use Indicator (EUI) is a product of the installed capacity, the average coefficient of performance of the plant, the average hours of usage per year and the percentage utilisation. The EUI in a standard air conditioned office is at least 10 times that for a naturally ventilated office and these figures are for a temperate climate with significantly lower cooling loads than a hot-humid climate.

Dehumidifiers work on basically the same principle as air conditioners and thus are also energy intensive. Desiccants have been used in various capacities for dehumidifying air and they can be used in conjunction with the HVAC system to reduce cooling loads.

Vernacular architecture in hot humid climates makes the most of natural materials and structure to minimise solar gain and maximise natural ventilation. A study of vernacular architecture in hot-humid regions of India revealed that the natural ventilation implemented in the design would be sufficient to provide cooling for 17% of the warmer part of the year, while 76% of the time would require some sort of artificial cooling; most likely air conditioning (Singh 2009). This describes part of the challenge of delivering thermal comfort in natural ventilated buildings in this climate; there will always be times during the year when the boundaries of thermal comfort will be exceeded.
The effects of adopting a series of passive cooling strategies have been investigated in the Ecotect Weather tool using weather files for Mumbai.

The strategies analysed are

1. Passive solar heating
2. Thermal mass effects
3. Exposed mass and night purge ventilation
4. Natural ventilation
5. Direct evaporative cooling
6. Indirect evaporative cooling

Figure 2: Analysis of thermal comfort in Mumbai before and after the addition of natural ventilation as a passive cooling strategy.

Figure 2 shows the percentage of time during a month that the thermal conditions lie within the thermal comfort boundaries - before and after a number of passive cooling strategies have been implemented. The yellow bars indicate that without passive cooling, up to 25% of the time from October to March falls within the comfort zone. The red bars show the improvement caused by passive cooling over the year; but there are still periods of discomfort. The last set of bars show the average effect over the whole year: before adopting these strategies there is thermal comfort for less than 10% of the year and 60% afterwards. Passive design strategies certainly have a positive effect in hot humid climates but are still limited in their ability to reduce the cooling load in buildings.

3. RESOLVING THE CONFLICT BETWEEN NATURAL VENTILATION AND HUMIDITY CONTROL
3.1 Passive Dehumidification

Since passive cooling strategies, including natural ventilation, still leave periods of thermal discomfort, passively reducing the relative humidity is a viable option. Examples of this exist:

- **Moisture buffering:**
  Hygroscopic materials normally used in buildings have been shown to help to improve comfort by reducing humidity. These materials (concrete, brick, wood, textiles and cellulose based materials) have a dynamic interaction with internal humidity thereby having an impact on the relative humidity and the thermal comfort.

- **Super-hydrophobicity and textiles**
  A biomimetic analogue – the *Lecanora conizaeoides* species of lichens-exhibit super-hydrophobicity; this is a phenomenon where a surface is hydrophobic and very rough. A very rough surface means that water droplets that fall on it have a very high contact angle. The high angle leaves the micro-pores open for gas to escape but not the ingress of moisture. This is the principle used in Gore-Tex®. These selective surfaces can prevent the flow of moisture into a building (Shirtcliffe 2006). Advancement on the super hydrophobic surface would be a textile that varies its ability to allow air to pass through in response to air humidity.

3.2 An Adaptive Fabric Facade for Passive Dehumidification.

Textiles have played, and are continuing to play, an important role in building design. Today advanced design and manufacture processes are allowing for the production of textiles that can incorporate useful properties on a small scale. These materials have the potential to act as a moisture buffer for the interior air supply as well as controlling the flow of humid air in or out of the building.

These attributes are the basis for an adaptive fabric facade system that responds to changes in relative humidity (RH) and air moisture content. The aim of this system would be to keep the internal RH below 63% or up to maximum of 71% during periods where interior RH exceeds 63%. This will be achieved by exploiting the inherent properties of hygroscopic (especially cellulose based) materials.

Consider the two conditions that will arise in Mumbai (Type A climate)

**Case 1:** when RH inside is less than RH outside.
**Case 2:** when RH inside is greater than RH outside.

In order to control the indoor RH, the fabric should:

- Have the ability to change its air permeability properties, i.e. prevent the flow of more humid air into the building in Case 1, and in Case 2 allow less humid air in.
- Act as a moisture buffer internally to reduce the air moisture content and RH, making it more comfortable.
- Allow a simple extraction of the moisture collected which can then be channelled for an alternative use.
Hygroscopic materials are able to absorb moisture and swell in the process. The principle behind the bi-metallic strip can be exploited to provide differential deformation in two hygroscopic materials where one can absorb more moisture than the other. The change in shape produced by the differential deformation of the materials will provide an open/close function for the facade system. In Case 1, the fabric pores will be ‘closed’ preventing the ingress of humid air. While closed the fabric will absorb any excess moisture built up from internal activities until a Case 2 situation is reached. When moisture absorption reaches a maximum point, the change of shape will cause the pores to ‘open’, allowing humid air to pass out from the building.

**Figure 3:** Case 1 – fabric absorbs interior moisture and closes up, preventing humid air from entering the building. (RH values are for illustration only)

![Diagram](image)

**Figure 4:** Case 2 – fabric pores open and humid air passes out of the building.

![Diagram](image)

This adaptable facade can be integral part of a building’s passive design strategy and placed over openings just like shutters or curtains. The adaptable fabric system can provide an engineering and aesthetic solution to thermal comfort issues where air conditioning is not an option.
4. REFERENCES


