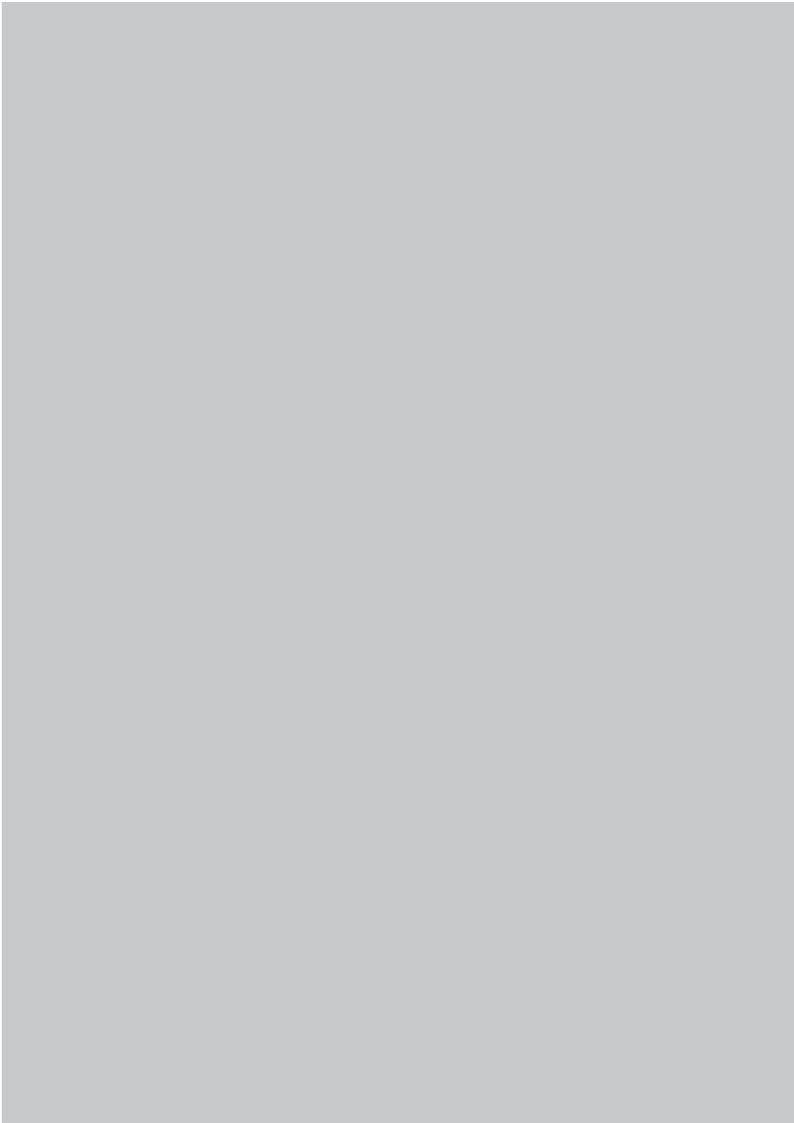**Review Article: Passive Design for Thermal Comfort in Hot Humid Climates**
บทความปริทรรศน์: การออกแบบโดยวิธีธรรมชาติเพื่อความสบายเชิงอุณหภาพในเขตอากาศร้อน–ชื้น

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**Abstract**

Passive design can be referred to a way of designing buildings that takes advantage of the prevailing climate and natural energy resources, such as daylight, wind and thermal buoyancy, to achieve a comfortable environment while minimising energy use and reliance on mechanical systems. This paper reviews a selection of work on key issues which are inherent to passive design for thermal comfort in hot humid climates, namely the comfort zone, the minimisation of cooling needs and techniques for cooling and dehumidification. Directions for future research are also discussed. The review highlights the need for acquiring generic design and control principles, which will help maximise the potential of various passive design techniques for providing thermal comfort in hot humid climates, and which will also complement the knowledge already gained from case studies and fieldwork carried out in the areas. Furthermore, continuous research and development, both technical and commercial, are required to develop high–potential passive climate control techniques to become viable alternatives to mechanical solutions.

บทคัดย่อ

การออกแบบโดยวิธีธรรมชาติหมายความถึงวิธีการออกแบบอาคารที่อาศัยประโยชน์จากสภาพภูมิอากาศและทรัพยากรพลังงานทางธรรมชาติ อาทิ แสงธรรมชาติ ลม และการลอยตัวของอากาศร้อนตามธรรมชาติ เพื่อสร้างสภาพแวดล้อมที่มีความสบายในขณะที่เป็นการลดการใช้พลังงานและการพึ่งพิงระบบเชิงกลด้วย บทความนี้พิจารณางานในประเด็นสำคัญที่เกี่ยวข้องกับการออกแบบโดยวิธีธรรมชาติเพื่อความสบายเชิงอุณหภาพในเขตอากาศร้อน–ชื้น อันได้แก่ ขอบเขตความสบาย การลดภาระทำความเย็น เทคนิคของการทำความเย็นและการลดความชื้น บทความได้รวมถึงการเสวนาถึงทิศทางของงานวิจัยในอนาคต โดยได้ชี้ให้เห็นถึงความต้องการการแสวงหาหลักการออกแบบและควบคุมอาคารที่มีลักษณะทั่วไป เพื่อให้สามารถใช้ระบบสภาพแวดล้อมแบบธรรมชาติได้อย่างสูงสุดตามศักยภาพ และส่งเสริมความรู้ที่มีอยู่แล้วจากกรณีศึกษาและการศึกษาภาคสนามในเขตอากาศนี้ นอกจากนี้ การวิจัยและพัฒนาที่ต่อเนื่อง ทั้งเชิงเทคนิคและเชิงพาณิชย์ ยังคงเป็นที่ต้องการเพื่อพัฒนาให้เทคนิคการใช้ประโยชน์จากธรรมชาติมีศักยภาพสูงจนสามารถกลายเป็นทางเลือกที่แข่งขันได้กับการใช้เครื่องปรับอากาศ

Review Article: Passive Design for Thermal Comfort in Hot Humid Climates
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**Keywords (คำสำคัญ)**

Passive Design (การออกแบบโดยวิธีธรรมชาติ)

Thermal Comfort (ความสบายเชิงอุณหภาพ)

Hot Humid Climates (เขตอากาศร้อน-ชื้น)

Cooling Requirement (ภาระทำความเย็น)

Cooling Techniques (เทคนิคการทำความเย็น)

Dehumidification (การลดความชื้น)

## 1. Introduction

Increasing concerns about global warming present the building industry with a challenge to cut its energy consumption. In countries such as the UK and the US, for example, the building sector consumes of order 40–50% of the total delivered energy [1–2]. Of this, climate control systems, namely ventilation, cooling and heating can account for as much as 70% of the total energy use [3]. However, this part of the energy consumption can be reduced significantly by employing passive environmental solutions instead of mechanical ones: for example, a well-designed naturally ventilated building can consume only a third of the energy consumed by an air-conditioned building [3], while arguably providing a comparable level of comfort. This is because passive design allows buildings to adapt more appropriately to their local climates and take better advantage of natural energy resources, such as wind and thermal buoyancy, to help condition their interior environments. Furthermore, passive, naturally ventilated buildings have potential to provide more pleasant and healthier environments for the occupants compared to their mechanically ventilated counterparts. Indeed, sick building syndrome is almost exclusively observed in the latter [4].

However, achieving thermal comfort through passive means in hot humid climates is not always easy. Characterised by relatively high temperatures and high humidities, these climates usually require both cooling and dehumidification. These difficulties lead to many buildings relying completely on air-conditioning. Nevertheless, a range of passive design techniques may be employed to help minimise or avoid this reliance.

This paper reviews some of the work on such passive design techniques. The subject matter is vast, whereas the length of this review is constrained. Therefore, only an outline of selected topics is presented, with the work chosen to add more depth to the discussion. Most of the work cited was carried out specifically for or in hot humid climates; basic work which transcends climatic boundaries is discussed when it provides essential background or perspective. The choice of coverage is admittedly subjective. For example, the review focuses on thermal comfort in interior environments but not outdoor spaces. The physics of ventilation and cooling techniques are better covered elsewhere [e.g. 5–8].

What remains in this review is discussions that centre on key issues that distinguish passive design for thermal comfort in hot humid climates from that in other climates, namely the comfort zone, techniques for minimising cooling needs and techniques for cooling and dehumidification. These discussions proceed as follows. Section 2 examines thermal comfort zones for hot humid climates, focusing on the impact of acclimatisation which makes comfort perception in these climates different from that in other climates. Section 3 reviews techniques for minimising cooling requirement. Then, Sections 4 and 5 review techniques for cooling and dehumidification, respectively. Finally, Section 6 presents conclusions. Throughout, opportunities for research and development are discussed.

## 2. Thermal Comfort Zone

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 [9], its derivative

ISO 7730 and most versions of ASHRAE Standard 55, were developed. However, adaptive models, such as those developed by Auliciems [10], Humphreys [11] and Szokolay [12], also consider acclimatisation an important factor in comfort sensation. This difference leads to the adaptive models 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 acclimatisation can significantly underestimate the thermal and humidity tolerance of the occupants of free-running buildings in hot humid climates [13-25]. For example, while ASHRAE Standard 55-1992 Addenda 1995 [26] suggests that the summertime comfort zone ranges from about 23.5°C at 25% relative humidity (RH) to about 26°C at 60% RH, comfort is experienced at a temperature as high as 32°C at over 85% RH in Bangladesh [17], and within higher ranges of temperatures and relative humidities of 25-31.5°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 humidities 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 [27], as well as the homoeothermic mechanisms of the body. Indeed, the degree of adaptive opportunity can influence thermal comfort expectation: people tend to accept warmer environments more readily in their homes than in offices, as they have more control over their environments and activities in the former situation [27]. Such impact of acclimatisation 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 acclimatisation, such as ISO 7730: 2005 [28], are likely to be inappropriate for free-running buildings in hot humid climates.

The impact of acclimatisation 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 [25] 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 [29]. Other examples include the work by Srivajana [18] that adjusts the Standard Effective Temperature (SET) comfort scale originally defined by Gagge et al. [30] to accommodate prediction of thermal sensation under higher air velocities and lower clo values commonly found in hot humid climates. Jitkhajornwanich [15] modifies Olgyay's bioclimatic chart [31] to take into account the acceptance of higher temperatures and humidities in hot humid climates (Figure 1). And Khedari et al. [16] 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' acclimatisation 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 humidities 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.
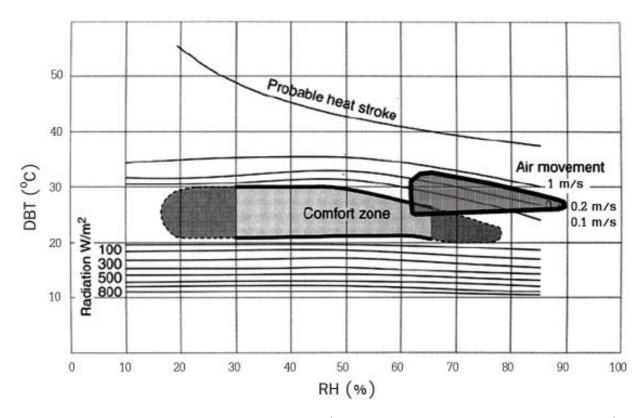
**Figure 1.** Bioclimatic chart modified for hot humid climates (adapted from Olgyay [31] following Jitkhajornwanich [15]). The new comfort zone is shown on the right of the original one.

## 3. Design for Minimising Cooling Requirement

In hot humid climates, a significant amount of energy can be saved if cooling needs can be minimised. 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 minimising cooling needs involve appropriate orientation and spatial organisation, shading, and appropriate use of materials, colours, textures and vegetation.

### 3.1 Orientation and Spatial Organisation

Orientation and spatial organisation affect the ability of a building to ventilate and receive solar radiation. To minimise solar gain and maximise ventilation, traditional buildings in hot humid climates usually employ spread-out plans and permeable internal organisation (Figure 2)
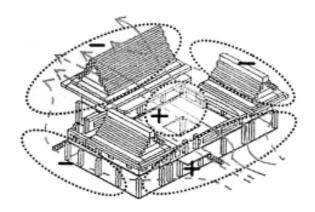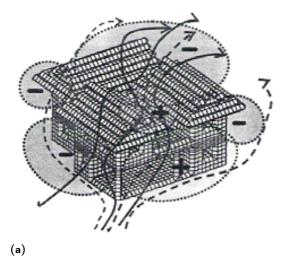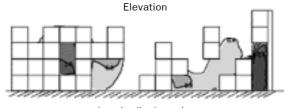


**Figure 2.** The orientation and spatial organisation of a traditional Thai house [32].
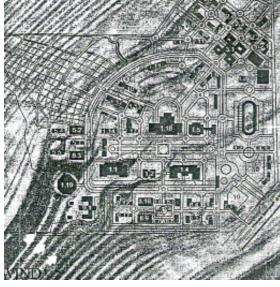
(a)



Elevation



Longitudinal section

(b)



(c)

[32-33]. By orientating the longer sides of the buildings to intercept prevailing winds and the shorter sides to face the direction of the strongest solar radiation, effective ventilation can be achieved, while thermal impact from solar radiation is minimised [33]. Such strategy can also be applied effectively to modern buildings, both in smaller scales, such as houses (Figure 3a) [32, 34-36] and larger scales, such as residential blocks (Figure 3b) [37-39] and campuses (Figure 3c) [40]. However, work is still required to overcome the challenge of applying such orientation and spatial organisation 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.

### 3.2  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 temperature of 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 pre-venting overheating in hot humid climates [38, 41-47]. 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 [41, 43].

**Figure 3.** Examples of modern buildings which employ spread-out plans and permeable spatial organisation to achieve good ventilation: a modern house (a [32]), a residential block (b [37]), and a campus (c [40]). The bottom diagram in figure 3b shows the age of air among the residential units as simulated by a computer programme; the prevalence of lighter tones signifies good overall ventilation. Figure 3c shows air movement among the campus buildings as simulated by a flow visualisation 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 receive direct solar radiation at a time is another possible shading technique [48].

A key issue which should be considered in shading design is its tendency to conflict with daylighting. 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 [49-50]. Such a conflict can be lessened, for example, by using interior surfaces of high reflectance values, such as those in light colours, or using light shelves to reflect daylight into the deeper part of the interior [49]. Movable shading devices, such as louvres, 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 reduction with that of daylighting. 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 [e.g. 50-51]. Overall, research opportunity is still open for developing quantitative principles of shading that will balance thermal and energy benefits with daylighting quality.

Shading as provided by vegetation is discussed in Section 3.4.

### 3.3  Material, Colour and Texture

In hot climates, materials for building envelopes and the surrounding surfaces, such as walkways and terraces, should help minimise heat gains into the buildings. A survey [33] 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 and population 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 [e.g. 52], 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 minimise thermal impact from solar radiation, multiple layers of materials may be required to make up a building envelope (Figure 4). A layer of insulation, such as foam or glass fibre, is probably required to cut effectively conductive heat transfer through opaque surfaces which receive strong solar radiation [53-58]. In addition, a ventilation gap may be beneficially provided between the different layers of the envelope materials to vent excessive heat accumulated within [59]. Such a gap may also be
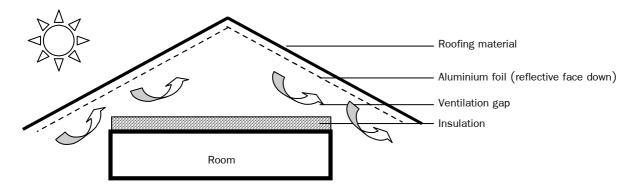
**Figure 4.** A schematic of a roof section showing an example of a combined use of insulation, a ventilation space and reflective lining to minimise thermal impact from solar radiation on the interior environment.

internally lined with a reflective material, such as aluminium foil, to help block radiative heat transfer [55]. 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 [56]. 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 [45, 60-61]. 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 colour

and texture of the building envelopes and the surrounding surfaces are important. In general, lighter colours and smoother surfaces lead to lower surface temperatures (Figure 5) [62-63], and therefore are desirable from the thermal comfort point of view. Indeed, it has been shown [64] that in hot humid climates a white roof can 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 climates, usually from local raw materials, such as agricultural wastes. Examples include particleboards from a mixture of rice straw and rice husks [65],
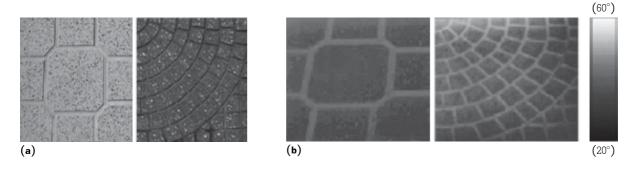


**Figure 5.** Visible (a) and infrared (b) images of light and dark paving materials under direct sun [62]. Darker colours in the infrared image represent lower temperatures. The temperature scale is given on the right.

and vetiver grass [66]; insulation boards from cassava and corncobs [67]; a composite concrete from a combination of durian peel, coconut fibre and coconut coir [68]; a brick from a combination of soil and coconut coir [69]; a cement board from coconut coir [70]; a concrete block from oil palm fibres and bagasse [71]; and sandwich walls from rice straw and rice husks [72]. 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.

### 3.4 Vegetation

Vegetation can be an effective means of moderating the temperature around a building and reducing the building's cooling requirement. Vegetation in the form of trees, climbers, high shrubs and pergolas, for example, can provide effective shading for the building's walls and windows. 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 evapotranspiration 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 [73].

Also, the average temperature of buildings' walls which are shaded by plants can be 5-15°C less than that of unshaded ones, depending on the local climates and planting details [41, 74 -76]. Likewise, a roof garden can attain a temperature 10-30°C below that of an exposed roof surface, depending on the roof construction, planting details and surrounding conditions [77-79] (The use of roof gardens is herein considered an indirect evaporative cooling technique and reviewed in Section 4.4c.) To complement such field studies, quantitative planting principles should be developed which will help optimise 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 evapotranspiration process, especially when plants are grown near ventilation inlets. Optimisation of the use of local plants should also be explored.

### 4. 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 thermal comfort. Key cooling techniques for hot humid climates involve appropriate utilisation of natural ventilation, thermal mass and heat dissipation by radiation and evaporation.

### 4.1 Ventilative 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.

### 4.1 a) Ventilative 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 the interior. 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°C, depending on the humidity level and the acclimatisation 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. [34-36] and Tantakitti and Jaturonglumlert [81]) 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 [18], due to it being able to disturb loose paper [7].

Several investigations [34-36, 82] 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 (Figure 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 6b) [35-36, 82]. Obstruction of the air path should be minimised (Figure 6c) [35-36]. Furthermore, windows should be at the body level

to increase potential for physiological cooling [82]. To complement these qualitative guidelines, quantitative design principles for maximising the cooling effect of wind in hot humid climates should be developed.
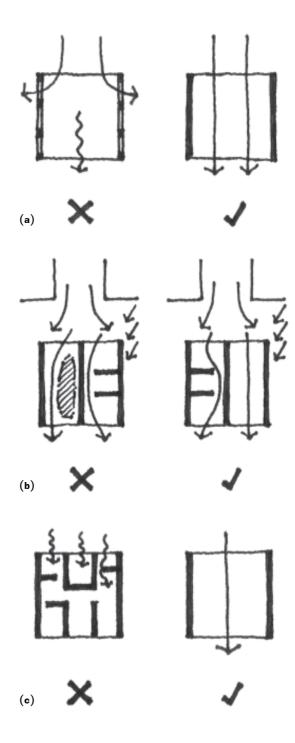


**Figure 6.** Examples of opening design to encourage interior air movement [36].

### 4.1 b) Ventilative 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 [35-36, 83].

In general, to maximise the heat removal potential of buoyancy-driven ventilation, the vent area should be maximised, 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 7), for example, which appears to have potential in hot humid climates where solar radiation is strong [84-87]. Work on the solar chimney shows that the optimum width of a chimney is independent of solar intensity [88-89], 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 [90-91] or made of a low-emissivity material to minimise radiative heat loss through its walls [90].
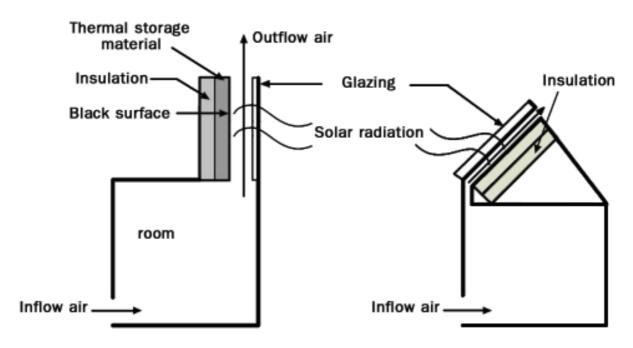


**Figure 7.** Examples of solar chimney configurations: vertical (a) and inclined (b) (adapted from [90]).

The heat removal performance of buoyancy-driven ventilation can be enhanced further by precooling 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 [92] 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 maximise the cooling potential of buoyancy-driven systems 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.

## 4.1 c) Ventilative 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 8a). 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 8b). 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 8c). 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 optimise the cooling potential of natural ventilation. This
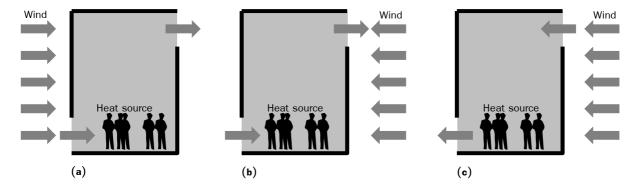


**Figure 8.** Wind-assisted ventilation (a); buoyancy dominated, wind-opposed ventilation (b); and wind dominated, wind-opposed ventilation (c).

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 in hot 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 optimise the cooling potential of this technique and complement the knowledge gained from specific case studies [e.g. 81, 83]. 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 [e.g. 93-95].

### 4.2 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 utilised 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 [96-97]. For modern buildings in hot humid climates, small-scale experiments [61] and computer modelling [38, 45, 60] 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 optimise 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 [96, 98] 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 $3-6^{\circ}$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 optimise 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.

### 4.3  Radiant Cooling

When two surfaces of different tem-
peratures face one another, radiative 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°C, which
could then be channelled into the building to
provide additional cooling (Figure 9) [5]. To
enhance the performance of such a system further,
a desiccant bed can be incorporated in the roof
structure to dehumidify the passing air [99]. More
work is still required to optimise the cooling
potential of this technique in hot humid climates.
To aid this, experience may be drawn from other
climates, particularly hot arid [e.g. 100-102], in
which nocturnal radiant cooling is more widely
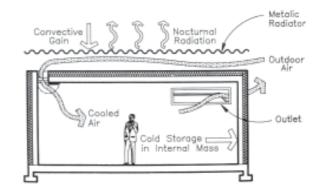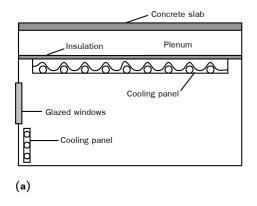used, thanks to their predominantly clear skies.



**Figure 9**. A schematic of a radiant cooling system which
involves cooling the roof by nocturnal radiation
and introducing cooled night air into the
occupied space [5].

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 a
heat sink for the interior space. A small system
has been tested in Thailand which shows a
promising performance (Figure 10) [103]. More
field-testing is required on such a system, along
with the development of generic design and control
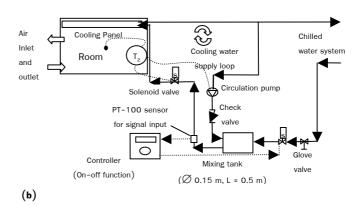principles to optimise its performance.



**(a)**



**(b)**

**Figure 10.** A schematic of the cool radiant panel system tested in Thailand (adapted from [103]). Figure 10a shows a
section indicating the location of the radiant panels in the test room. Figure 10b shows the diagram of the
cool-water circulation system.

### 4.4 Indirect Evaporative Cooling

Water left on a surface of a building has a natural tendency to evaporate in order to achieve phase equilibrium with the water vapour in the surrounding air. As it evaporates, every gramme 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.)

#### 4.4 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 [104], 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 11). The performance of this so-called 'Coolroof' is significant: it can cool the interior air by as much as 10–13°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 optimising the design of the pond's components, such as its depth and the roof's mass, in order to maximise its cooling potential under different climatic and occupancy conditions. Insights could be drawn from work carried out in drier climates [e.g. 105–106], in which a number of systems have been tested.

#### 4.4 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°C being possible [84, 86, 107–108]. Research opportunity is still open for developing the design and control principles of this technique, both qualitative and quantitative, that will help maximise its potential.
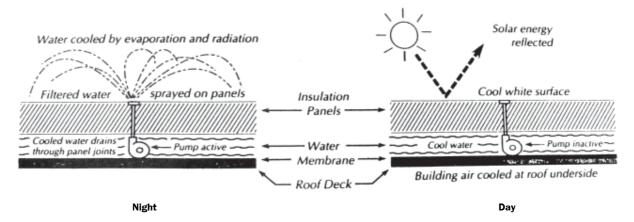


**Figure 11.** A schematic of the Coolroof system (i.e. roof pond with floating insulation; adapted from [5]).

### 4.4 c) Roof Garden

A roof garden can provide cooling in several ways. The plants shade the roof, and together with the substrate layer, act as insulation. Also, the substrate layer and roof structure combined serve as thermal mass that delays heat transfer from the exterior while absorbing heat from internal sources. Furthermore, the evapotranspiration process provides cooling. Case studies in hot humid climates show that roof gardens have significant cooling potential, with a reduction in the roof surface temperature of about 10-30°C being achievable, depending on the roof construction, planting details and surrounding conditions [77-79]. Generic design principles need to be acquired that will maximise the cooling potential of this technique in hot humid climates. Some fundamentals may be drawn from theoretical and experimental work done in other climates [e.g. 109]. Local plants of high cooling potential should also be identified.

## 5. Dehumidification Techniques

In hot humid climates where the humidity level is often above the comfortable limit, dehumidification is an important part of thermal comfort strategy. Typically, dehumidification in these climates is accomplished by mechanical air-conditioning. However, this can be highly energy consuming, as often to reduce moisture to a required level, humid intake air has to be cooled to a temperature below that required for thermal comfort.

Work has been carried out to find alternative passive dehumidification techniques. An example is a system which uses an attic lined with plywood as a dehumidification chamber (Figure 12) [110]. At night when the exterior air is uncomfortably humid, the plywood acts as a desiccant, absorbing moisture from the air from an occupied space below. The dried air is then fed back to the occupied space to enable it to ventilate without being in contact excessively with the humid exterior air. Then, during the day when the humidity of the exterior air is comfortably low, the occupied space is ventilated directly with the exterior air. Solar radiation onto the attic warms the plywood and makes it release the stored moisture into the attic air, which is then vented out to return the system to its original dry state. Another technique uses a double-glazing window unit, whose gap is filled with louvres coated with a silica powder desiccant (Figure 13) [111]. At night, humid exterior air is passed through the gap between the glass panes to allow the desiccant louvres to remove moisture from the passing air, before the dried air is delivered to the occupied space. Then, during the day, the moisture absorbed in the desiccant louvres is driven out using direct solar heating, which regenerates the system. Tests on the above two dehumidification techniques showed that up to 4-5 g/kg dry air of moisture could be removed, depending on the set-up details and the local climate. This level of performance may be sufficient in many situations in hot humid climates, given the people's acclimatisation to higher humidities. More field and theoretical work are required to develop such high-potential techniques for wider commercial use. Efforts should also be made to integrate passive dehumidification techniques with appropriate passive cooling systems to develop viable alternatives to conventional air-conditioning.

## 6. Conclusions

We have reviewed work on passive design for thermal comfort in hot humid climates, focusing on the issues that distinguish such design in these climates from that in other climates. Along the way,
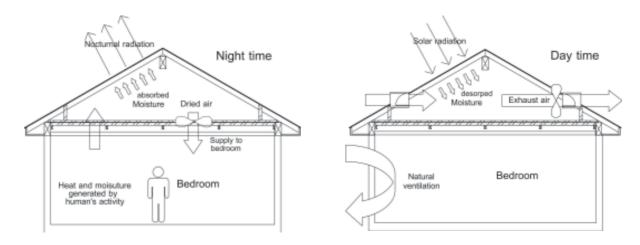
**Figure 12.** A schematic of the dehumidification system that uses an attic as a dehumidification chamber (adapted from [110]).
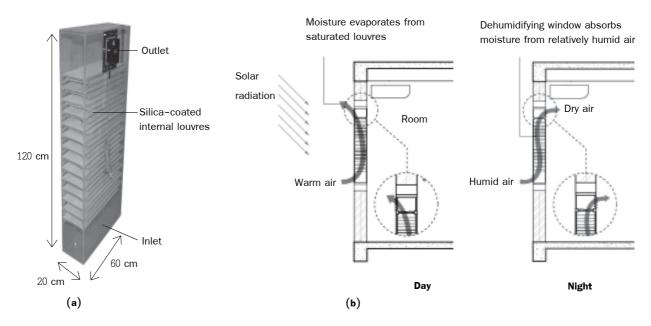


**Figure 13.** Dehumidifying window (a) and its operation (b) [111].

research and development opportunities have been pointed out. The review has highlighted the need for taking into consideration the effects of acclimatisation when identifying thermal comfort zones in hot humid climates. To achieve thermal comfort while minimising energy use, cooling requirement should be minimised. This can be achieved through various means, notably, appropriate orientation and spatial organisation, effective shading, and the use of suitable materials, colours, textures and vegetation. Spread-out planning and permeable internal organisation allow a building to take advantage of wind for cooling and humidity removal. Shading should be provided for both glass and opaque surfaces, and balanced with daylight strategy. Appropriate insulation is required to minimise thermal impact from solar radiation. Heavyweight materials may be suitable as envelopes for spaces occupied primarily during the day, whereas light-weight materials are more

suitable for spaces occupied primarily at night. Light-coloured external surfaces are preferable, as they help minimise the surface temperature and the heat load of the building. Use of vegetation should be encouraged to provide shading for buildings and the surrounding areas.

A range of passive cooling techniques may be used to help achieve thermal comfort. Ventilation by wind and thermal buoyancy has high potential to prevent overheating when used with appropriate fenestration, flow path design and buoyancy enhancement techniques. Wind-driven ventilation, in particular, can often induce sufficient air movement indoors to provide physiological cooling. Indirect evaporative cooling by a roof pond or a roof garden has significant potential. Radiant cooling shows a promising performance and deserves further exploration, particularly in areas where the skies are predominantly clear. More use of thermal mass for cooling should be encouraged, probably in conjunction with nocturnal ventilation, especially in buildings which are occupied mainly during the day. Passive dehumidification has potential to aid or replace conventional dehumidification by air-conditioning, and deserves further technical and commercial development. To maximise thermal comfort in a building, a combination of passive cooling and passive dehumidification techniques may be employed, as appropriate for the building's use and the climate in which it is located. Lessons can also be learned from traditional wisdom and work carried out in other climates.

Throughout, the review has emphasised the need for developing generic design and control principles for the various passive climate control techniques, which can complement the knowledge already gained from the case studies and fieldwork, and which can help optimise the potential of the techniques for providing thermal comfort. To this end, accurate understanding of the underlying science is necessary, which may be obtained through collaboration between architects and people from other disciplines. For example, fluid dynamists can provide insights into ventilation mechanisms and help develop appropriate ventilative cooling strategies, while physicists and chemists can shed light on the properties and behaviour of desiccants and help develop effective dehumidification schemes. Continuous research and development, both technical and commercial, are also central to developing high-potential passive environmental control techniques to become viable alternatives to mechanical solutions.

**References**

[1]  Department of Trade and Industry (DTI). (2003). Renewables innovation review. Retrieved May 1, 2007, from http://www.berr.gov.uk/files/file21955.pdf

[2]  U.S. Environmental Protection Agency (EPA). (2004). Buildings and the environment: A statistical summary. Retrieved September 1, 2007, from http://www.epa.gov/greenbuilding/pubs/gbstats.pdf

[3]  Building Research Establishment, Sustainable Construction Unit (BRESCU). (2000). Energy consumption guide 19: Energy use in offices. Watford, UK: Energy Efficient Best Practice Programme, BRE.

[4]  Baker, N. V., & Steemers, K. (2000). Energy and environment in architecture: A technical design guide. London: E & FN Spon.

[5]  Givoni, B. (1994). Passive and low energy cooling of buildings. New York: John Wiley & Sons.

[6]  Linden, P. (1999). The fluid mechanics of natural ventilation. Annual Review of Fluid Mechanics, 31, 201–238.

[7]  Allard, F. (Ed.). (1998). Natural ventilation in buildings: A design handbook. London: James & James.

[8]  Ghiaus, C., & Allard, F. (Eds.). (2005). Natural ventilation in the urban environment. London: Earthscan.

[9]  Fanger, P. O. (1970). Thermal comfort, analysis and application in environment engineering. Copenhagen, Denmark: Danish Technical Press.

[10]  Auliciems, A. (1981). Towards a psycho-physiological model of thermal perceptions. International Journal of Biochemistry, 25, 109–122.

[11]  Humphreys, M. (1978). Outdoor temperatures and comfort indoors. Building Research & Practice, 6(2), 92–105.

[12]  Szokolay, S. V. (2004). Introduction to architectural science: The basis of sustainable design. Oxford, UK: Architectural Press.

[13]  Zhang, G., Zheng, C., Yang, W., Zhang, Q., & Moschandreas, D. J. (2007). Thermal comfort investigation of naturally ventilated classrooms in a subtropical region. Indoor and Built Environment, 16(2), 148–158.

[14]  Wong, N. H., Feriadi, H., Lim, P. Y., Tham, K. W., Sekhar, C., & Cheong, K. W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. Building and Environment, 37, 1267–1277.

[15]*  Jitkhajornwanich, K. (2006). สภาวะสบาย และการปรับตัวเพื่ออยู่แบบสบายของคนในท้องถิ่น [Thermal comfort and adaptation for thermal comfort of local populations]. The 2006 National Research Council of Thailand Award. Bangkok, Thailand, 117–120.

[16]  Khedari, J., Yamtraipat, N., Pratintong, N., & Hirunlabh, J. (2000). Thailand ventilation comfort chart. Energy and Buildings, 32, 245–249.

[17]  Mallick, F. H. (1996). Thermal comfort and building design in the tropical climates. Energy and Buildings, 23, 161–167.

[18]  Srivajana, W. (2003). Effects of air velocity on thermal comfort in hot and humid climates. Thammasat International Journal of Science and Technology, 8(2), 45–54.

[19]  Hwang, R. L., Lin, T. P., & Kuo, N. J. (2006). Field experiments on thermal comfort in campus classrooms in Taiwan. Energy and Buildings, 38, 53–62.

[20] Kwok, A. G. (1998). Thermal comfort in tropical classrooms. ASHRAE Transactions, 104, 1031–1047.

[21] Wong, N. H., & Khoo, S. S. (2003). Thermal comfort in classrooms in the tropics. Energy and Buildings, 35, 337–351.

[22] de Dear, R. J., Leow, K. G., & Foo, S. C. (1991). Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. International Journal of Biometeorology, 34, 259–265.

[23] Busch, J. (1990). Thermal responses to the Thai office environment. ASHRAE Transactions, 96(1), 859–872.

[24] Busch, J. (1992). A tale of two populations: Thermal comfort in air-conditioned and naturally ventilated offices in Thailand. Energy and Buildings, 18, 235–249.

[25] de Dear, R. J., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104(1a), 145–167.

[26] American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). (1995). ASHRAE standard 55-1992, addenda 1995: Thermal environmental conditions for human occupancy, including ANSI/ASHRAE addendum 55a-1995. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

[27] Feriadi, H., & Wong, N. H. (2004). Thermal comfort for naturally ventilated houses in Indonesia. Energy and Buildings, 36, 614–626.

[28] International Standards Organisation (ISO). (2005). ISO 7730: 2005 Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva, Switzerland: International Standards Organisation.

[29] American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). (2004). ANSI/ASHRAE standard 55-2004: Thermal environmental conditions for human occupancy. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

[30] Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). A standard predictive index of human response to the thermal environment. ASHRAE Transactions, 66(2), 709–731.

[31] Olgyay, V. (1953). Bioclimatic approach to architecture (Building Research Advisory Board, Conference Report No. 5). Washington, DC: National Research Council.

[32] Wongfun, S., Chindavanig, T., & Sreshthaputra, A. (2006). แนวทางการใช้รูปแบบการไหลเวียนกระแสลมของเรือนไทยในบ้านพักอาศัย [Guidelines for utilization of natural air flow pattern of traditional Thai house in residence]. Journal of Energy Research, 3, 31–50.

[33] Leaurungreong, V., Oranratmanee, R., Sihalarth, P., & Insisiengmay, S. (2005). ภูมิปัญญาพื้นถิ่นทางสถาปัตยกรรมเพื่อความสบายในอาคารพักอาศัยของเชียงใหม่และหลวงพระบาง [The local intelligence for a dwellings comfort living in Chiang Mai & Luang Prabang]. Journal of Energy Research, 2, 17–38.

[34] Tantasavasdi, C., Jareemit, D., Suwanchaiskul, A., & Naklada, T. (2007). Natural ventilation: Evaluation and design of houses in Thailand. Proceedings of the 3rd Conference on Energy Network of Thailand [CD-ROM]. Bangkok, Thailand.

[35] Tantasavasdi, C. (2002). การคำนวณพลศาสตร์ของไหลเพื่อการออกแบบโดยวิธีธรรมชาติ: แนวทางสำหรับบ้านในประเทศไทย [CFD approach towards natural ventilation design: Guidelines for houses in Thailand]. Journal of Architectural Research and Studies, 1, 45–63.

[36] Tantasavasdi, C., Srebric, J., & Chen, Q. (2001). Natural ventilation design for houses in Thailand. Energy and Buildings, 33, 815–824.

[37] Murakami, S., Kato, S., Ooka, R., & Shiraishi, Y. (2004). Design of a porous-type residential building model with low environmental load in hot and humid Asia. Energy and Buildings, 36, 1181–1189.

[38] Wang, L., & Wong, N. H. (2007). The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore. Building and Environment, 42, 4006–4015.

[39] Tantasavasdi, C., & Jareemit, D. (2005). การระบายอากาศโดยวิธีธรรมชาติ: แนวทางการออกแบบผังอาคารชุดพักอาศัยประเภทอาคารสูง [Natural ventilation: Planning design guidelines for residential high-rises]. Journal of Architectural/Planning Research and Studies, 3, 23–36.

[40]* Srisuwan, M. (2001). การศึกษาและวิเคราะห์ทิศทางกระแสลมที่สัมพันธ์กับทิศทางอาคาร การหมุนเวียนของกระแสลมและการระบายอากาศสำหรับโครงการมหาวิทยาลัยเขียวสะอาด วิทยาเขตสารสนเทศ เพชรบุรี [Analysis of relationships between wind direction, building orientation and ventilation at green and clean university project Phetchaburi Information Technology Campus]. Sarasatr, 5, 145–158.

[41] Laopanitchakul, V., Sunakorn, P., & Srisutapan, A. (2007). Climbing-plants on solid wall reducing energy in tropical climate. In S. W. Shin, & H. W. Lee (Eds.), Proceedings of the International Conference on Sustainable Building Asia, SB07 Seoul (pp. 271–278). Seoul, Korea: Korean Green Building Council (KGBC).

[42] Luxmoore, D. A., Jayasinghe, M. T. R., & Mahendran, M. (2005). Mitigating temperature increases in high lot density sub-tropical residential developments. Energy and Building, 37, 1212–1224.

[43] Meng, Q., & Zhang, L. (2006). The rooftop shading system of the Humanities Building at SCUT. Energy and Buildings, 38, 1356–1359.

[44] Mingozzi, A., & Bottiglioni, S. (2005). Logical use of traditional technologies for housing passive cooling in hot humid Italian climate areas. Proceedings of International Conference: Passive and Low Energy Cooling for the Built Environment. Santorini, Greece, 579–584.

[45]* Wimolwattewee, A., Chindavanig, T., & Sreshthaputra, A. (2006). แนวทางการออกแบบปรับปรุงบ้านเอื้ออาทรเพื่อสภาวะน่าสบายและการใช้พลังงานอย่างมีประสิทธิภาพ [Design guidelines for improving thermal comfort and energy efficiency of Baan Ua-Arthorn]. Journal of Energy Research, 3, 51–88.

[46] Suriyothin, P. (2002). Climatic design for energy efficient house in Thailand: Case study of a prototype house for four regions. Sarasatr, 5, 129–164.

[47] Garde, F., Mara, T., Lauret, A. P., Boyer, H., & Celaire, R. (2001). Bringing simulation to implementation: Presentation of a global approach in the design of passive solar buildings under humid tropical climates. Solar Energy, 71(2) 109–120.

[48] Sumanon, R. (2004). ลักษณะเฉพาะของมุมเอียงหลังคาที่มีผลต่อความรู้สึกร้อนหนาวภายในเรือนไทย [The unique angle of roof slope effecting thermal comfort in the traditional Thai house]. Sarasatr, 7, 193–218.

[49]* Chukiatman, K. (1998). การใช้แสงธรรมชาติเสริมเพื่อลดพลังงานในอาคาร กรณีศึกษาอาคารในจุฬาลงกรณ์มหาวิทยาลัย [Natural lighting for reducing energy consumption: Case study of buildings at Chulalongkorn University]. Sarasatr, 2, 66–84.

[50]* U-Sanno, K. (1997). รูปแบบอุปกรณ์บังแดดที่เหมาะสมสำหรับห้องเรียน [Appropriate shading devices for classrooms]. Sarasatr, 1, 140–155.

[51]   Srivirote, S. (2004). ผลกระทบของความร้อนที่เกิดจากการนำแสงธรรมชาติมาใช้ในอาคาร โดยผ่านช่องแสงกระจกด้านข้าง [The effect of heat transmittance from utilization of daylighting in buildings through side-glazings]. Journal of Energy Research, 1, 36-79.

[52]*  Simcharoen, P., & Pikultong, P. (2006). คุณสมบัติทางความร้อนและการดูดซึมความชื้นของวัสดุก่อสร้าง [Thermal and moisture absorption properties of construction materials]. Journal of Energy Research, 3, 89-96.

[53]   Majed, M., & Al-Hazmy, M. M. (2006). Analysis of coupled natural convection-conduction effects on the heat transport through hollow building blocks. Energy and Buildings, 38, 515-521.

[54]   Boonnasa, S. (2006). การเปรียบเทียบอัตราการถ่ายเทความร้อนที่ผ่านผนังระหว่างอิฐ Block ธรรมดา และอิฐ Cool Block [Comparison of heat transfer through the wall made of the conventional concrete block and Cool Block]. Proceedings of the 2<sup>nd</sup> Conference on Energy Network of Thailand. Nakhon Ratchasima, Thailand.

[55]*  Puthipiroj, P. (2007). การศึกษาประสิทธิผลในการลดความร้อนจากหลังคา โดยวิธีการระบายอากาศและการใช้ฉนวนกันความร้อน [Comparison of effectiveness of attic ventilation and insulation in reducing heat transfer through roof]. Journal of Energy Research, 4, 59-72.

[56]   Kanisthakhon, B. (2001). Optimal materials for hot and humid climate: A case study of a contemporary Thai house. Sarasatr, 4(2), 110-126.

[57]   Alvarado, J. L., & Martinez, E. (in press). Passive cooling of cement-based roofs in tropical climates. Energy and Buildings.

[58]   Thongkamsamut, C. (2005). การป้องกันความร้อนผ่านผนังก่ออิฐฉาบปูนสัมพันธ์กับการระบายอากาศ [A protection of heat flow through common brick wall related to natural ventilation]. Journal of Faculty of Architecture, Khon Kaen University, 4(1), 117-123.

[59]   Srisutapan, A. (1999). การปรับปรุงหลังคาเพื่อลดปริมาณการถ่ายเทความร้อน [Reduction of heat gain through roof modification]. Sarasatr, 2, 151-158.

[60]   Yimprayoon, C. (2004). การจำลองประสิทธิภาพการถ่ายเทความร้อน ของบ้านพักอาศัยระบบพึ่งพาธรรมชาติ ด้วยการเลือกใช้วัสดุประกอบอาคารต่าง ๆ กรณีศึกษา: โครงการบ้านเอื้ออาทร [Passive residential building indoor thermal performance modeling using various building components. Case study: Baan Ua-Arthorn low-cost housing project]. Raneang, 4, 231-245.

[61]   Piriyasatta, P. (1999). ผลกระทบของสีผนัง และมวลสารภายในต่อการถ่ายเทความร้อนเข้าสู่อาคาร [Effects of wall colors and thermal mass to thermal conduction in building]. Sarasatr, 2, 174-192.

[62]   Doulos, L., Santamouris, M., & Livada, I. (2004). Passive cooling of outdoor urban space. The role of materials. Solar Energy, 77, 231-249.

[63]   Khamput, P., & Suweero, K. (2007). การเลือกวัสดุสำหรับใช้ออกแบบอิฐปูพื้นภายนอกอาคารเพื่อลดอุณหภูมิ [Selecting materials for design the exterior floor-covering blocks for reducing temperature]. Proceedings of the 3<sup>rd</sup> Conference on Energy Network of Thailand [CD-ROM]. Bangkok, Thailand.

[64]   Givoni, B., & Hoffman, M. E., (1968). Effects of building materials on internal temperatures (Research report). Haifa: Technion Israel Institute of Technology, Research Station.

[65]   Pasilo, A., Hanchaiyungwa, N., & Teeboonma, U. (2007). การศึกษาสมบัติปาร์ติเกิลบอร์ดที่ทำจากฟางข้าวและแกลบ [A study of particle board properties manufactured from straw rise and rise husk]. Proceedings of the 3<sup>rd</sup> Conference on Energy Network of Thailand [CD-ROM]. Bangkok, Thailand.

[66]   Leaurungreong, V. (2004). เทคโนโลยีหญ้าแฝกเพื่องานสถาปัตยกรรม [Vetiver grass technology for architecture]. Proceedings of the 1<sup>st</sup> Professional and Academic Collaborative Symposium. Bangkok: Council of Deans of Architecture Schools of Thailand, 235-242.

[67] Pakunworakij, T., Puthipiroj, P., Oonjittichai, W., & Tisavipat, P. (2006). ประสิทธิภาพการป้องกันความร้อน ของฉนวนอาคารจากวัสดุเหลือใช้ทางการเกษตร [Thermal resistance efficiency of building insulation material from agricultural waste]. Journal of Architectural/Planning Research and Studies, 4(1), 2-13.

[68] Khedari, J., Suttisonk, B., Pratinthong, N., & Hirunlabh, J. (2001). New lightweight composite construction materials with low thermal conductivity. Cement & Concrete Composites, 23, 65-70.

[69] Khedari, J., Watsanasathaporn, P., & Hirunlabh, J. (2005). Development of fibre-based soil-cement block with low thermal conductivity. Cement & Concrete Composites, 27, 111-116.

[70] Asasutjarit, C., Hirunlabh, J., Khedari, J., Charoenvai, S., Zeghmati, B., & Shin, U. C. (2007). Development of coconut coir-based lightweight cement board. Construction and Building Materials, 21, 277-288.

[71] Boonma, P., Phethuayluk, S., Waewsak, J., Klompong, N., & Sompech, S. (2005). สมบัติทางฟิสิกส์ บางประการของคอนกรีตบล็อกแบบกลวงที่ผสมเส้นใยกากปาล์มน้ำมันและผสมเส้นใยชานอ้อย [Some physical properties of hollow concrete block mixed with oil palm fibers and bagass fibers]. Proceedings of the 1st Conference on Energy Network of Thailand. Chon Buri, Thailand.

[72]* Thongkamsamut, C. (2003). การพัฒนาผนังวัสดุธรรมชาติพื้นถิ่นเพื่อปรับปรุงสภาวะน่าสบายในอาคาร กรณีศึกษา อาคารเรียนไม่ปรับอากาศ ภาคตะวันออกเฉียงเหนือ ประเทศไทย [Development of walls from local materials for thermal comfort improvement: Case study of non air-conditioned schools in North-eastern Thailand]. Journal of the Faculty of Architecture, Khon Kaen University, 2(1), 39-48.

[73] Chen, Y., & Wong, N. H. (2006). Thermal benefits of city parks. Energy and Buildings, 38, 105-120.

[74] Parker, J. H. (1983). The effectiveness of vegetation on residential cooling. Passive Solar Journal, 123-132.

[75] Parker, J. H. (1987). The use of shrubs in energy conservation plantings. Landscape Journal, 6, 132-129.

[76] Parker J. H. (1989). The impact of vegetation on air conditioning consumption. Proceedings of Conference on Controlling the Summer Heat Island, LBL-27872. Berkeley, CA: Lawrence Berkeley Laboratory, 46-52.

[77] Wong, N. H., Tan, P. Y., & Chen, Y. (2007). Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Building and Environment, 42, 25-54.

[78] Nualsakul, N. (2004). การเปรียบเทียบศักยภาพของการป้องกันความร้อนระหว่างการใช้สวนหลังคากับระบบหลังคา ที่ใช้กันทั่วไป [A comparative study of thermal benefit between roof garden and conventional roof systems]. Sarasatr, 7, 219-234.

[79] Wong, N. H., Chen, Y., Ong, C. L., & Sia, A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. Energy and Buildings, 38, 261-270.

[80] Givoni, B. (1991). Performance and applicability of passive and low energy cooling systems, Energy and Buildings, 17, 177-199.

[81] Tantakitti, C., & Jaturonglumlert, S. (2005). ผลของช่องเปิดอากาศโรงงานที่มีต่อค่าความสบายโดยการถ่ายเท อากาศแบบธรรมชาติ [Effect of factory openings on comfort by natural ventilation]. Journal of Energy Research, 2, 37-47.

[82] Srisuwan, M. (2001). การศึกษาความสัมพันธ์ของทิศทางกระแสลมกับการเจาะช่องเปิดที่ผนังอาคาร สำหรับภูมิอากาศ ร้อนชื้นในประเทศไทย [The study of air flow patterns in relation to building wall opening for the tropical climate of Thailand]. Sarasatr, 4, 234-248.

[83] Thanadsillapakul, C. (2005). แนวทางการออกแบบปล่องระบายอากาศสำหรับบ้านพักอาศัยในประเทศไทย [Stack ventilation design guidelines for houses in Thailand]. Journal of Energy Research, 2, 1-16.

[84]   Limmeechokchai, B., & Chungloo, S. (2007). Application of solar chimney and wetted roof in the test cell for natural ventilation and heat reduction in the hot and humid climate. Proceedings of the 3$^{rd}$ Conference on Energy Network of Thailand [CD-ROM]. Bangkok, Thailand.

[85]   He, J., Okumura, A., Hoyano, A., & Asano, K. (2001). A solar cooling project for hot and humid climates. Solar Energy, 71, 135–145.

[86]   Chungloo, S., & Limmeechokchai, B. (2006). A numerical study of natural ventilation in buildings-utilized solar chimney and cool ceiling. Proceedings of the 2$^{nd}$ Joint International Conference on Sustainable Energy and Environment. Bangkok, Thailand.

[87]   Khedari, J., Boonsri, B., & Hirunlabh, J. (2000). Ventilation impact of a solar chimney on indoor temperature fluctuation and air change in a school building. Energy and Buildings, 32, 89–93.

[88]   Bouchair, A. (1994). Solar chimney for promoting cooling ventilation in Southern Algeria. Building Services Engineering Research & Technology, 15(2), 81–93.

[89]   Spencer, S., Chen, Z. D., Li, Y., & Haghighat, F. (2000). Experimental investigation of a solar chimney natural ventilation system. Proceedings of 20$^{th}$ AIVC Conference: Ventilation Technologies. Edinburgh, UK, 813–818.

[90]   Harris, D. J., & Helwig, N. (2007). Solar chimney and building ventilation. Applied Energy, 84, 135–146.

[91]   Hamdy, I. F., & Fikry, M. A. (1998). Passive solar ventilation. Renewable Energy, 14, 381–386.

[92]   Chenvidyakarn, T., & Woods, A. W. (2004). Top-down pre-cooled natural ventilation. Building Services Engineering Research & Technology, 26(3), 1–14.

[93]   Lishman, B., & Woods, A. W. (2006). The control of naturally ventilated buildings subject to wind and buoyancy. Journal of Fluid Mechanics, 557, 451–472.

[94]   Hunt, G. R., & Linden, P. F. (2000). Multiple steady airflows and hysteresis when wind opposes buoyancy. Air Infiltration Review, 21, 1–3.

[95]   Hunt, G. R., & Linden, P. F. (2004). Displacement and mixing ventilation driven by opposing wind and buoyancy, Journal of Fluid Mechanics, 527, 27–55.

[96]   Sreshthaputra, A. (2003). Building design and operation for improving thermal comfort in naturally ventilation buildings in a hot-humid climate. Dissertation Abstracts International, 64(04), 1109A. (UMI No. 3088186)

[97]   Sreshthaputra, A., Haberl, J., & Andrews, M. J. (2004). Improving building design and operation of a Thai Buddhist temple. Energy and Buildings, 36, 481–494.

[98]   Shaviv, E., Yezioro, A., & Capeluto, I. G. (2001). Thermal mass and night ventilation as passive cooling design strategy. Renewable Energy, 24, 445–452.

[99]   Fairy, P., & Vieira, R. (1984). Proposal for hybrid building cooling and dehumidification through desiccant, enhanced nocturnal radiation (Submitted by the Florida Solar Energy Center to the US Department of Energy).

[100]  Givoni, B., & Hoffman, M. E. (1970). Preliminary study of cooling of houses in desert regions by utilizing outgoing radiation (Research report). Haifa: Technion Israel Institute of Technology, Research Station.

[101]  Givoni, B. (1981). Experimental studies on radiant and evaporative cooling of roofs. Proceedings of International Passive and Hybrid Cooling Conference. Miami Beach, FL: AS/ISES, 279–283.

[102] Etzion Y., & Dover, S. (1989) Radiative cooling of buildings (Research report). Sede Boqer, Israel: Ben Gurion University, Institute for Desert Research.

[103] Vangtook, P., & Chirarattananon, S. (2006). An experimental investigation of application of radiant cooling in hot humid climate. Energy and Buildings, 38, 273-285.

[104] Sandoval, L., Pineda, J., Castaneda, R., & Sanchez, L. (1991). Cooling ceiling pond in hot-humid climates. Proceedings of ISES Solar World Congress. Denver, CO.

[105] Givoni, B. (1980). Experimental studies on passive cooling at the Institute for Desert Research in Israel. Proceedings of Solar Energy Symposium. Nice, France, 296-300.

[106] Bourne, R. C., & Hoeschele, M. A. (1992). Cool storage roof (Demonstration project monitoring report). Davies, CA: Davis Energy Group.

[107] Nutalaya, S. (1999). Passive cooling application in hot and humid country: Theory and experimentation. Case study: Khon Kaen, a city of Northeastern Thailand. Dissertation Abstracts International, 60 (08), 2712A. (UMI No. 9940524)

[108] Choi, D. H., Joe, K. R., & Lee, B. Y. (2007). An evaluation on passive cooling effects of roof water spraying through the comparative experiments of indoor thermal environment on the top floor. In S. W. Shin, & H. W. Lee (Eds.), Proceedings of the International Conference on Sustainable Building Asia, SB07 Seoul (pp. 789-794). Seoul, Korea: Korean Green Building Council (KGBC).

[109] Onmura, S., Matsumoto M., & Hokoi, S. (2001). Study on evaporative cooling effect of roof lawn gardens. Energy and Buildings, 33, 653-666.

[110] Areemit, N., & Sakamoto, Y. (2007). Numerical and experimental analysis of a passive room-dehumidifying system using the sorption property of a wooden attic space. Energy and Buildings, 39, 317-327.

[111] Chenvidyakarn, T., Jongsuwanpaisan, T., & Tantasavasdi, T. (2007). Low-energy, building envelope-integral system for air dehumidification. Manuscript in preparation.

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