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A SHORT REVIEW ON PASSIVE STRATEGIES APPLIED TO MINIMISE THE BUILDING COOLING LOADS IN HOT LOCATIONS

[1]*Qudama Al-Yasiri*, [2]*Márta Szabó*

[1]Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary
[2]Institute of Technology, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary
Corresponding author e-mail: qudamaalyasiri@uomisan.edu.iq

ABSTRACT

Cooling and air-conditioning systems are responsible for the highest energy consumption in buildings located in hot areas. This high share does not only increase the building energy demand cost but also increases the environmental impact, the topmost awareness of the modern era. The development of traditional systems and reliance on renewable technologies have increased drastically in the last century but still lacks economic concerns. Passive cooling strategies have been introduced as a successful option to mitigate the energy demand and improve energy conservation in buildings. This paper shed light on some passive strategies that could be applied to minimise building cooling loads to encourage the movement towards healthier and more energy-efficient buildings. For this purpose, seven popular passive technologies have been discussed shortly: multi-panned windows, shading devices, insulations, green roofing, phase change materials, reflective coatings, and natural ventilation using the windcatcher technique. The analysis of each strategy has shown that the building energy could be improved remarkably. Furthermore, adopting more passive strategies can significantly enhance the building thermal comfort even under severe weather conditions.

Keywords: Passive strategies, energy saving, cooling load reduction, insulations, thermal mass

1. INTRODUCTION

Buildings in hot locations require efficient cooling systems to overcome the high temperature and reach occupants' thermal comfort [1]. This is mainly due to the high thermal conductivity construction materials used, which causes high cooling loads [2]. These cooling and air-conditioning systems consume more than 50% of the total electric power provided by local electric networks. The researchers and experts resort to modern strategies that reduce thermal loads in buildings, which lead to environmental and economic benefits [3].

Recently, many methods have been used to reduce the cooling loads in buildings, actively and passively [4,5]. Passive strategies represent the intelligent use of renewable energy sources like the sun and wind to cool, ventilate, and light the building without using any equipment. This leads to a reduction of electrical energy, making buildings more energy-efficient. There is interest in such techniques as part of the evolution in architecture, and the world tends towards zero energy buildings [6]. The use of passive cooling strategies in modern buildings aims to eliminate the need for mechanical cooling equipment or reduce the size and cost of equipment, thus reducing maintenance operations [7]. Many types of passive cooling techniques could be used in hot locations that could be adopted for a better, healthier and efficient built environment.

In this paper, some popular passive strategies that can be applied to improve the building energy in hot locations have been presented and discussed briefly. These strategies are mainly applied for openings (windows and transparent building envelops), building thermal mass (roofs and walls), minimising the incident solar radiation or improving air quality. Therefore, the heat response and energy performance of the building will be improved. Despite the brief description of these techniques, the information presented in this paper is believed to provide a sound vision of what and how passive strategies can be used to improve the building energy in hot locations.

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2. STRATEGIES APPLIED ON THE WINDOWS

The primary role of these techniques is to control the solar radiation incident on building windows, taking into account the importance of sunlight for natural lighting. These strategies are popularly used worldwide despite the prevailing weather conditions. The main two types discussed in this regard are the multi-panned windows and shading devices.

2.1. Multi-panned windows

Huge heat gain of buildings comes through the open spaces such as windows. Controlling such elements and making them more efficient is one of the essential passive methods to reduce cooling loads. Multi-panned windows (MPWs) have developed a lot during the last century, and they could be double-pane, triple-pane and quadruple-pane windows [8]. For instant, the MPW is two glass panes placed away from each other by a 12-16 mm, discharged from the air or filled with argon gas. Triple-pane windows have the same construction as double-pane windows with an extra pane layer. Fig. 1 shows the typical illustration of single, double and triple-pane windows. The primary objective of MPWs is to increase the insulating of windows, wherein these panes and gas are used to reduce the amount of heat transfer that moves from outside to inside the buildings.

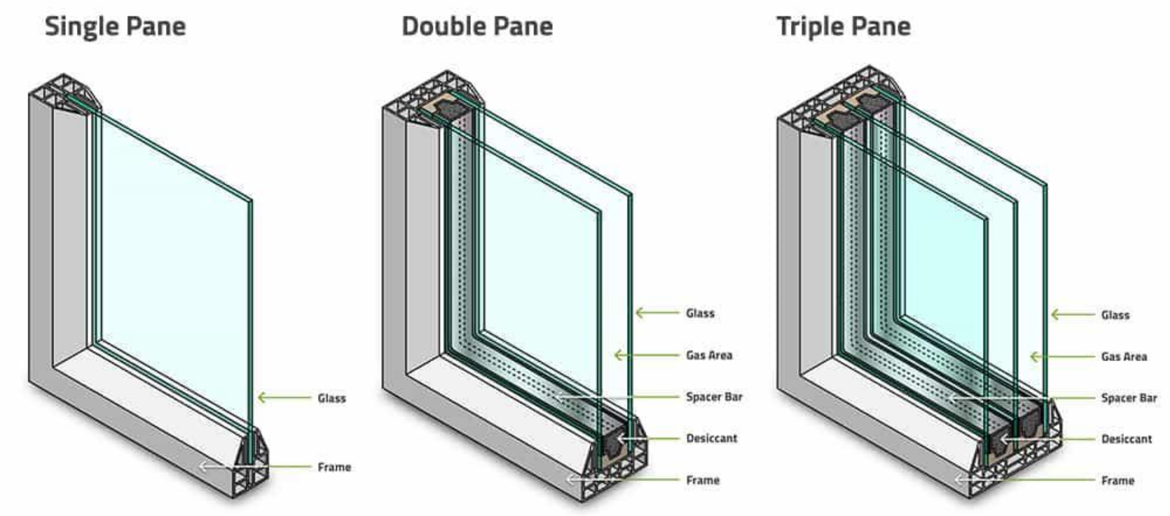

Figure 1. Typical single, double and triple-pane windows [9].

The number of panes can significantly influence the performance of MPWs, meaning that increasing pane number results in more energy saving. In this regard, Julián et al. [10] claimed that replacing clear single-pane windows with double-pane windows was reduced the heat flux by 72.6% under Mexican weather conditions. Furthermore, Arıcı et al. [11] revealed that replacing double-pane windows with triple or quadruple pane windows can save energy by about 50% or 67%, respectively.

The pane's U-value (U is the heat transmission coefficient) affects the MPWs in which low U-value panes performed better. Baek and Kim [12] reported that changing commercial panes of U-value ranging from 1.2-3.3 $W/m^2.K$ to 0.7 $W/m^2.K$ can reduce the greenhouse gas emissions and related heat flux by 45%-79% while using panes of 0.2 $W/m^2.K$ can improve the window by up to 82%-93%.

Filling gaps between panes with gases denser than air is another modification strategy in MPWs. These gases can decrease the conductive heat coming from outside and reach better thermal comfort [13]. Filling panes' gaps with gas decrease the radiative heat transfer by absorbing, emitting, and scattering, reducing

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heat flux [14]. This can contribute to up to 20% energy saving in buildings. Other strategies have been studied in the literature and showed remarkable contributions, such as pane coating with low thermal emissivity materials [15], a vacuum of panes gaps [16] and using of solar control coatings [17].

2.2. Shading devices

Shading devices are used to shade the sun radiation fallen on the building windows. The use of such devices can improve the internal environment of buildings [18]. Windows should well control the sun to reduce the radiation in the summer and get maximum radiation in the winter. These shading devices could be inside the building through blinds, rollers, curtains, or outside, such as fins, louvres, and overhangs. Venetian blinds are the most studied literature among other shading devices, particularly office buildings [19]. Fig. 2 shows some popular practical types of shaded devices.

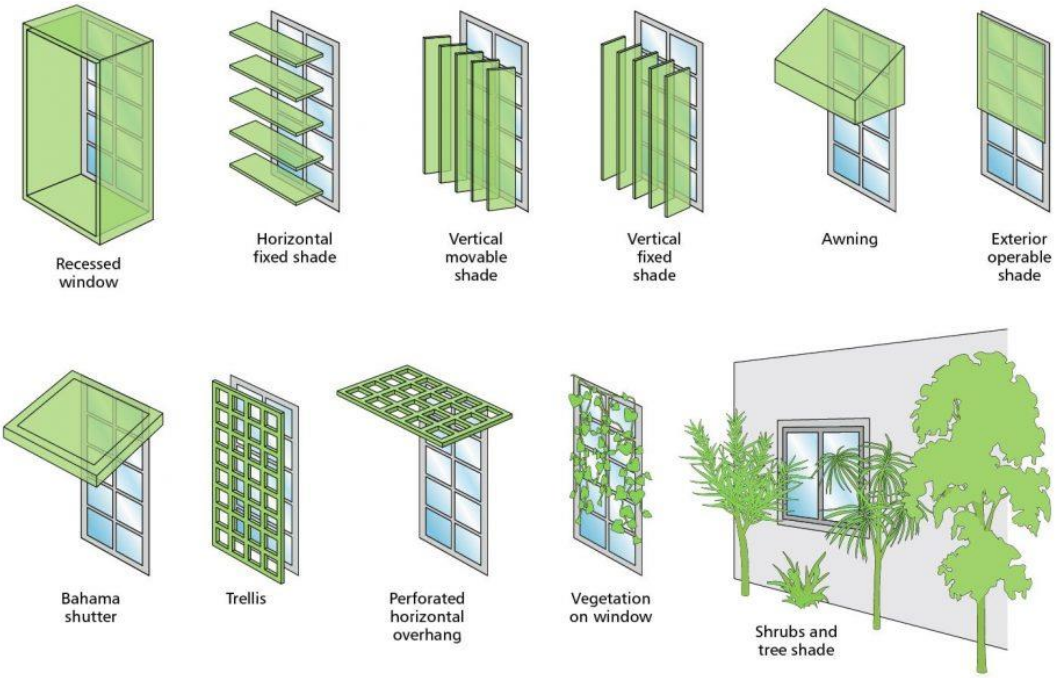

Figure 2. Types of external shading devices [20].

Shading devices can be placed horizontally or vertically in front of the window in various ways, and their effectiveness depends highly on the building geographical location [21]. Their shape, type, depth, and height differ depending on the building location, inclination angle, and window area [22]. The shading device is designed to block the sun in summer yet allows it to enter in winter. Typically, the inside shading device places behind the glass and can only reflect part of the radiation, while the rest is absorbed, convected and re-radiated into the room. External shading devices shade the window from direct radiation and prevent a large part of heat to get in. Hence, the location of these devices is very important. Glazed areas that are fully shaded from the outside can reduce the solar heat gain by up to 80% compared to those located behind the glazing surface [23].

3. THERMAL MASS STRATEGIES

Different successful passive strategies have been applied to enhance the building's thermal mass, especially for heavy and thermally-poor construction materials. Such techniques significantly impact future building sustainability by constructing thin buildings with minimal cost and raw construction materials. The main strategies discussed in this section include green roofing, insulations, and the incorporation of phase change materials.

3.1. Green roofing

Studies indicate that a massive amount of heat comes from the sun passes through the building roof. Therefore, using insulating techniques on the roof surface to reduce thermal loads is essential and gives promising results. Covering the roof with a layer of grass or plants situated over the waterproof membrane is one of the modern methods used and called green roofing (see Fig. 3). Studies have shown that green roofing decreases the indoor air temperature in the closed buildings by about 2 °C and reduces annual energy demand by 6% [24]. Other benefits of green roofing are the production of oxygen, which improves air quality around the building and rainwater absorption.

Figure 3. Green roofing technique [25].

Green roofing technique consists of sewage and barriers that prevent roots in addition to water channels composition. Spaces without panels allow air to move and create heat in the roots and thus provide better ventilation without membranes locked together to create a platform and stay stable. It will also include some of the sewage water runoff. The materials used for such purposes are mostly recycled plastics. There are two types of green roofing; intensive and extensive green roofs. The first type is thick with a minimum depth of 12.8 cm and allows a variety of plants to be planted. This type is heavy and requires more maintenance. The extensive roofs are shallow, ranging from 2-12.7 cm depth, lighter than intensive green roofs, and require minimal maintenance [26].

3.2. Insulation

Literature studies indicate that highly effective insulating materials are used to maintain acceptable comfort levels in buildings, significantly reduce heat gain, and reduce energy demand [27]. Many materials used as insulators, and mainly classified into three categories according to their origin and chemical composition: conventional (organic and inorganic insulation such as polystyrene, formaldehyde insulators, polyurethane and polyisocyanurate, cellulose, cork, mineral wool, calcium silicate, foam glass, perlite, and vermiculite),

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state-of-the-art (closed-cell foam, aerogel, Transparent Insulation Materials, vacuum insulation panels, reflective multi-foiled insulation materials, and Nano Insulation materials) and
sustainable insulators (natural insulation materials derived from agro and forest residues, and sheep wools Recycled insulation materials) [28].
As shown in Fig. 4, the insulation could be installed for walls, ceilings, and roofs in the internal or external building elements.

Figure 4. Insulations applied to the interior and exterior building envelope.

Insulations are working to reduce the heat gain through the building envelope by trapping large amounts of air (or other gases) in a way that results in a material that employs low thermal conductivity of small pockets of gas instead of the much higher than conventional solids conductivity. The effectiveness of insulation is commonly evaluated by its R-value (the temperature difference ratio across an insulator that measures the thermal resistance) [29]. The importance of insulations revealed more for multi-story buildings due to large building surfaces exposed to the incident solar radiation. For instance, a study conducted for a four-story building in Thailand indicated that mean overheating days can be reduced by 21.43% using insulation [30].
The type and quantity of insulations depend on the design of buildings, climate, energy costs, budget and personal preference [31]. Building insulation needs careful consideration of how (and where) the energy and heat transfer direction change during the day and season [32,33]. It is crucial to choose the right design, insulation materials and construction techniques fitted with the building [34].

3.3. Phase change materials

Phase change materials (PCMs) are materials that can store and release a considerable amount of heat in a latent form (in addition to the sensible form) within a relatively stable temperature called phase change/transition temperature [35][36]. PCMs have proved to control the heat through the building envelope by acting as a heat barrier under hot locations, resulting in an essential building thermal comfort and energy saving [37,38]. The working principle of PCMs is that the heat accumulated during the day is restricted and stored in a latent form (which is huge in these materials) and then released during the nighttime [39]. This mechanism is the same as insulations, except PCMs are more dynamic against heat transfer than insulators. PCMs have been integrated in different forms and techniques with the building

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elements, such as roofs [40,41], walls [42], floors [43], mortars and concrete [44-46], insulation [47], bricks [48,49], windows [50], shading devices [51], etc. Considering the building thermal mass (i.e. roofs and external walls), studies have shown that PCMs can effectively shave and shift the peak indoor temperature, which maintains an acceptable thermal comfort even in severe hot locations [52,53]. Rathore and Shukla [54] experimentally showed that incorporation PCM with cubicles can reduce the maximum and total peak heat flux by 41.31% and 27.32%, respectively, compared with a cubicle without PCM under Indian weather conditions. At the same location, Saxena et al. [55] reported that the PCM can decrease 4.5 °C-7 °C of bricks inner surface temperature and the heat flux can be reduced by 40%-60%.

Several influential parameters need to be studied to use PCMs as efficient as possible for a longer time and minimal operational cost. These are mainly the optimal phase change temperature, the optimal position within the building element, and the optimal quantity to be involved [56-58]. Arıcı et al. [59] found that PCM temperature varied between 6 °C to 34 °C and a PCM layer thickness varied between 1–20 mm can improve the building thermal performance and time lag by 10.3 h in three different Turkish cities. Zhang et al. [60] indicated that PCMs of melting temperature varied between 22 °C-28 °C, placed to the interior position with 5mm thickness could reduce the indoor building surface temperature and the heat transfer by 6.6 °C and 52.9% under China weather conditions. All in all, these parameters need to be studied in parallel to obtain the best thermal performance of PCMs [61].

4. OTHER STRATEGIES

Many other passive strategies, other than those discussed above, have been used in hot location buildings. Some of them are used to minimise the incident solar radiation, such as coatings, and others adopt the night cooling effect and low-temperature air for ventilation. The main two strategies discussed in this section are the light colour reflective coatings and wind catchers.

4.1. Light colour reflective coatings

The indoor environment is affected by thermal loads that come through the building envelope exposed to the sun, wherein a large amount of heat is transferred into buildings of large envelopes. Painting exterior building envelopes with light-coloured coatings reduce the transferred heat remarkably thanks to the high reflectivity of these coatings against solar rays, as shown in Fig.5.

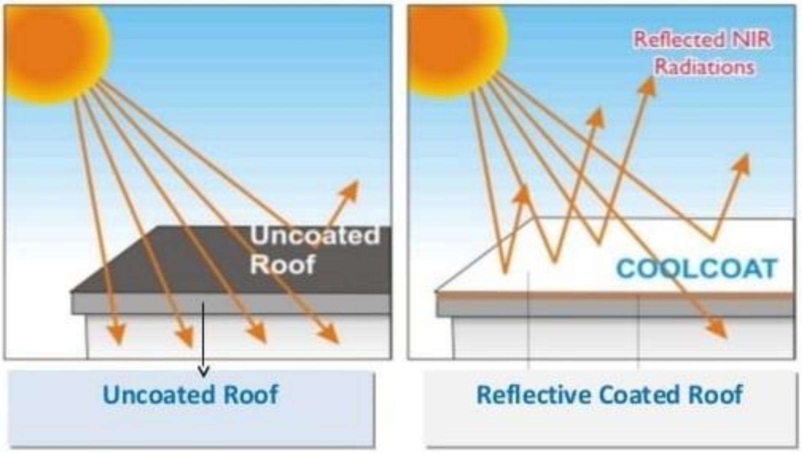

Figure 5. Principle of using light colour coatings to minimise solar radiation [62].

An experimental study reported that using light reflective paints has reduced the interior building temperature by up to 4.7 °C compared with painting with grey or dark colours [63]. This remarkably reduced the power consumption and cooling loads. The coating of the light colours depends on both the climate and the type of material used [64]. Pal et al. [65] investigated indoor temperature reduction through building envelope by applying exterior coloured coatings, namely white, yellow, pearl, straw, and sand. Findings showed that light colours (white and yellow) reduced the indoor temperature more than the others. The sand colour showed the worst performance in which the maximum difference of indoor temperature for sand/white and sand/yellow colour was 0.9 °C and 0.7 °C, respectively.

Thermochromic coatings (TCCs) are an advanced class of coatings that work dynamically to control the thermal load entering buildings [66]. TCCs change their optical properties according to the surface temperature; the colour becomes light at high temperatures, reflecting more sunlight and dark at lower surface temperatures and absorbing heat [67,68]. This property has a significant influence on the building energy in the summer and winter seasons. It has been reported that using TCCs can reduce the annual energy consumption and CO2 emissions by 4.28–5.02 kWh/m2 and 3.40–3.98 kg/m2, respectively, compared with the common coatings [69].

4.2. Natural ventilation: windcatcher

Natural ventilation (sometimes called passive ventilation) is a knowledgeable method used to reduce thermal loads and improve occupants comfort in buildings. One of the oldest methods of natural ventilation systems is the windcatcher [70]. In windcatchers, the temperature and pressure directing the air inside buildings in which the airspeed and its direction are essential elements to control the airflow [71]. Windcatcher does not need any mechanical devices (fans) to provide buildings with fresh and healthy air with minimal pollution and dust.

Originally, the windcatcher was one of the traditional Persian architectural elements used to ventilate buildings with cool air during the summer period. It was built as a tall tower containing slots facing wind direction to catch the air and direct it down to cool the building. In the sandy places that carry dust and sand, windcatchers place away from the wind direction. Windcatchers were often used in combination with courtyards and domes (as shown in Fig. 6-a), and they do not necessarily cool the air itself but instead rely on the airflow rate to provide a cooling effect [72].

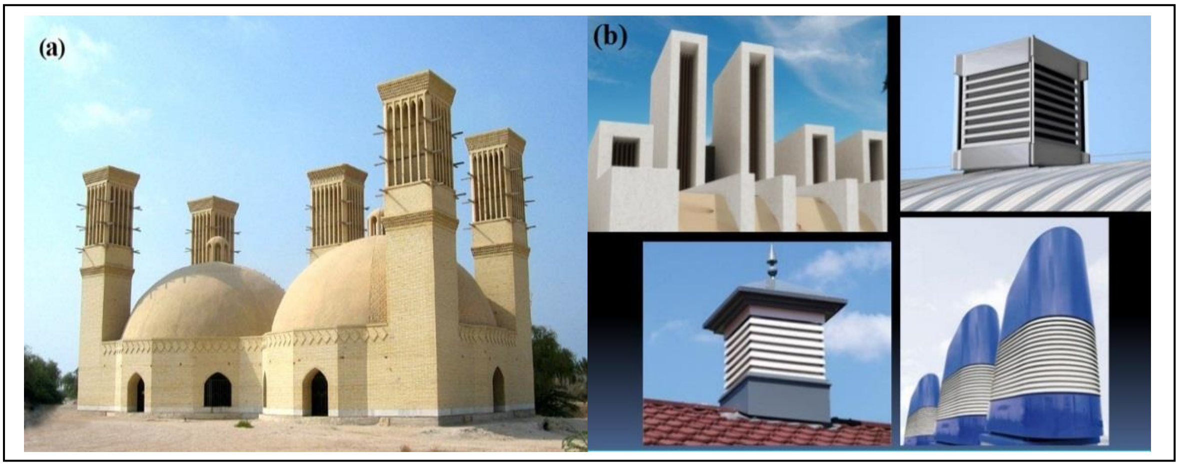

Figure 6. (a) Persian domes with wind catchers, (b) Modern wind catchers.

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New advancements have recently been adopted to improve wind catchers with more control options (see Fig. 6-b). For instance, a newborn type of windcatcher has dampers, various types of sensors and an adjustable ceiling ventilator known as Monodraught, which is usually automatic and allows the temperature, humidity, airflow, noise level, and CO2 to be adjusted depending on the need of the space [73].

5. CONCLUSIONS

The current paper presents and discusses the main passive strategies that could reduce the cooling loads in hot location buildings and maintain acceptable thermal comfort. These strategies are essential to improving building energy by decreasing the reliance on mechanical systems to cool buildings. All strategies have proven remarkable enhancements in the building energy by decreasing the indoor temperature. Most of them can be used in any building, and others can be only used for specific building types such as windcatchers. Matching some of these strategies can significantly improve the building energy performance and air quality, which results in further economic benefits. Modern life requirements required some control of these passive strategies to be more beneficial and competitive to the high-cost mechanical and electrical cooling devices.

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