Pertanika J. Sci. & Technol. 30 (1): 813 - 839 (2022)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

A Review of Thermal Design for Buildings in Hot Climates

Sahar Najeeb Kharrufa* and Firas Noori

Department of Architecture, Ajman University. University rd, Al Jurf, Ajman, UAE

ABSTRACT

Most of the developed world currently lives above the tropic of Cancer in cold climate regions. It follows that most of the top architectural firms are from the same countries, and most of their work is based on that experience. Experience that does not travel well to hotter countries. This paper is mainly concerned with the climates of the Middle East region, which are hot in summer and have mild or cold winters, and where the humidity ranges from dry to humid. It is a review of the factors, designs, and solutions that designers sometimes ignore, undervalue, or on the other hand, put too much weight on when working in such climates. An overview of thermal solutions is conducted, and a critique and suitability of each one for hotter climates are offered. Some of the solutions, which are thought to be helpful, have little benefit, especially traditional ones, which are not up to present-day standards and lifestyles. Others, such as courtyards, do more harm than good. A couple of case studies to evaluate houses with and without thermal measures showed improvements of 23-48%. The paper will evaluate architectural, cooling, and building design solutions according to suitability in dry and medium humidity, warm and hot countries.

Keywords: Buildings in hot climates, cooling loads, evaporative air conditioning, traditional building designs

ARTICLE INFO

Article history:
Received: 4 August 2021
Accepted: 19 November 2021
Published: 10 January 2022

DOI: https://doi.org/10.47836/pjst.30.1.45

E-mail addresses:
s.sulaiman@ajman.ac.ae (Sahar Najeeb Kharrufa)
f.noori@ajman.ac.ae (Firas Noori)
*Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

Many of the world's top architectural firms are from countries located in cold climates, such as Europe or America. Consequently, their designs for primarily hot regions, such as the Middle East or North African (MENA), are rooted in practices and conventions established in their home countries. It is sometimes difficult to fully appreciate the differences. Designing for hotter climates is not just about knowing the solutions but also recognizing the priorities (Butera et al., 2014).

A considerable amount of work has been conducted on the various elements involved in designing for hot climates. Al-Homoud (2016) studied the "impact of building envelope thermal design on the effectiveness of thermal performance of buildings in hot climates" in the MENA region. The purpose was to evaluate its effectiveness numerically. Kharrufa (2008) and Derradji and Aiche (2014) studied the use of earth structures and basements. Both reached positive conclusions. However, below-ground spaces are not suitable for every application. Mushtaha and Helmy (2016) studied the effect of building form on thermal conditions in the Gulf city of Sharjah and suggested that it could reduce energy consumption by 10%. Fasi and Budaiwi (2015) was concerned with the contribution windows made to visual comfort and unsurprisingly recommended low energy types.

Evaporative cooling continues to attract attention due to its low energy consumption. Yang et al. (2019) studied the latest developments in this field and recommended several technologies to enhance their potential. Sajjad et al. (2021) conducted a comprehensive review of indirect coolers and concluded that they might be a viable alternative to vapor-compression cycle air conditioners.

Sustainability and energy saving regulations have been introduced in many MENA regions countries. For example, Alalouch et al. (2019) assessed the effect of new sustainability regulations on energy savings in the Gulf country of Oman and concluded that they save up to 48.2% of energy.

Rackes et al. (2016) simulated building parameters to evaluate thermal comfort. He recommended ceiling fans and night ventilation. Garde et al. (2011) made similar conclusions on a specifically built low energy building in La Reunion in the Indian Ocean. Such simple solutions are only sufficient when the weather is reasonably mild. Ceiling fans are one of the cheapest methods of achieving thermal comfort in terms of capital and energy consumption.

Traditional solutions have also been studied. Bagasi and Calautit (2020) investigated the effect of the Mshrabiay in Jeddah and concluded that it is insufficient to provide thermal comfort even with some evaporative cooling involved. Wind catchers are a prominent feature in many traditional buildings in the middle east. Hedayat et al. (2015) measured their efficiency in a house in Yazd, Iran. They found that it had a significant effect ranging from 17-70%. However, their measurements were taken in the winter.

This paper will review the factors, and solutions that designers sometimes ignore, devalue, or on the other hand, put too much weight on. The emphasis will be on technologies related to designing for the hot, relatively dry areas of the MENA region. More specifically, hot areas require architectural intervention to make the buildings thermally comfortable**.** For a building design to be "suitable," it should reduce energy consumption using solutions relevant to the specific local conditions. The study will review and critique the options available to designers.

HOT AND COLD CLIMATE BUILDING DESIGN SIMILARITIES

If the climate outside is uncomfortable thermally, and the interior requires artificial cooling or heating, many treatments are similar between cold and hot weather. In both cases, the building shell needs to protect the interior environment from the harsh outside. Good thermal insulation, limiting air infiltration, and thermally efficient windows, are recommended in both conditions (Hawkes & Forster, 2002).

MILDLY HOT WEATHER

In warm seasons, the design and treatments vary according to how hot the weather is. If it is relatively mild, good ventilation and a ceiling fan are often sufficient. Ventilation increases the evaporation of human sweat, which cools the body resulting in improved thermal comfort (Nicol et al., 2012). In addition, designing for ventilation and air movement is cheap. The simplest solution, of course, is to use good window and opening designs. However, to ensure that good ventilation can be had at any time, adding a ceiling fan is a cheap, low-energy option and is the next solution to consider.

At the time of writing this paper, a ceiling fan costs in the region of $60.00 online (Amazon, 2017) and does not use much electricity. Compared to a compressor air conditioner, the $60.00 fan uses 50 Watt/hr while a small, single room, 12000 BTU air conditioner, needs 3500 Watt/hr (ASHRAE, 2009). Furthermore, a ceiling fan takes up no space and provides air movement for the whole room. Unlike a standing fan, for instance, which needs to rotate to do the same, and then only improves comfort for one part of the space at a time as it does so. It is also noisier, and the air movement is too strong for office work as it disturbs the paper lying around. Nevertheless, a ceiling fan is always a good option in hot weather, whatever the circumstances.

HOT WEATHER

If the climate is hot enough to require air conditioning, then the picture changes considerably. Before solutions are considered, it must first be determined which hot weather is being dealt with, hot humid or hot dry. In all hot conditions, the effect of humidity is more of a concern than in cold climates. High humidity reduces sweat evaporation, reducing thermal comfort (Nicol et al., 2012).

Hot Dry Weather

If the weather is hot and air conditioning is necessary, especially if the heat is not excessive, and the weather is relatively dry, an evaporative air conditioner can do a good job (Kharrufa & Adil, 2012a). Regrettably, the evaporative cooler is only suitable within certain conditions. Beyond that, a direct expansion compressor air conditioner must be employed.

Literature regarding evaporative coolers is abundant. A large portion of it is concerned with improving efficiency. Most attempt to achieve this is by modifying the wetting media. It is a layer that is moistened with water and whose evaporation leads to cooling. Some papers claim an efficiency of 80% or more (Saleem, 1986). Saleem (1986) tested various wetting media to raise it. He achieved gains of 87% by using honeycomb cardboard corrugated sheet layers (ibid).

The evaporative cooler has a well-deserved reputation as a “green” or “environmentally friendly” appliance. The fresh air it provides is cooled and filtered while using considerably less energy than a phase change compressor air conditioner (Mehere et al., 2014; Cuce & Riffat, 2016). Unfortunately, it cannot be relied on to deliver a constant, thermally acceptable air stream. An evaporative cooler’s performance varies depending on climatic conditions, including temperature, relative humidity, and the unit’s efficiency. When the humidity rises, its cooling powers diminish. It is why it is not popular in humid coastal and tropical areas.

In hot, dry climates, the evaporative cooler can increase the gap between the ambient exterior temperature and the cooler’s output when it is hotter outside and the humidity is lower. It seems ideal for hot, dry climates if not for two inherent drawbacks that affect all evaporative systems and reduce thermal comfort.

1. The cooling unit’s output will carry along with it increased moisture.
2. When the outside temperature passes a certain threshold, the temperature difference between the outside and the cooler output air will not be sufficient, even in dry conditions.

Tests were conducted in dry weather on a commercial evaporative cooler, which can provide an output of 7600m3/h (4500cfm) and maximum cooling of 16kW (54000 BTU) during the summer of 2006. The results are shown in Table 1 (Kharrufa & Adil, 2012b).

Table 1 shows that while the temperatures were less than the low 30’s, the output air was quite good. When it exceeded the higher thirties, the comfort value results plummeted, as shown in Table 2. Based on residential thermal conditions, which were assumed to be (Ibid):

- Low residential human movement.
- Light summer clothing.
- Moderate ventilation of 0.5m/s.
- A radiant temperature is similar to the ambient.

Table 1

Performance of evaporative cooler in Baghdad as recorded by Kharrufa. Average cooler efficiency was 67% (Kharrufa & Adil, 2012b)

Exterior Ambient temp °C	Exterior RH	Outside air WB °C	Output air temp °C
24.9	58.2%	19.2	22.3
27	41%	18	23
32	32%	20	23.8
34.4	27.5%	20.7	25.3
37.5	23.6%	21.8	27
39.8	19.5%	22.1	28.5
3.5	16.2%	24	30.3
44.3	16.4%	23.8	31.3

Table 2

Thermal comfort conditions from the evaporative cooler output are based on the figures from Table 1. PMV levels are based on ISO 7730-1993 (Kharrufa, & Adil, 2012a)

Exterior ambient temp. °C	Interior ambient temp. °C	Interior RH	PMV	Dissatisfaction rates
37.5	27	74.8%	0.28	8%
39.8	28.5	73.4%	0.95	24%
44.3	31.3	70.7%	1.80	67%

Tables 1 and 2 show that even in dry weather, if the ambient temperature approaches the 40°C thresholds, the comfort figures start to deteriorate, and at 44°C, it becomes completely unsatisfactory.

By comparison, in the same conditions but without the evaporative cooling, when the outside temperature was 37.5°C, thermal measurements in the room revealed the interior at a very hot 39°C in the daytime (Kharrufa & Adil, 2012a). At this temperature, the PMV rating rises considerably to 4.4 even with a fan working, and the dissatisfaction rate rises to 99% (Ibid).

Comparing a compressor air-conditioner with an evaporative cooler reveals big differences between the two systems. A compressor unit with a capacity of 7kW (24000 BTU) output cooled air to a temperature of 14–16°C, while outside, it was 43°C. The conditioner also dehumidifies the air inside the room. This same unit required around 15 Amperes of electric current, the equivalent of around 3.3kW of electric power. The evaporative cooler, which was used for the tests, required considerably less at only 2.1 Amps and 220V, which equals 0.45kW of electric power (Ibid).

Table 3

Comparison of direct expansion compressor and evaporative air conditioners assuming similar airflow output (Kharrufa & Adil, 2012a)

Cooler type	Flow cfm	Cooling kW	Outside temp°C	Output cooler air temp°C	Electric Power kW
Compressor	600	7	43	15	3.3
Evaporative	600	2	43	30.3	0.066

Finally, a comparison of compressor air conditioner performance relative to an evaporative cooler is provided in Table 3. The measurements of the output flow from the latter have been converted to match those of the direct expansion compressor AC. The data are for an ambient outside temperature of 43°C (Ibid).

The conclusion is that the evaporative cooler is much more energy-efficient and needs considerably less power but within limits. If the temperature or humidity is too high, it will not provide comfort. The only choice in such conditions is to use a direct expansion compressor air conditioner or an indirect evaporative cooler (Sajjad et al., 2021).

Excessively Hot Dry and Hot Humid Weather

Once it is determined that neither ventilation nor an evaporative cooler is sufficient to provide thermal comfort, then direct expansion compressor air conditioners must be used. These use electrical compressors to forcefully induce a phase change in a suitable refrigerant (ASHRAE, 2009). The process can deliver the required cooling capacity, but on the downside, it consumes considerable energy. In many hot countries, such as those in the Middle East, the energy production of the country may use up to 80% of for air conditioning of buildings (DEWA, 2015; DEWA, 2018).

Air conditioning is necessary not just for human comfort but also to cool such facilities as data centers filled with heat-producing electronics, computer servers, and power amplifiers. It is also used to protect and store artwork (McQuiston et al., 2004).

Air conditioners circulate the air, usually through ducts, to the interior space. It improves both thermal comfort and indoor air quality. Electric compressor-based units can be found in many shapes and sizes. The smaller units will only cool a small bedroom and are light enough to be carried by a single person. The larger ones can be massive and installed in dedicated spaces to cool entire buildings (Ibid.).

Considering how much energy this type of air conditioning consumes, as shown in Table 3, it becomes imperative that the designer use all means available to reduce the cooling load. Many of these are similar to treatments in colder weather and include (Hawkes & Forster, 2002):

a. Add insulation.
b. Use double glazing and e-energy efficient windows and doors. UPVC windows in walls not facing sunlight are a good option.
c. Add multiple heavy layers of interior curtains and shades.
d. Protect against air infiltration

The following sections will review the relevant building parts particular to cooling and explain how each should be treated.

Windows and Shading. Windows and doors are sources of air infiltration, lower insulation values, and direct and indirect sunlight. Except for the latter, all the other factors should be treated the same as cold countries. Sunlight, on the other hand, is different and very important. While it has the same effect as in cold countries in that it results in heating the building, this is considered a positive contribution in these climates, and completely the opposite in hot ones. Therefore, the goal here must be to reduce direct and indirect sunlight, which contains significant thermal energy (McQuiston et al., 2004).

1. The best way to protect against direct sunlight is to use exterior shading. Various solutions are used. The following rules of thumb are popular (Arasteh et al., 2003; Lee et al., 2013).
2. North orientations require very little protection and are preferable in the northern hemisphere.
3. South is second best as it is easy to shield using horizontal cantilevers or sunshades.
4. East and West are very difficult to protect completely, but vertical or combined vertical and horizontal sun breakers are preferable. It is difficult to protect windows in these two orientations fully, so it remains the designer's choice to best shade them.

The north and south conditions are reversed in the bottom half of the globe, south of the equator. The south becomes best followed by the north.

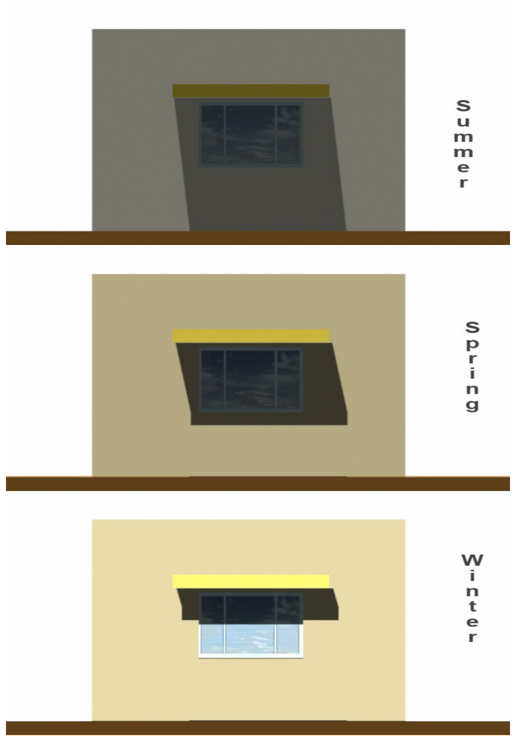

Figure 1. Sunshade from a cantilever protruding 1m and facing south, during the four seasons at 12:00 noon. The geographic position is 25°N. Spring and Fall are the same in terms of shading (Author's images)

The south orientation is especially advantageous as the sun is less intense during the summer and more during the winter. This is due to the earth's tilt and movement around the sun. Figure 1 shows how a cantilever above a window facing south in the northern hemisphere can protect it from sun rays during the four seasons.

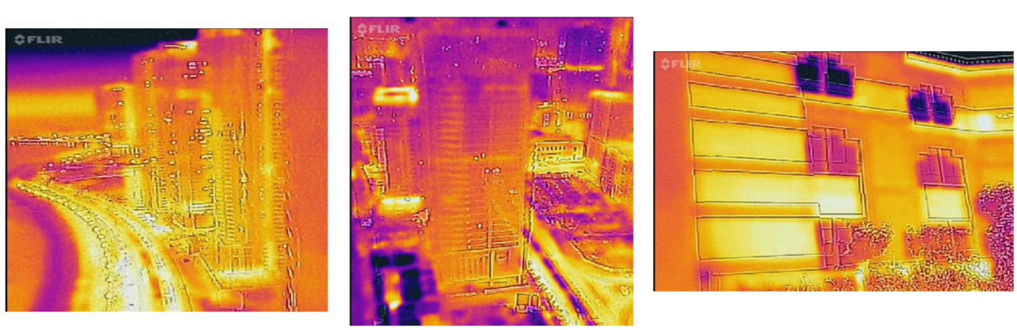

Figure 2. Thermal image of several occupied buildings. Brighter yellow indicates hot, magenta, then blue indicates colder. Upper floors are clearly cooler (taken by the author, June 2016, Sharjah, UAE)

Even after protecting from direct sunlight, indirect or reflected sunlight can still have a considerable heating effect. A series of exterior, infrared thermal images in Figure 2 reveal that lower floors, closer to the ground, are always hot than upper floors, which receive less reflected light, even for three-story buildings. The brighter yellow colors are hotter, magenta then blue are colder. The images were taken in the UAE during June. Plant cover surrounding the buildings help (Kanaan et al., 2021).

Drapes and Shutters. Drapes, or any other internal shading devices, are usually less effective compared to exterior ones, as the heat will have already penetrated the glazing into the building. All interior shading devices, such as roller shades, Venetian blinds, and draperies provide less effective shading and thermal insulation. On the other hand, they offer easy operation by room occupants. Traditionally, internal shading devices have been primarily intended to provide a varying degree of privacy from the outside. Fortunately, they also reduce discomfort from radiation through the window. Curtains universally reduce sunlight and provide protection from glare (Bansal & Mathur, 2006; Ariosto et al., 2019). Adding layers of protection can improve insulation. The image in Figure 3 shows a window partially blacked out by a 7mm insulation board, thick dual-layer blinds, then a curtain covering both.

Figure 3. Window showing three layers of protection. 1. Insulation covering glass pane (the black surface behind the curtain and the blind) 2. Thick blinds, 3. Curtain (taken by the author, June 2016, Sharjah, UAE)

Figure 4. Exterior shutter from the inside. The strap on the right slides it up and down. The slits allow light in but close when the shutters are completely shut, thus improving insulation with the outside. (Taken by author June 2017, Amman, Jordan)

Exterior shutters, on the other hand, can be quite effective. They can be found in many shapes and forms. They cut off the sun before it enters the room and, depending on the type, they may provide some measure of insulation as well. For example, the shutters in

Figures 4 and 5 are outside the window but can be opened and shut from the inside, and they are sealed from the sides too, which improves their thermal performance.

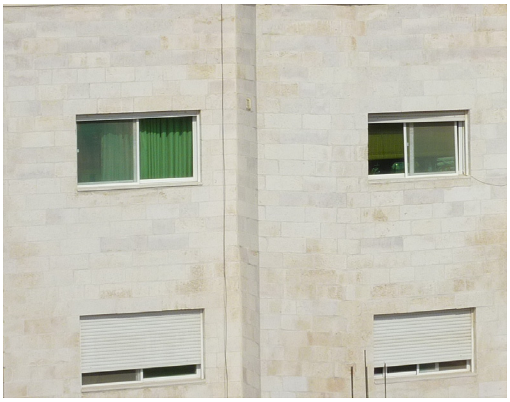

Figure 5. Exterior shutters from the outside. The two at the bottom are partially drawn close, similar to the one in Figure 5. (Picture taken by author June 2009, Amman, Jordan)

Many solutions for cold weather work in hot ones too. These include storm panels, sometimes called secondary glazing, and good drapes. When fitted with a quilt or other insulated backing, conventional draperies become thermal barriers. They will perform as operational insulation shutters located on the interior. They can be in hinged, sliding, folding, or bi-folding. It is important to provide some form of the airtight seal around the edges of any draperies, if possible, to improve its thermal performance and to prevent condensation (Bansal & Mathur, 2006; Buesing, 1981).

Insulation. Insulation is just as important in hot climates as cold with a slight change in priorities (Dylewski & Adamczyk, 2011; Kaynakli, 2012). While in cold areas, it is important to insulate the roof and ceiling to prevent the heat escaping by hot air gravitating upwards; the situation is reversed in hot ones. In an air-conditioned room with minimal air movement in a hot climate, the cold air will stay low. The heat transferred through the roof to the layer of air below the ceiling will be stuck close to the top of the room because the light hot air will float above the colder layer under it. That changes when air movement and ventilation are introduced, which is often the case. However, the effect remains relatively less than in cold countries. Insulating floors become important for the same reason. Heavy cold air descends downwards and needs to be protected thermally. That is not to say that insulating the roof is not necessary or important; it is. However, paying more attention to walls and windows reaps a better return for the investment.

Green Roofs. Much interest has been shown in green roofs recently. Seeing greenery on top of a roof gives many the impression that the building is "Green." A green roof rarely becomes cold enough to act as a cooling element. It does, however, have quite a few benefits, as well as a few drawbacks (Vijayaraghavan, 2016). Thermally speaking, it is more useful in a hot climate than in a cold one. Regrettably, in many hot countries, such as those in the Middle East, the water necessary to irrigate the plants is not readily available. So, it is also necessary to find plants that can withstand the regional climate, which becomes even more difficult if it is dry and hot.

Briefly speaking, in hot countries, the pros and cons of a green roof are as follows (idib) (Del Barrio, 1998):

Benefits

- Some evaporative cooling
- Thermal mass keeps the interior temperature stable
- Absorb sunrays without much increase in mass temperature by plants, which reduces the heat island effect of the urban surroundings
- Pleasant psychological effect
- Reduced air pollution
- Easier to install since almost all roofs in these areas are horizontal.

Drawbacks

- Requires water and maintenance
- Heavy load on the structure
- Requires good waterproofing of the roof construction
- Occupy space on the roof

Roof ponds and roof cooling. Roof ponds can cool the envelope through evaporative cooling, radiant cooling, or through the effect of their heat mass (Kharrufa & Adil, 2008; Sharifi & Yamagata, 2015). In all these processes, the roof acts as a heat exchanger cooled mostly by surface evaporation. Infra-red radiation may also account for some cooling at night. Its thermal mass also functions as a heat sink absorbing the building's heat and keeping the temperature relatively steady. Because the ceiling is thermally coupled to the pond, the interior spaces are cooled by convection and a lower mean radiation temperature (MRT). Since the roof acts as a heat exchanger and is not in direct contact with the interior, roof pond evaporative cooling does not raise the humidity inside the building.

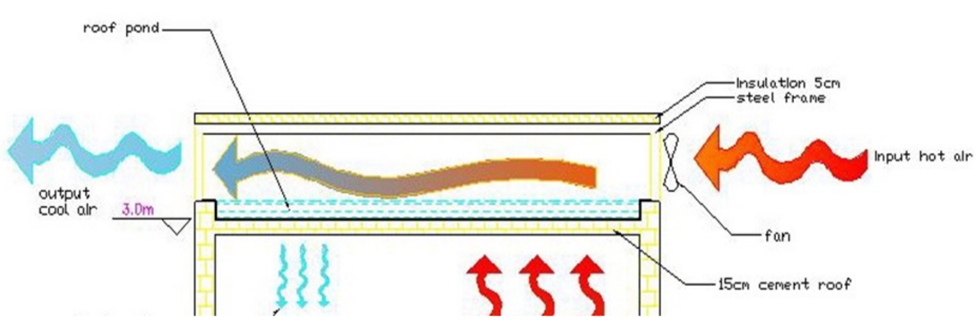

Figure 6. Roof pool with forced ventilation (courtesy of the author, Kharrufa & Adil, 2008)

Encouraging tests were done on a ventilated evaporative roof pond in the hot, dry climate of Baghdad (Kharrufa & Adil, 2008). A diagram of the system is shown in Figure 6. It shows a roof pond in a compartment above the roof with air movement forced mechanically. The results revealed that the pool installation alone, without a fan, lowered the average temperature inside by 3.36^{o}C compared to a lone room with no means of cooling. Adding the fan to ventilate the pond dropped it a further 1.28^{o}C for a final drop of 4.5^{o}C. As a cooling solution, roof ponds are the least popular of all the solutions reviewed in this article.

Double Skin Walls. Double exterior curtain wall systems, or double skin facades, consist of an outer glazed skin surrounding the building. The inner wall is usually glazed, fully or partially. A large air gap between the two walls is left. The width of the gap and its ventilation are supposed to have a significant effect on the effectiveness of the envelope. The system often relies on air movement within the gap. Figure 7 shows how such a system may work. It can be natural, mechanical, or both. The outer wall can be either continued along the whole of the façade or interrupted every several floors (Boake et al., 2014).

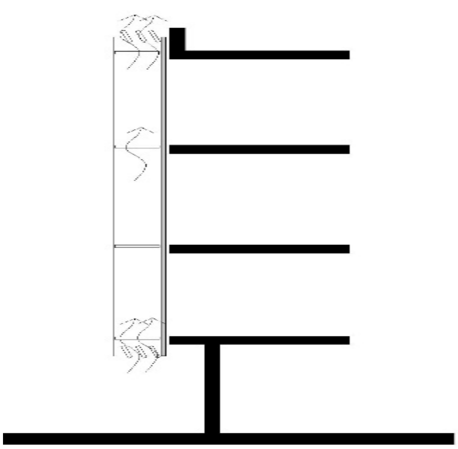

Figure 7. Cross-section of a double skin wall showing ventilation vents at the bottom and top (drawing by author)

Double skin walls were designed for office buildings to gain a wholly glazed facade in the hope that it would, at the same time, conserve heating energy. They were also touted as doing the same for cooling because of the ventilation between the two leaves of the wall. However, research and tests have not been able to verify such claims (Boake et al., 2014; Hashemi et al., 2010).

Boake et al. (2014) wrote that many independent research projects attempted to verify the case for or against this solution. He goes on to say, *"The results seem not to have been gathered into a definitive or conclusive text, meaning that "the jury is still out."* However, he goes on to say that *"the construction of double façade envelope systems has continued to increase and persist in spite of the lack of conclusive hard data to prove the energy benefits*".

In Iran, for instance, which has a hot arid climate in summer, the cavity walls facing the sun heat up because of the high ambient temperature and the solar incidence. Therefore, it naturally increases the cooling load requirements rather than vice-versa. As a result, it is essential to ventilate the cavity at nighttime to cool down the inner facade (Hashemi et al., 2010).

The Iranian measurements specifically show that in summer, throughout most of the day, the cavity temperature was up to 10°C more than the outside temperature. Shading the cavity has a positive effect on cooling, as might be expected, and reduces such differences (Hashemi et al., 2010).

Exterior Colors and Surface Reflectivity. Color has an enormous effect on the amount of heat absorbed and gained by any building. Dark colors reflect less solar energy falling on a surface and thus absorb more heat than light colors. Therefore, using light color paints, or reflective surfaces, in exterior walls and roofs in a hot climate can be considered an important passive strategy to reduce the amount of heat gained by building components and reduce the amount of heat penetrating inside. This strategy can also be used in moderate climates, as using light colors will help reduce the amount of unrequired heat gained during the hot season (Pal et al., 2020; Shi & Zhang, 2011).

Buildings with good insulation will be less affected by exterior color, while light color and reflective surfaces can be more effective when less, or no insulation, is used.

Both roof incline and color can have a combined effect on the process of heat gain. In a cold climate, for example, it is highly recommended to use dark, highly pitched roofs to gain more heat. A hot climate, on the other hand, requires the use of less slope (flat) roof with light color paint. Flat roofs absorb more heat only when the sun is at its highest point in the sky during summer mid-day. In the early morning or late afternoon, the sun will be very low, and a flat white roof will reflect most of the low-angle solar energy falling on it, reducing the amount of heat gain during the hot season (Pal et al., 2020).

Geothermal Heat Pumps. Geothermal heat pumps utilize the difference between the temperature above and below ground to improve air conditioning efficiency. The soil temperature near the ground surface is very close to the ambient temperature of the air above. On the other hand, the deeper we move underground, the fewer the temperature variations. It is because earth soil has a large thermal mass. It retains the heat for a longer period the deeper we go. At a depth of 6m, there will be little or no fluctuation, and a relatively steady state is reached. As a result, the soil temperature is almost the same during the whole year. It should be equivalent to the average annual air temperature in the area (Lechner, 2014). Figure 8 shows how depth affects temperature. At 6 meters, the fluctuation year-round is no more than ± 3°C. It varies, however, according to the type of earth, cover, and moisture content.

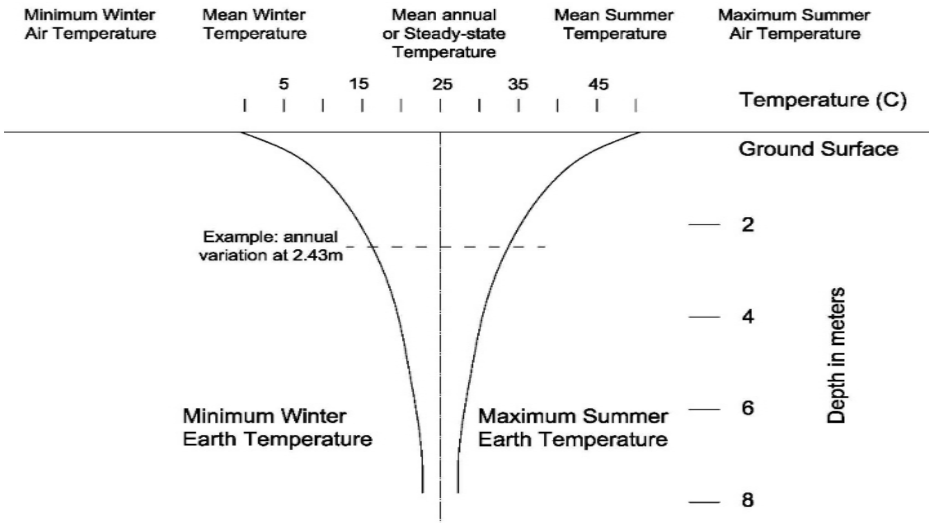

Figure 8. Graph showing the relationship between depth underground and ground temperatures. At 6 meters, the temperature is almost steady at the average yearly ambient temperature (Drawing by the author based on Williams & Gold, 1976)

Depending on the outside temperature and the efficiency of the particular unit, heat pumps can save from 30 to 60% on electric bills, depending on the geographical location and the equipment used (Lechner, 2014).

Earth cooling is efficient if the ground temperatures are cold in summer. However, this happens only if a wide temperature difference between seasons results in cold winters. In such cases, the ground temperature deep in the ground will be significantly less than the ambient temperature in summer and higher in winter.

Table 4 shows the example of two hot cities, Dubai and Baghdad (NCM, 2021; Central Statistics Organization, 2015). Dubai is hot in summer and has mild weather in winter. Baghdad, on the other hand, while also hot in summer, is cold in winter. Table 4 shows that the average yearly temperature, which should be close to the ground temperature deep in the ground, is 28.1°C in Dubai and 22.8°C in Baghdad. During August, the difference between the deep earth temperatures and ambient would be (36–28.1) 7.9°C in Dubai and (34.5–22.8) 11.7°C in Baghdad. A heat pump in summer would be more efficient in the latter, where it can benefit from the more significant temperature difference.

Heat pumps work through the use of heat exchangers in the ground to benefit from the lower temperature. Pipes will extend from the air conditioner compressor unit above ground to the underground heat exchangers. However, it costs money and exposes the equipment and installation to corrosion. In addition, ground temperatures need to be significantly lower than the ambient air temperature to make it feasible.

Table 4
Monthly average temperatures in Dubai and Baghdad (NCM, 2021; Central Statistics Organization, 2015)

Month	Dubai °C	Baghdad °C
Jan	19.3	10
Feb	20.6	12.5
Mar	23.2	15.5
Apr	27.2	22
May	31.4	28
Jun	33.6	32
Jul	35.7	34
Aug	36	34.5
Sep	33.4	30.5
Oct	30	25
Nov	25.4	18
Dec	21.3	11.5
Average	28.1	22.8

Earth Structures. Earth structures use the same principles as heat pumps. They use the thermal mass to stabilize the temperature. They help keep it close to the daily, or even yearly, average inside a building. Thus, earth sheltering provides a warmer environment in the winter and a cooler one in the summer (Derradji & Aiche, 2014; Kharrufa, 2008).

Light dry soil reaches a near-constant ground temperature at a shallower depth than heavy, damp soil. Earth sheltering can stabilize interior temperature swings during all seasons. Figure 9 shows comparative temperature readings in a building with a basement and no air conditioning. Its floor is 2 meters below ground level, and its ceiling is above ground by 1.5m. The basements' temperature is significantly lower than the ground floor, without climate control.

The graph in Figure 9 illustrates how the basement temperature was consistently lower than the average outside by around 5°C during the whole of the summer period. Considering that summer afternoon in central Baghdad can reach up to 50°C, the basement would be 17–18°C less than that. However, at 32-34°C, it is still not thermally comfortable.

Although the graph in Figure 9 shows some fluctuation in the basement's monthly readings, Figure 10 shows that it is stable throughout a single 24-hour day [ibid].

Basements are not for every region, nor are they a universal solution. However, it must be mentioned that in some places, they are ingrained in the local culture to ease the pain of hot summers. In many areas in Iraq, for instance, the residents would use the basement for the afternoon naps, thus avoiding the hottest times of the day (Akram et al., 2015).

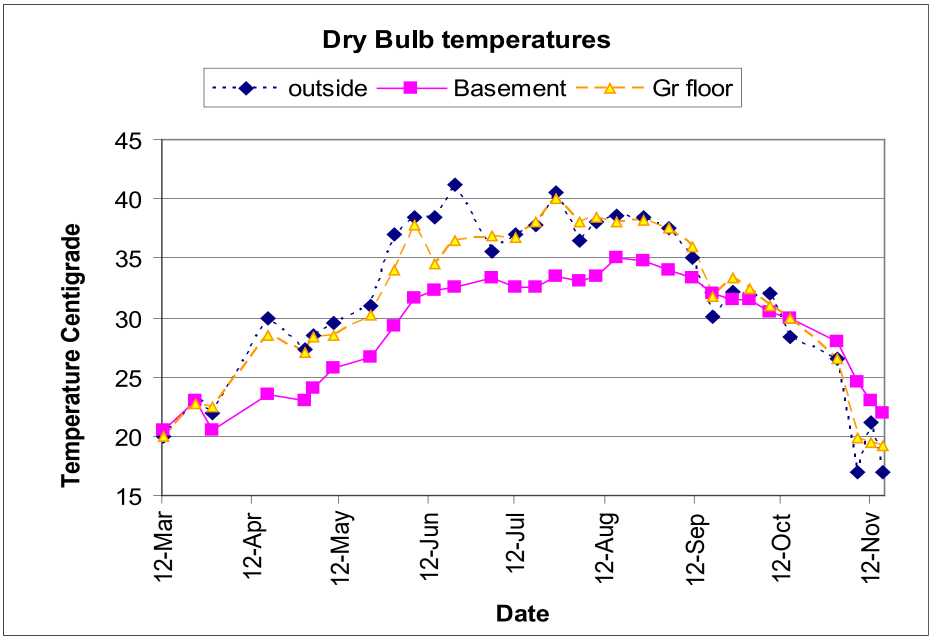

Figure 9. Monthly dry bulb temperature readings for the ambient, ground floor, and basement during the summer of 2006 in Baghdad (Courtesy of the author, Kharrufa, 2008).

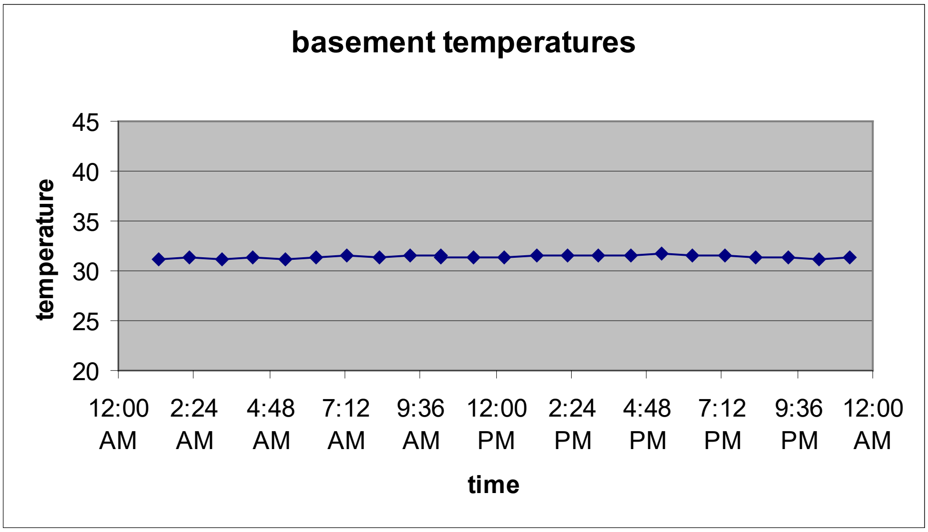

Figure 10. Basement temperature during a 24-hour in September shows a stable temperature reading (Courtesy of the author, Kharrufa, 2008).’

Evaporative Assisted Cooling. It would be extremely useful if it were possible to use the energy efficiency of the evaporative cooler to supplement the cooling capability of the compressor air conditioner to configure a system that could combine the first's low energy requirements with the second's cooling prowess. Regrettably, these two cannot be used simultaneously to cool an interior space. The evaporative cooler requires that the air be expelled from the room. The compressor air conditioner re-cools return air. These are opposing and conflicting workflows.

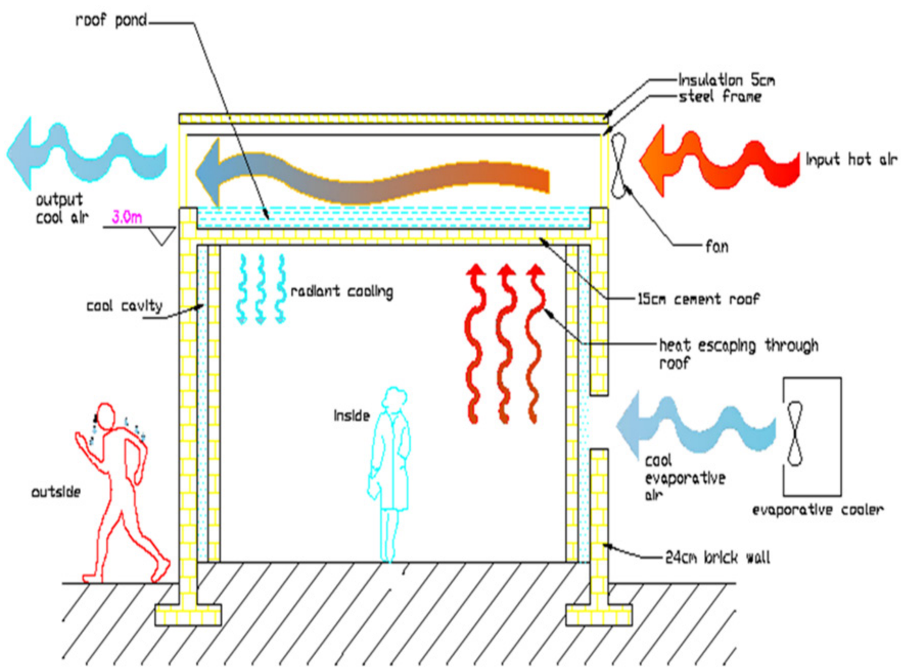

Figure 11. Diagram showing how the building structure can be cooled by evaporation (Courtesy of the author, Kharrufa & Adil, 2012a).

Several researchers have suggested using evaporative systems to cool the building envelope. One such system is shown in Figure 11. It uses evaporative conditioners and roof ponds to cool parts of the structure, not the interior. Compressor air conditioners can support it inside (Kharrufa & Adil, 2012a).

Cooling the walls uses a water spray or output from an evaporative cooler. The roof may be cooled by a pond, evaporative cooler, or a green roof. The results have been encouraging. In suitable conditions, savings of up to 80% of electric power have been calculated through simulation. These are results well worth further investigation (Ibid.).

The system does have some constraints. Primarily because it suffers from the same issues that plague all evaporative systems, it works better in dry climates, and its efficiency varies from region to region. Furthermore, conversion of existing buildings to such a system is difficult.

MISCONCEPTIONS

Several misconceptions prevail in hot countries about using traditional methods for climate control that date back to pre-air-conditioning days. However, most of these are no longer suitable. The changes to how we conduct our daily routines and modern-day expectations render them obsolete. Often, they may even have an adverse effect.

Courtyards

In many hot countries, and even cold ones, houses utilize an internal courtyard. Usually included for privacy, it was also part of the thermal solution. The whole house was arranged to be used as a system that relied on occupying certain areas during certain times of the day. These would sometimes include a basement or semi-basement, interior spaces, the roof, a garden, and the courtyard. The roof or the court would be slept on at night when it would be cold outside and hot inside. The courtyard or garden would be occupied in the early morning and evenings—the interior rooms and basements in the afternoons (Kharrufa, 2008). Figure 12 shows such a design. The picture is of the former residence of the ruler of Ajman in the UAE. The view is from the courtyard.

Figure 12. The courtyard of the ruler of Ajman's former residence. It is a traditional Emirati house that was occupied until the early eighties (picture taken by author August 2011, Ajman, UAE).

Modern-day life cannot accommodate such an arrangement. Furthermore, installing a courtyard becomes a thermal strain. Small houses add to the exterior surface area considerably and increases the heat transfer into the building.

Windcatchers

These are special duct-type arrangements that can increase ventilation inside the building (Zarandi, 2009; Hedayat et al., 2015). Before the age of electricity, any design that encouraged ventilation was welcome.

However, during the hot summer months, an ordinary windcatcher introduces hot air from the outside. Figure 13 is of such a system. It is an Emirati windcatcher. Its main purpose is purely ventilation.

Figure 13. Emirati windcatcher (picture taken by the author, October 2009, Dubai, UAE).

More articulate forms of catchers exist. Some will utilize the cooler building mass surrounding it during the day to cool the air that slowly filters down, as shown in Figure 14. This catcher is common in the southern areas of Iraq and Iran. It is designed to face the cooler northern breeze. In addition, a small fountain or porous clay water pitcher is often put at the bottom to cool the air further. Nevertheless, the introduced temperatures remain relatively high by present-day standards and are not suitable for modern-day comfort.

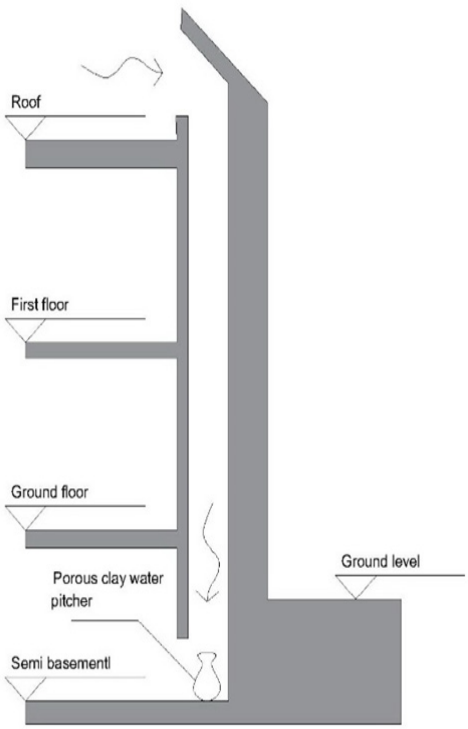

Figure 14. Cross-section of wind tower cooled by building mass (drawing by author).

Building Mass

Thick 50-80cm walls were the rule rather than the exception before modern construction methods (Kharrufa, 2008). Introduced because of their mass, these benefitted from performing like earth structures. They tended to keep the interior temperatures close to the daily average and delay the heat transfer through the structure. This time lag results in daytime temperatures inside that are lower than the outside, but nighttime and mornings would be higher.

This system is also not suitable for modern-day architecture. Notwithstanding the extra cost and weight of using so much material, the heavy building mass requires considerable energy to cool. It increases the cooling load rather than the other way around.

BUILDING REGULATIONS AND GUIDELINES

The building guidelines in the countries of the MENA region vary from one to the other. The countries of the Gulf have been more diligent in proposing and implementing thermal and sustainability guidelines. Dubai issued its first decree for thermal insulation in 2003 and followed it by comprehensive green building regulations, 2013 (Dubai Municipality, 2021). These include guidelines for shading and glazing to wall ratio. Other Gulf states followed. In many other countries of the region, no such rules apply (Al-Taie et al., 2014).

The setback rules also vary and significantly affect both the design and thermal transmission. For instance, in both Jordan and the Gulf, most buildings are required to have a three-meter setback on all sides, although the front is sometimes exempt. In Iraq, it is the exact opposite. There are no setback limitations on the sides, while the front varies according to size. In addition, having the buildings adjacent to each other reduces the heat transfer in three of the five exterior surfaces of the building, leaving only the front and the roof exposed.

CASE STUDIES

Two cases are compared to assess the effectiveness of thermal measures in reducing the cooling load. Each was simulated with and without. The analysis was performed using Ecotect 5.5. The houses are in two cities that represent the main climate zones of the MENA region: the hot, dry city of Baghdad (NCM, 2021; Central Statistics Organization, 2015), and the coastal city of Dubai, which has higher humidity levels (NCM, 2021). By necessity, the design will be different as per municipality rules for each region and city. Primarily, in Baghdad, there are no setbacks except in the front, while in Dubai, in non-freehold land, the setback is required on all four sides. The construction of both houses follows local traditional practices. The design of each is shown in Figure 15.

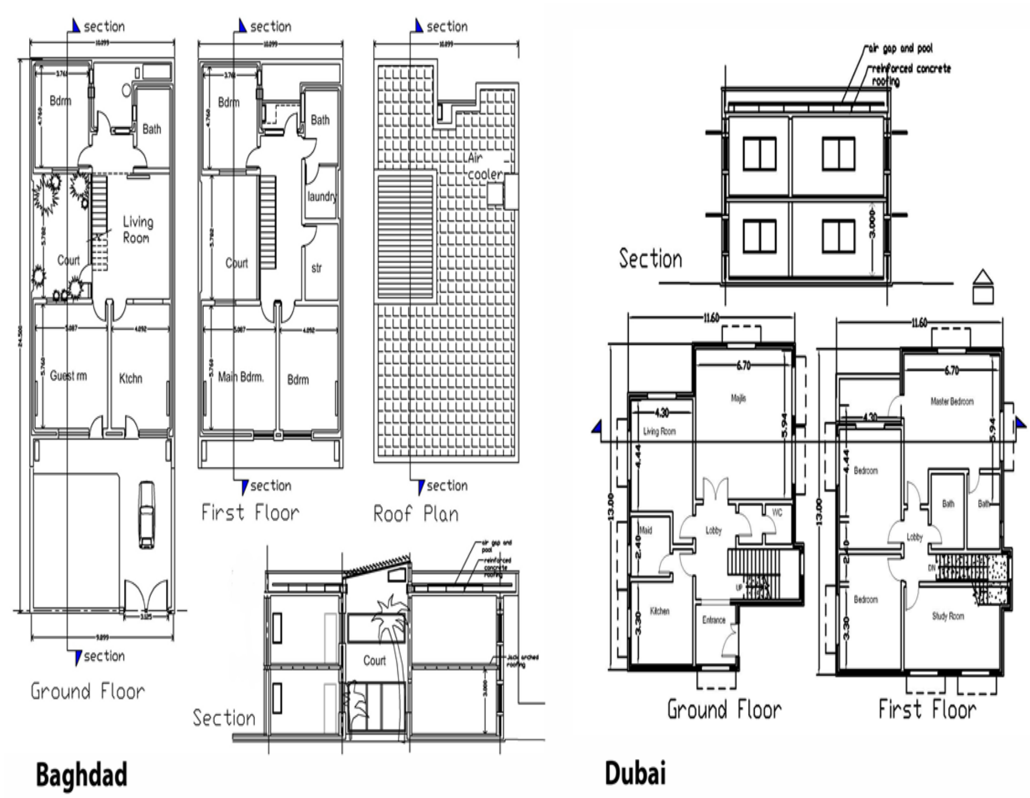

Figure 15. Layout of the two houses that were thermally simulated. The one on the left is designed for Baghdad, and Dubai on the right. The variations in design are primarily due to differences in municipality building guidelines of each city (Drawings by author)

The total built-up floor area for the Dubai house was 261m^2 and 266 m^2 for Baghdad. The indoor temperature was set at 26ºC in Dubai, where such a setting results in a Predicted Mean Vote (PMV) of 0.1. In the drier climate of Baghdad, a higher temperature of 27°C was sufficient to achieve the same. All other variables, such as clothing and activity, were set similarly. The weather data was imported from the US Department of Energy, EnergyPlus website (https://energyplus.net/weather-region/asia_wmo_region_2). For simulation, the construction and material are assumed to be:

1. Walls: 20cm thick block concrete with cement plaster finishing and paint on both sides.
2. Roof: 10cm reinforced concrete with cement tile finishing.
3. Exterior doors: low infiltration 7 cm wood
4. Aluminum windows.

The parameters of the thermal simulations were Sedentary activity, light clothing of trousers, and a T-shirt. The air movement was at 0.5m/s, and the radiant temperature was assumed to equal the interior. Figure 16 shows the Ecotect model of the houses.

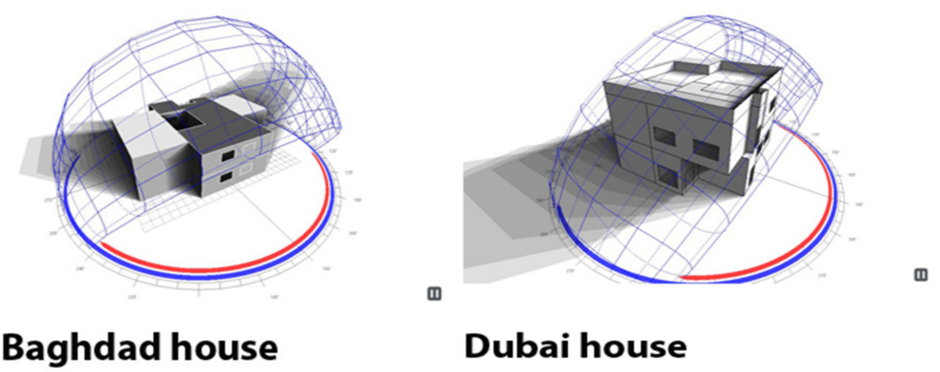

Figure 16. Ecotect models of the thermal simulations

The measures that were added to improve the thermal efficiency were:

1. For the walls, 5–6 cm of polystyrene thermal insulation and 10 cm in the roof.
2. Windows: Double glazed low-e aluminum frame
3. Increased airtightness of the envelope
4. An increase in interior air movement.
5. Horizontal cantilevers for shading above windows

These are moderate changes and do not reflect best-case scenarios but rather financially feasible ones. The u-values of the software were used for both houses, although they differ slightly according to manufacture and raw material. Slight differences may exist between the two countries. There are also differences in construction, although both countries use cement and concrete construction. In Baghdad, the walls are used as load-bearing elements, while in Dubai, thin columns are hidden inside the walls to carry the load. It should have a minimal effect on the thermal conditions. The simulations revealed the results as shown in Table 5.

Table 5

Thermal simulation results of the cooling load of the two case study houses

City	Without thermal measures	With thermal measures	Savings
Dubai	46.36 kWh	23.86 kWh	48.5%
Baghdad	28.37 kWh	21.6 kWh	23.86%

The cooling load in Dubai is higher primarily because the differences between night and day are slight, and air conditioning is required almost all year round. In Baghdad, the weather is cool during the night, and temperatures are cold in winter, requiring no cooling.

The savings are significant, especially in Dubai, where they are higher mainly because all four sides of the buildings are exposed, which highlights the effect of the added wall insulation, while in Baghdad, the adjacency to neighboring houses results in less heat gain.

CONCLUSIONS

The design of buildings in hot countries often requires distinct solutions. Sunlight, as one of the main sources of heat, requires shading and preventive measures to mitigate its effect. The use of white or light colors for the exterior is recommended. Windows should be protected from direct sunlight. Horizontal cantilevers should be used on southern facing walls in the northern hemisphere and on north-facing walls in the southern. Vertical sun-breakers on the east and west-facing walls are better in most cases; vegetation around the building is recommended to reduce reflected sunlight.

Climate variations demand different solutions. In mildly hot climates, the priority is for ventilation. Installing a ceiling fan is both cheap and low on power consumption.

In hot, dry climates, adding evaporative coolers is recommended. If the weather does not allow for comfortable cooling, then energy heavy compressor air conditioners need to be used in tandem with measures that ensure the lowest possible electrical consumption. Insulation should be added; double glazing and e-energy efficient windows and doors.

Using UPVC windows in walls not facing sunlight is a good option as the frame conducts less heat. The possibility of using exterior sliding shutters should be assessed, as well as multiple layers of interior curtains and shades. Protection against air infiltration is also useful. Geothermal heat pumps may be feasible in many regions. Some innovative measures, such as roof ponds and evaporative assisted cooling, should be studied.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support received from the university of Ajman. We would also like to thank Ms Shafiya Rizwan and Ms Foutoun Daboul for their help in improving the presentation of this article.

REFERENCES

Akram, O. K., Ismail, S., Utaberta, N., Yunos, M. Y. M., Ismail, N. A., & Ariffin, N. F. M. (2015). The important values of architectural Baghdadi heritage. *Advances in Environmental Biology, 9*(24), 46-53.

Alalouch, C., Al-Saadi, S., AlWaer, H., & Al-Khaled, K. (2019). Energy saving potential for residential buildings in hot climates: The case of Oman. *Sustainable Cities and Society*, *46*, Article 101442. https://doi.org/10.1016/J.SCS.2019.101442

Al-Homoud, M. S. (2016). The effectiveness of thermal insulation in different types of buildings in hot climates. *Journal of Thermal Envelope and Building Science, 27*(3), 235-247. https://doi.org/10.1177/1097196304038368

Al-Taie, E., Al-Ansari, N., Knutsson, S., Al-Taie, E., Al-Ansari, N., & Knutsson, S. (2014). The need to develop a building code for Iraq. *Engineering*, *6*(10), 610-632. https://doi.org/10.4236/ENG.2014.610062

Amazon. (2017). *Ceiling fan price*. Retrieved April 1, 2017, from https://goo.gl/GYgk1F

Arasteh, D., Apte, J., & Huang, Y. (2003). Future advanced windows for zero-energy homes. *ASHRAE Transactions, 109*(2), 871-882.

Ariosto, T., Memari, A. M., & Solnosky, R. L. (2019). Development of designer aids for energy efficient residential window retrofit solutions. *Sustainable Energy Technologies and Assessments*, *33*, 1-13. https://doi.org/10.1016/J.SETA.2019.02.007

ASHRAE. (2009). *2009 ASHRAE handbook: Fundamentals*. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

Bagasi, A. A., & Calautit, J. K. (2020). Experimental field study of the integration of passive and evaporative cooling techniques with Mashrabiya in hot climates. *Energy and Buildings*, *225*, Article 110325. https://doi.org/10.1016/J.ENBUILD.2020.110325

Bansal, N. K., & Mathur, J. (2006). *Energy efficient windows*. Anamaya Publishers.

Boake, T. M., Bes, B., & Arch, M. (2014). Hot climate double façades: Avoiding solar gain. *Facade Tectonics, 14*, 2-24.

Buesing, J. W. (1981). *Energy conserving window treatments: Insulated shades and draperies*. Publication-Cooperative Extension Programs.

Butera, F., Adhikari, R., & Aste, N. (2014). *Sustainable building design for tropical climates: Principles and applications for Eastern Africa*. UN-Habitat.

Central Statistics Organization. (2015). *Environmental indicators, Iraqi environmental statistics, (Table 3.1) daily average temperature and relative humidity for Baghdad*. Iraqi Ministry of Planning.

Cuce, P. M., & Riffat, S. (2016). A state of the art review of evaporative cooling systems for building applications. *Renewable and Sustainable Energy Reviews*, *54*, 1240-1249. https://doi.org/10.1016/J.RSER.2015.10.066

Del Barrio, E. P. (1998). Analysis of the green roofs cooling potential in buildings. *Energy and Buildings, 27*(2), 179-193. http://dx.doi.org/10.1016/S0378-7788(97)00029

Del Barrio, E. P. (1998). Analysis of the green roofs cooling potential in buildings. *Energy and Buildings, 27*(2), 179-193. https://doi.org/10.1016/S0378-7788(97)00029-7

Derradji, M., & Aiche, M. (2014). Modeling the soil surface temperature for natural cooling of buildings in hot climates. *Procedia Computer Science*, *32*, 615-621. https://doi.org/10.1016/J.PROCS.2014.05.468

DEWA. (2015). *Set your AC to 24°C*. Dubai Electricity and Water Authority. Retrieved February 13, 2018, from https://www.dewa.gov.ae/en/customer/sustainability/spread-the-message/24-degrees-campaign

DEWA. (2018). *Abu Dhabi power reduction*. Dubai Electricity and Water Authority. Retrieved February 13, 2018, from http://www.powerwise.gov.ae/en/section/how-can-i-save-electricity/residential/air-conditioning

Dubai Municipality. (2021). *Green building in Dubai*. Retrieved October 14, 2021, from https://www.dm.gov.ae/municipality-business/al-safat-dubai-green-building-system/green-building-in-dubai/

Dylewski, R., & Adamczyk, J. (2011). Economic and environmental benefits of thermal insulation of building external walls. *Building and Environment*, *46*(12), 2615-2623. https://doi.org/10.1016/j.buildenv.2011.06.023

Fasi, M. A., & Budaiwi, I. M. (2015). Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates. *Energy and Buildings*, *108*, 307-316. https://doi.org/10.1016/J.ENBUILD.2015.09.024

Garde, F., David, M., Lenoir, A., & Ottenwelter, E. (2011). Towards net zero energy buildings in hot climates: Part 1, new tools and methods. *ASHRAE Transactions, 117*(1), 450-457.

Hashemi, N., Fayaz, R., & Sarshar, M. (2010). Thermal behavior of a ventilated double skin facade in hot arid climate. *Energy and Buildings, 42*(10), 1823-1832. https://doi.org/10.1016/j.enbuild.2010.05.019

Hawkes, D., & Forster, W. (2002). *Energy efficient buildings: Architecture, engineering, and environment*. WW Norton & Company.

Hedayat, Z., Belmans, B., Ayatollahi, M. H., Wouters, I., & Descamps, F. (2015). Performance assessment of ancient wind catchers - An experimental and analytical study. *Energy Procedia*, *78*, 2578-2583. https://doi.org/10.1016/J.EGYPRO.2015.11.292

Kanaan, A., Sevostianova, E., Donaldson, B., & Sevostianov, I. (2021). Effect of different landscapes on heat load to buildings. *Land, 10*(7), Article 733. https://doi.org/10.3390/LAND10070733

Kaynakli, O. (2012). A review of the economical and optimum thermal insulation thickness for building applications. *Renewable and Sustainable Energy Reviews, 16*(1), 415-425. https://doi.org/10.1016/j.rser.2011.08.006

Kharrufa, S. N. (2008). Evaluation of basement's thermal performance in Iraq for summer use. *Journal of Asian Architecture and Building Engineering*, *7*(2), 411-417. https://doi.org/10.3130/jaabe.7.411

Kharrufa, S. N., & Adil, Y. (2008). Roof pond cooling of buildings in hot arid climates. *Building and Environment, 43*(1), 82-89. https://doi.org/10.1016/j.buildenv.2006.11.034

Kharrufa, S. N., & Adil, Y. (2012a). Reducing the cooling load by evaporative cooling of the roof. In *Energy and Buildings: Efficiency, Air Quality, and Conservation* (pp. 235-255). Nova Publishers. https://doi.org/10.1016/j.enbuild.2012.09.006

Kharrufa, S. N., & Adil, Y. (2012b). Upgrading the building envelope to reduce cooling loads. *Energy and Buildings, 55*, 389-396. https://doi.org/10.1016/j.enbuild.2012.09.006

Lechner, N. (2014). *Heating, cooling, lighting: Sustainable design methods for architects*. John Wiley & Sons.

Lee, J. W., Jung, H. J., Park, J. Y., Lee, J. B., & Yoon, Y. (2013). Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renewable Energy, 50*, 522-531. https://doi.org/10.1016/j.renene.2012.07.029

McQuiston, F. C., Parker, J. D., & Spitler, J. D. (2004). *Heating, ventilating, and air conditioning: Analysis and design*. John Wiley & Sons.

Mehere, S. V, Mudafale, K. P., & Prayagi, S. V. (2014). Review of direct evaporative cooling system with its applications. *International Journal of Engineering Research and General Science*, *2*(6), 995-999.

Mushtaha, E., & Helmy, O. (2016). Impact of building forms on thermal performance and thermal comfort conditions in religious buildings in hot climates: A case study in Sharjah city. *International Journal of Sustainable Energy, 36*(10), 926-944. https://doi.org/10.1080/14786451.2015.1127234

NCM. (2021). *Climate yearly report 2003-2017*. National Center of Meteorology. Retrieved June 2, 2021, from https://www.ncm.ae/services/climate-reports-yearly?lang=en

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive thermal comfort: Principles and practice*. Routledge.

Pal, R. K., Goyal, P., & Sehgal, S. (2020). Thermal performance of buildings with light colored exterior materials. *Materials Today: Proceedings*, *28*, 1307-1313. https://doi.org/10.1016/J.MATPR.2020.04.508

Rackes, A., Melo, A. P., & Lamberts, R. (2016). Naturally comfortable and sustainable: Informed design guidance and performance labeling for passive commercial buildings in hot climates. *Applied Energy*, *174*, 256-274. https://doi.org/10.1016/J.APENERGY.2016.04.081

Sajjad, U., Abbas, N., Hamid, K., Abbas, S., Hussain, I., Ammar, S. M., Sultan, M., Ali, H. M., Hussain, M., Ur-Rehman, T., & Wang, C. C. (2021). A review of recent advances in indirect evaporative cooling technology. *International Communications in Heat and Mass Transfer*, *122*, Article 105140. https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2021.105140

Saleem, J. (1986). Improving performance of evaporative coolers. In *Proceedings of Fifth Annual Scientific Symposium of Iraqi Research Council*. Baghdad, Iraq.

Sharifi, A., & Yamagata, Y. (2015). Roof ponds as passive heating and cooling systems: A systematic review. *Applied Energy, 160*, 336-357. https://doi.org/10.1016/j.apenergy.2015.09.061

Shi, Z., & Zhang, X. (2011). Analyzing the effect of the longwave emissivity and solar reflectance of building envelopes on energy-saving in buildings in various climates. *Solar Energy*, *85*(1), 28-37. https://doi.org/10.1016/J.SOLENER.2010.11.009

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, *57*, 740-752. https://doi.org/10.1016/J.RSER.2015.12.119

Williams, G. P., & Gold, L. W. (1976). *CBD-180 ground temperatures*. National Research Council Canada.

Yang, Y., Cui, G., & Lan, C. Q. (2019). Developments in evaporative cooling and enhanced evaporative cooling - A review. *Renewable and Sustainable Energy Reviews, 113*, Article 109230. https://doi.org/10.1016/J.RSER.2019.06.037

Zarandi, M. M. (2009). Analysis on Iranian wind catcher and its effect on natural ventilation as a solution towards sustainable architecture (Case Study: Yazd). *World Academy of Science, Engineering and Technology, 54*, 574-579.