Effects of Tall Office Building Envelope Technologies and Design Strategies on Comfort and Energy Consumption in Hot, Arid Climate

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Abstract

In the Middle East 40% of energy is used in buildings, more than in industry or transport, and the absolute figure is rising fast, because of the recent construction boom. In hot arid climate, the energy consumption in office building for cooling and lighting is enormous due to problems of overheating and high solar gain. Since the building envelope functions as an environmental filter, and controls the influence of the outdoor on the indoor environment, appropriate design strategies and technologies are necessary to create a climate responsive envelope. This paper is directed to optimizing thermal, visual comfort and energy efficiency through the application of different technologies and design strategies for office building envelope in hot arid climate. The study analysed the outdoor and indoor climatic conditions, to understand the problems of overheating, discomfort, and the energy needed to achieve the indoor environment quality. Building simulation programs were used to evaluate the effects of different technologies and design strategies on the comfort and energy consumption. The technologies included: glazing performance, shading and solar control, insulation, thermal mass, and daylight systems. In addition, the design strategies included: opaque to transparent ratio, orientation, and natural day and night ventilation. The results show the potential for a significant decrease in energy consumption for cooling and lighting. On the other hand, thermal and visual comfort can be increased. Reducing the energy consumption for cooling and lighting as well as improving the indoor comfort are of great importance towards sustainable and climate responsive buildings.

Keywords: hot arid climate, comfort, energy efficiency, intelligent envelope, design strategies

1. Introduction

The building envelope functions as an environmental filter; it forms a skin around the building and controls the influence of the outdoor on the indoor environment. In tall buildings, walls cover more than 90% of the shell and highly influence the indoor environment. Moreover, the annual solar energy received at the envelope surfaces of the building is in the same order as the energy needed to operate it as suggested by Andresen et al. (2005). Much interest has recently been focused on building envelope, which by adaptive or responsive actions will make it possible to utilize more of this energy for building purposes, and reducing the energy use. In line with a sustainable development approach, it is critical for practitioners to create healthy, sustainable office building envelopes especially in climates where the energy consumption for air conditioning is very high. Furthermore, we are in front of global challenges: currently around the world, 40% of the energy is consumed in buildings. The construction sector uses 30% of our resources and 20% of our water, producing up to 40% of the world greenhouse gases and generating 40% of the world solid waste (World sustainable building conference 2008). According to Hass and Amato (2006) building facades are responsible for around one third of buildings energy bill. Yeang (1999) suggested that tall buildings present in cities around the world will continue to extend and to develop with increasing intensity.

The analyses of the outdoor conditions in hot arid climates underline the problems of overheating and discomfort due to high temperature and solar radiation. The main problems in arid climate are the dry air with a large diurnal temperature variation, low relative humidity, and high solar radiation: this leads to a high risk of overheating. The analysis of the outdoor air temperature for five cities in hot arid climate (Basra in Iraq, Kuwait city in Kuwait, Dubai in UAE, Doha in Qatar, and Riyadh in Saudi Arabia) showed the extreme high temperature especially in summer time, when the average highs arrive at around 40-43°C. In addition, the difference between the average low and average high temperature is relatively high and it could reach between 10-23°C. On the other hand, the analysis of the outdoor solar radiation (monthly average) on the horizontal and vertical planes for the five cities mentioned above shows very high values, as can be seen in table (1). This means that special attention should be taken in designing the south, east, and west facades.

Table 1: Average solar radiation, air temperature, and relative humidity for the five locations

City	*Dubai*	*Doha*	*Riyadh*	*Kuwait*	*Basra*
Monthly average solar radiation, Wh/m²	*6292*	*3470*	*6206*	*4926*	*5540*
Min. average air temperature, Cº	*17*	*21.5*	*15.5*	*14.6*	*19*
Max. average air temperature, Cº	*39*	*33*	*37*	*38*	*31.5*
Average relative humidity, %	*43.8*	*46.7*	*23*	*29.7*	*33*

The humidity average for the major part of the year ranges from 20 to 50%. For such an arid climate, special consideration should then be taken in the design phase to avoid discomfort due to high temperatures. The analysis of the precipitation shows the low amount of falling. For this reason special consideration should be taken at the design phase to minimize the water consumed in building construction and operation.

Thermal comfort is very difficult to define because of the need to take into account a range of environmental and personal factors when deciding what will make people feel comfortable. Thermal comfort is defined in British Standard EN ISO 7730 as “that condition of mind which expresses satisfaction with the thermal environment”. The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) proposed a definition of the suitable quality level for an indoor environment, as stated in Table (2). The most commonly used indicator of thermal comfort is air temperature. However, air temperature alone is not an accurate indicator of thermal comfort. Air temperature should always be considered in relation to other environmental (radiant temperature ,air velocity ,and humidity) and personal (clothing insulation ,metabolic heat) factors. Daylight, on the other hand, is one of the most important requirements for natural, healthy and productive working environment. Good natural lighting and unimpeded views out of a building belong to the minimum standards required by guidelines for workplaces in many countries.

Table 2: indoor environment quality level according to ASHRAE

Season	*Comfort temperature*	*Comfort temperature range*	*Relative humidity*	*Air velocity*
Summer	*24.5 °C*	*23~26 °C*	*30~65%*	*0.25 m/s*
Winter	*22 °C*	*20~23.5 °C*		*0.15 m/s*

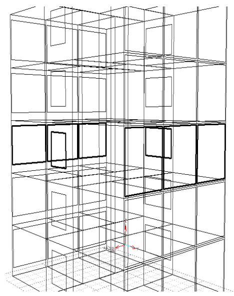
Until recent years, energy efficiency has been a relatively low priority to building owners and investors. However, with the dramatic increase and awareness of energy use concerns, energy efficiency is fast becoming part of real estate management, design, and operations strategy (Omer 2008). Economic and industrial development in countries with hot, dry climate led to an increasing demand for electricity for air conditioning and lighting to overcome the discomfort during the harsh summer. Al-Hadhrami & Ahmad (2009) found that air conditioning requires about 73% of total electricity consumed in residential buildings in Saudi Arabia, for the cooling loads season extends over more than 7 months of the year. In most Gulf States, 40% of energy use is consumed in buildings, more than by industry or transport. The absolute figure is rising fast, as construction booms, especially in countries such as UAE. AboulNaga & Eisheshtawy (2001) found that the annual total energy use in buildings varies from 120-312 Kwh/m², while the average annual energy consumption for contemporary buildings is 268 Kwh/m².

2. Methodology

The study used two simulation programs in order to evaluate the effects of different building envelope technologies and design strategies on comfort and energy efficiency. ECOTECT and TRNSYS dynamic simulation programs were used for these evaluations. The building simulation model used and other inputs are stated in table (3). The simulation model is selected to represent a typical tall office building in which each floor is divided into 9 thermal zones; each thermal zone has

4m width, 6m depth and 3.5m height. The simulations were performed for five cities in hot climate: Riyadh (Saudi Arabia), Abu Dhabi (UAE), Doha (Qatar), Kuwait city (Kuwait), and Basra (Iraq). Meteonorm climate data files were used. The study evaluated different technologies to be applied in tall building envelope in hot arid climate including: glazing performance, shading and solar control, insulation, thermal mass, and daylight systems, as well as design strategies including: opaque to transparent ratio, orientation, and natural day and night ventilation. Thermal, visual comfort and energy consumption were used as performance parameters.

Table 3: building simulation model and input data

Comfort temperature: 20-26 °C *Thermal zone: 4mx6m = 24 m², height 3.5m* *Cooling operation: 7 AM to 9 PM week days* *Occupancy: 1 person per 10 m^2* *Internal wall: brick temper frame, 19 cm thick, U value 1.77 W/m²K, solar absorption 0.7*	*Internal gains* *Persons: 14 W/m², Computer: 50 W, Lighting: 5 W/m²* *Luminance level: 500 lux* *Relative Humidity: 50%* *Ventilation rate: 5 l/s occupied, 1 l/s unoccupied.*	

This paper presents the first results of an on-going study aimed at finding design guidelines to evaluate the performance of different envelope technologies and the related design alternatives during the early design stage. Although the study was conducted for the five cities mentioned above, this paper presents a sample for selected cities as the results are close for some of the design alternatives considered.

3. Results and discussion

3.1 Effects of window wall ratio and orientation

Minimizing the effect of solar radiation within the hot urban environment may often be a desirable design criterion, the effect of building orientation and window to wall ratio being crucial factors on cooling loads and discomfort in that context. The control of indoor air temperature can be achieved by the correct orientation of the building and by a balanced ratio of opaque to transparent areas, while ensuring adequate sky view in order to moderate the harshness of the climate.

The simulations were done for different windows to walls ratio (30%, 50%, 70% and 90%), and orientations: (south, north, east, west, 30º from N to E, 30 º from S to W, 60 º from N to E, 60 º from S to W, 30 º from N to W, 30 º from S to E, 60 º from N to W, and 60 º from S to E). The simulation was performed using ECOTECT software for Riyadh city in Saudi Arabia. Figure (1) shows the results in terms of cooling loads, and discomfort hours. For 30% glazing size, the difference in cooling loads for different orientations remains small; this can reach maximum 20 Kwh/m² yr. This percentage can then be used for east and west orientation. For 50% glazing size, the orientation effect starts to appear and the cooling loads difference can reach more than 35 Kwh/m² yr. For 70% glazing size, the cooling loads difference by changing the orientation is clear and can reach up to 45 Kwh/m² yr., so this glazing ratio could be used in certain orientations, such as north. For 90% glazing size, the cooling loads difference due to orientation is even more evident and can reach 60 Kwh/m² yr.

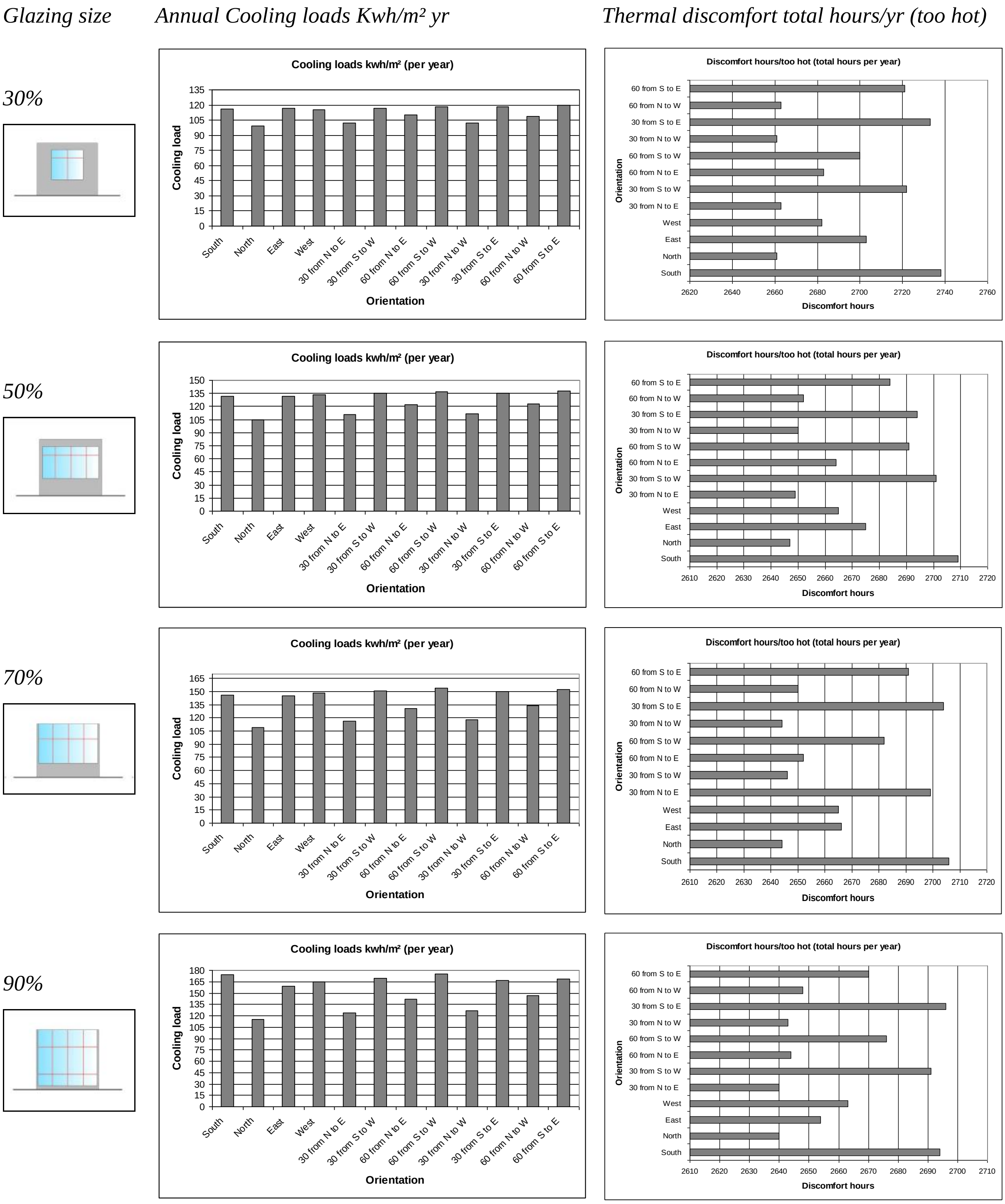


Fig. 1: the effect of window to wall ratio and orientation on the cooling load and thermal comfort

It can be concluded from the simulations, that the minimum cooling load was for the north and south orientations and it can be seen that variation of the transparent to opaque ratio causes only a small difference in the cooling load in the north orientations and a large difference for other orientations.

3.2 Effects of natural day and night ventilation

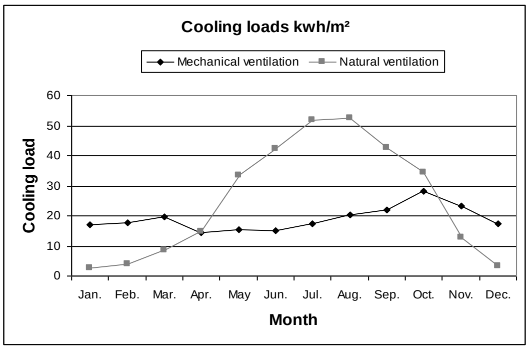
Natural ventilation has two different functions: to supply fresh air and, potentially, to provide cooling in summer. Haase & Amato (2009) examined the potential for natural ventilation to achieve thermal comfort in hot and humid climate and found that the improvement in comfort by natural ventilation ranges between 9-41% in tropical climate, between 3-14% in subtropical climate and between 8-56% in temperate climate. On the other hand, night ventilation may contribute to reducing cooling loads and improving thermal comfort. This technique uses the outdoor cool air to decrease the indoor air temperature and the temperature of building structure, especially for buildings with high thermal mass. In certain climates with large variation in diurnal outdoor temperatures (as in our case) night time ventilation can be used to cool down the thermal mass of the buildings and reduce the cooling loads.

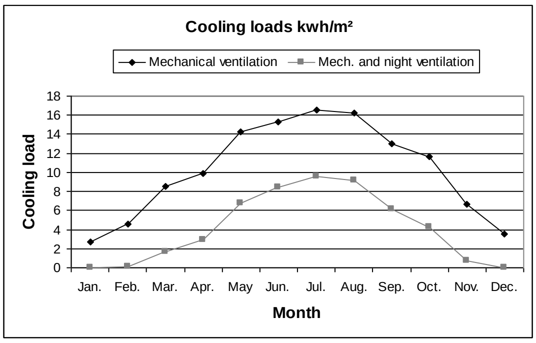
The simulations about the use of all day natural ventilation were done for five different cities using TRNSYS software. Figure (2) shows the evaluation of cooling loads and discomfort hours for 30% glazing to the west orientation zone and 70% glazing to the south orientation zone for three cities. The results showed a dramatic increase in cooling loads and discomfort hours using the daytime ventilation strategy except for a few months (January, February, and December). This can be justified by the high outdoor air temperature during the day for the rest of the year. For this reason, natural daytime ventilation can be used in a limited period of the year. Moreover, the effects of night ventilation, used for 3 hours in the early morning between 2:00 AM - 5:00 AM, were evaluated. The evaluation of cooling loads and discomfort hours for 30% glazing to the west orientation zone, and 70% glazing to the south orientation zone shows a significant decrease in cooling loads and discomfort hours using the night ventilation strategy around the year.

Daytime ventilation, 70% glazing to south orientation/ Monthly Cooling loads

Night ventilation, 30% glazing to west orientation/ Monthly Cooling loads

Basra, Iraq





Dubai, UAE

Doha, Qatar

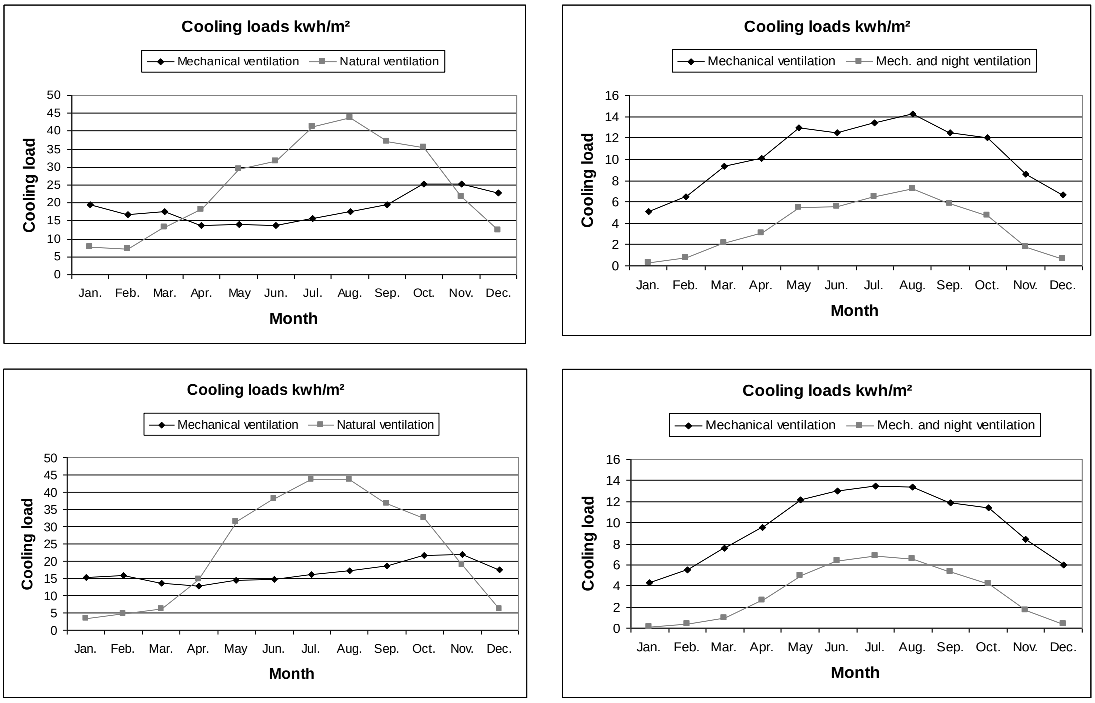


Fig. 2: the effect of natural day-time and night-time ventilation on the cooling loads

3.3 Effects of glazing performance

There is a growing interest in the use of transparent facades in commercial buildings, even in hot climates, with relatively high transmittance glazing systems. In Europe there is an earnest attempt to achieve high performance using advanced façade concepts. In the Gulf region, architects and engineers are further behind but remain interested in pursuing the environmental and performance goals. It is often dangerous to take a design solution from one climate and location and transport it to a new one without a good understanding to how the systems work. A study in the UAE by AboulNaga (2006) examined the impact of glazing on daylight and energy consumption for commercial buildings and found that the glazing properties – especially the shading coefficient – have a large influence on daylight and energy consumption.

The simulations in this work were done for different glazing types: single, double, double argon filled, and tinted glazing. The simulations considered the cooling load for 30% glazing to the west orientation zone, and 70% glazing to south orientation zone, as of the optimization presented in 3.1. The simulations were done for the five cities in hot arid climates Abu Dhabi in UAE, Basra in Iraq, Doha in Qatar, Kuwait city in Kuwait and Riyadh in Saudi Arabia. TRNSYS simulation software and Meteonorm climate data files were used. For the zone with 30% glazing to the west, the effect of glazing types on cooling loads is significant and the difference can reach more than 60 Kwh/m² yr. between single clear and double tinted glazing in all tested cities. For the zone with 70% glazing to the south, the effect of glazing types on cooling loads is also important and the difference can reach more than 70 Kwh/m² yr. between single clear and double tinted glazing in all tested cities. Figure (3) shows the annual cooling loads and solar gain for three cities. For this region, with high solar radiation and high outdoor temperature around the year, the use of solar control glazing either body tinted (absorbing) or coated (reflective) is crucial to reduce unwanted solar gain. Moreover, using advanced glazing and shading elements may help to reduce cooling loads and discomfort hours.

Annual cooling loads, kWh/m² yr *Annual Solar gain, kWh/yr*

Doha, Qatar

Kuwait, Kuwait

Riyadh, Saudi Arabia

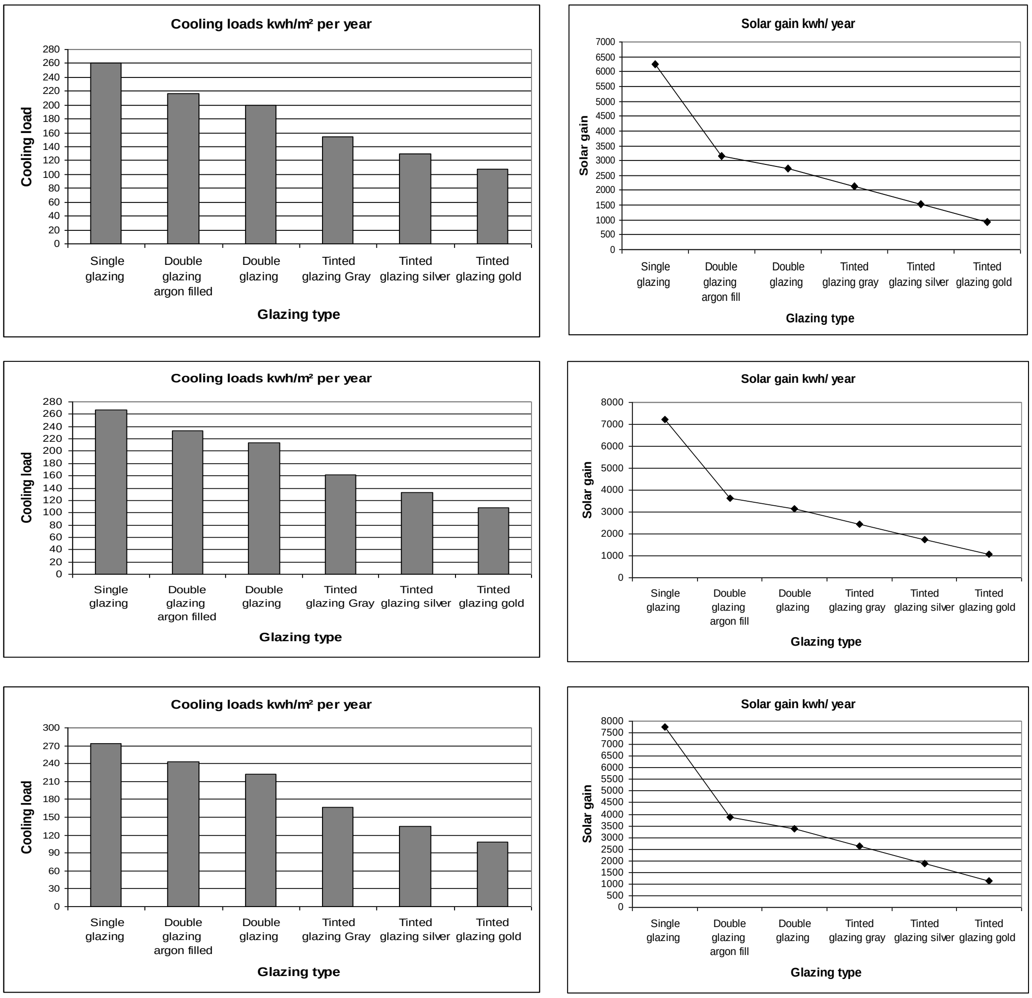


Fig. 3: the effects of changing glazing types on the cooling loads and solar gain in hot climates

3.4 Effects of fixed and movable shading

The simulations were done for the use of fixed shading and its effect on the cooling loads and comfort. The conditions were set at 30% clear double glazing to the west, and 70% to the south orientation thermal zones. TRNSYS simulation software was used. Horizontal overhangs were used for the south orientation and vertical ones for the west orientation. The results showed a significant decrease in the cooling loads of up to 60 Kwh/m² yr., when shading was applied. The same simulations were also done for the use of movable shading and its effect on the cooling loads and comforts. Again, horizontal louvers were used for the south orientation and vertical ones for the west orientation. The shading is closed when the total solar radiation on the façade surface higher than 400 W/m² and open when it is lower than 380 W/m². The results show a significant decrease in the cooling loads up to 70 Kwh/m² yr. Figure (4) shows the effect of shading on the monthly cooling loads for three cities.

Fixed shading, 70% glazing and south orientation/ Monthly cooling loads

Movable shading, 30% glazing and west orientation/ Monthly cooling loads

Dubai, UAE

Kuwait, Kuwait

Riyadh, Saudi Arabia

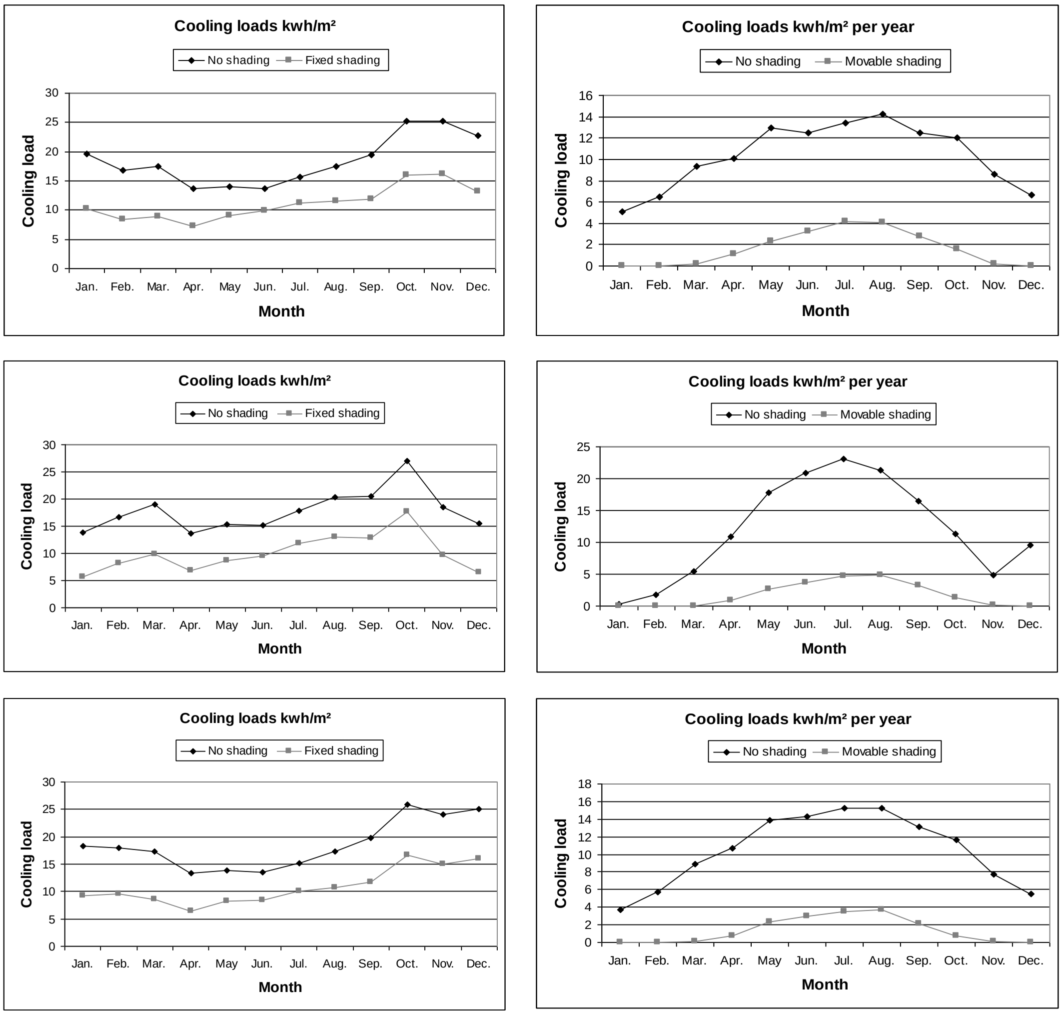
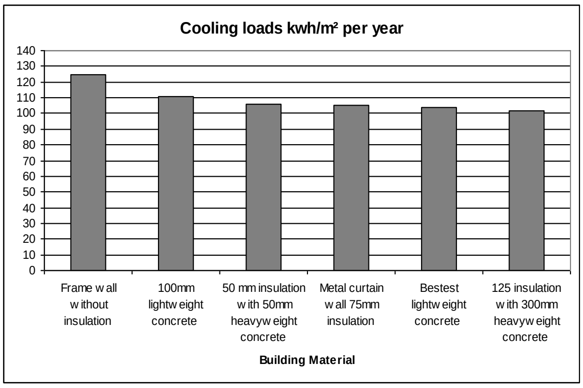


Fig. 4: effect of fixed and movable shading on the monthly cooling loads for different locations

3.5 Effects of insulation and thermal mass

The simulations were done for different materials and U-values, using TRNSYS simulation software. Conditions were set at 30% clear double glazing to the east and 50% glazing to the west. The simulations used the climate data file for the city of Riyadh, Saudi Arabia. The results show that increasing insulation for traditional opaque materials types has a limited effect on the comfort and cooling loads in hot arid climates. It can be concluded from the simulations, that changing the U-values for opaque materials has a limited effect on the cooling load – up to 20 Kwh/m² yr. The discomfort hours remain high in all passive cases due to the high air temperature and high solar radiation. The difference in discomfort hours due to changing U-values may reach at maximum 25 hours per year, and in some cases the discomfort may increase by decreasing the U-value (higher thermal resistance). The results indicate that the impact of the U-value of envelope components in office buildings is not significant if the glazed surface is significant (50% at least). It was found that adding more wall insulation does not always reduce annual energy consumption and in some cases adding thermal insulation directly increases annual energy consumption. That can be justified by the internal gains from equipment, lighting and occupants. Therefore, reducing thermal insulation and using relatively high U-values encourage heat losses and reduce the total cooling loads. On the other hand, using high thermal mass materials combined with night-time natural ventilation may have a positive effect on reducing the cooling loads and discomfort hours.

30% glazing to the east orientation



50% glazing to the west orientation

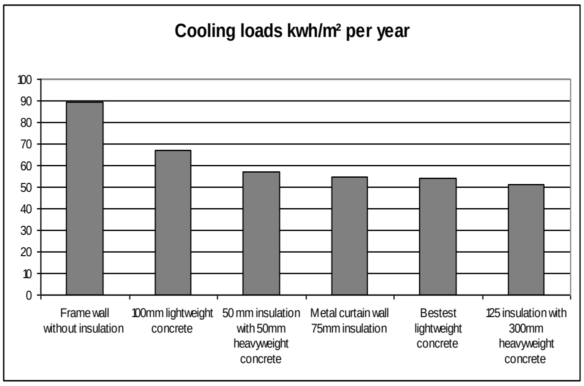


Fig. 5: effects of changing U-value and building materials on the cooling loads

3.6 Effects on daylight and visual comfort

In locations with clear skies and high levels of solar radiation, natural light can be used for energy saving and visual comfort. Providing the building interior with daylight can contribute to the reduction in the energy used for artificial lighting, and helps improve visual comfort. In order to achieve visual comfort and in the same time reduce heat gain, sunlight must be controlled and daylight redirected into the space. Lighting quality and daylight play an important role in architecture and building envelope design. For these reasons, care should be taken to apply building envelope technologies and design strategies to enhance daylight and visual comfort while controlling overheating.

The simulations were done using ECOTECT software for Riyadh, Saudi Arabia to evaluate the influence of building envelope technologies and design strategies on daylight use. The results show that the daylight factor is influenced by the following: opening size, orientation, glazing types and shading, as shown in figure (6). For these reasons, attention for daylight use should be taken when applying the technologies and design strategies mentioned before.

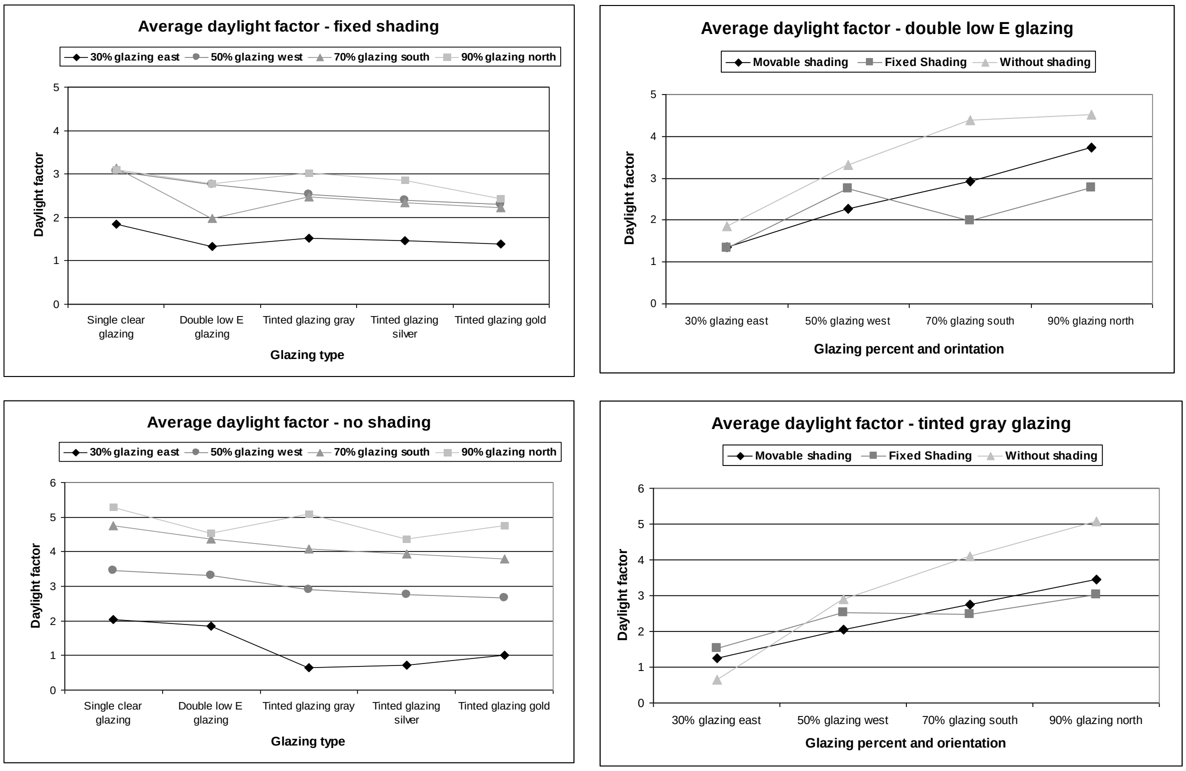


Fig. 6: Effect of shading and glazing type on daylight factor

4. Conclusions

This paper presents the first results of an on-going study aimed at finding design guidelines for tall office building envelope in hot arid climates. In addition, it aims to find guidance for the envelope performance evaluation in the early design stage. These guidelines will provide designers with preliminary indications about the potential effects of different technologies and design strategies. This evaluation is important to ensure thermal, visual comfort and energy efficiency, and increasing the awareness of designers about climate responsive design. The main findings, at this stage of the research work, are the following:

- windows to wall ratio has an effect on cooling loads and comfort and should be decided according to the orientation;

- using the daytime natural ventilation in winter and night ventilation in summer will improve comfort and energy efficiency (dynamic envelope);

- tinted and reflective glazing types have a significant effect on comfort and cooling loads in office buildings in hot climates;

- fixed and movable shading should be used according to the orientation (adaptive envelope);

- decreasing U-values may have a negative effect on comfort and cooling loads in hot climate, while the use of materials with high thermal capacity can help improve comfort and energy efficiency;

- finally, for the previous technologies and design strategies care should be taken to daylight efficiency and visual comfort.

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