# THERMAL AND DAYLIGHT PERFORMANCE OF TILTED GLASS AS SHADING ALTERNATIVE IN HOT ARID CLIMATE OF BAGHDAD

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*To my beloved parents and siblings,*
*For their love, support and prayers.*

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# ABSTRACT

Solar gain mitigation in buildings is essential to achieve thermal comfort and reduce cooling load in hot arid climate. Opaque shading is a useful strategy to block solar radiation in excessively hot locations like Baghdad. However, such shading comes at the expense of daylight illuminance and the openness of the window. A review of previous studies showed a gap in investigating the potentials of the clear glass in reducing solar gain. Solar transmittance through glass is angular dependent. The transmitted radiation decreases with bigger angles of incidence following increased reflection and reduced solar intensity. This research investigated the effects of using glass slats tilted away from the sun as an alternative to conventional horizontal shading on thermal and daylight performances of southwest rooms in commercial buildings in Baghdad. Integrated Environmental Solutions-Virtual Environment simulation tool was used to conduct the study. Six simulation cases were formulated; the base case used the common 75 centimetres overhang, the horizontal shading case had an additional three 75 centimetres horizontal shading devices, and four cases of 50°, 60°, 70° and 80° tilted glass slats in addition to the overhang. The simulation was run for seven representative days during the predominantly cooling season from April to October. Reductions in the solar gain, air temperature and mean radiant temperature using the slats were significant, especially at lower solar angles. For example, on September 21$^{st}$, the solar gain of the base case was reduced by 71%, 69%, 57% and 46% with the glass slats tilted at 50°, 60°, 70° and 80° respectively compared to 61% reduction through horizontal shading. On the same day, the average air temperature was reduced between the range of 2.2–3.3°C with the slats compared to 2.7°C with the horizontal shading; the mean radiant temperature was reduced by 2.3–3.4°C with the slats compared to 2.8°C with the horizontal shading. The daylight average illuminance was decreased by around 58%, 32%, 24% and 23% by using glass slats tilted at 50°, 60°, 70° and 80° respectively compared to around 78% decrease by using horizontal shading with an average illuminance of below 100 lux in most simulated hours. However, the glass slats failed to raise the low illuminance uniformity to the acceptable threshold due to higher illuminance levels near the window and lower illuminance levels at the rear part of the room, unlike the horizontal shading that reached the acceptable to the preferable uniformity levels in most simulated hours. This study showed that replacing the conventional opaque horizontal shading with tilted glass slats, especially at an angle of 60°, can have a better impact in improving the heat mitigation by solar radiation and increasing daylight availability in the study area. Furthermore, these improvements were obtained without compromising the openness of the window.

# ABSTRAK

Pengurangan penerimaan solar dalam bangunan adalah penting untuk mencapai keselesaan terma dan mengurangkan beban penyejukan dalam iklim panas yang kering. Pelindung legap adalah strategi yang berkesan untuk menghalang radiasi solar di lokasi yang sangat panas seperti Baghdad. Walau bagaimanapun, pelindung ini memberi kesan terhadap kuantiti pencahayaan cahaya siang dan keterbukaan tingkap. Tinjauan terhadap kajian sebelum ini menunjukkan adanya jurang dalam mengkaji potensi kaca jernih untuk mengurangkan penerimaan solar. Kepancaran solar melalui kaca bergantung kepada sudut. Radiasi yang dipancarkan berkurangan dengan sudut tuju yang lebih besar berikutan peningkatan pantulan dan pengurangan intensiti solar. Kajian ini menyelidik kesan penggunaan bilah kaca condong yang dicondongkan dari matahari sebagai alternatif kepada pelindung mendatar konvensional terhadap haba dan cahaya siang di bilik barat daya dalam bangunan komersial di Baghdad. Program simulasi *Integrated Environmental Solutions-Virtual Environment* digunakan untuk menjalankan kajian ini. Enam kes simulasi telah dirumus; kes asas mempunyai unjuran yang biasa digunakan sebanyak 75 sentimeter; kes pelindung mendatar mempunyai tambahan tiga 75 sentimeter alat pelindung mendatar, dan empat kes bilah kaca dicondongkan sebanyak 50°, 60°, 70° dan 80° selain unjuran. Simulasi dijalankan selama tujuh hari yang mewakili musim sejuk yang dominan dari April hingga Oktober. Pengurangan penerimaan solar serta suhu udara dan min pancaran oleh bilah tersebut adalah ketara, terutamanya pada sudut matahari yang lebih rendah. Sebagai contoh, pada 21 September, penerimaan solar bagi kes asas berkurangan sebanyak 71%, 69%, 57% dan 46% oleh bilah kaca yang dicondongkan pada 50°, 60°, 70° dan 80° berbanding pengurangan 61% oleh pelindung mendatar. Pada hari yang sama, purata suhu udara berkurang antara 2.2–3.3°C bagi penggunaan bilah kaca berbanding 2.7°C oleh pelindung mendatar; suhu min pancaran berkurang antara 2.3–3.4°C bagi penggunaan bilah kaca berbanding 2.8°C oleh pelindung mendatar. Purata cahaya siang menurun sebanyak 58%, 32%, 24% dan 23% oleh bilah kaca yang dicondongkan pada 50°, 60°, 70° dan 80° berbanding dengan pengurangan 78% oleh alat pelindung mendatar dengan purata pencahayaan di bawah 100 lux dalam kebanyakan masa simulasi. Walau bagaimanapun, bilah kaca gagal untuk meningkatkan keseragaman pencahayaan yang rendah sehingga ke tahap yang dapat diterima disebabkan tahap pencahayaan yang lebih tinggi berhampiran dengan tingkap dan tahap pencahayaan yang lebih rendah di bahagian belakang bilik, berbeza dengan pelindung mendatar yang mencapai tahap keseragaman diterima hingga lebih baik dalam kebanyakan masa simulasi. Kajian ini menunjukkan bahawa dengan menggantikan pelindung mendatar legap konvensional dengan bilah kaca condong, terutamanya pada sudut 60°, boleh memberi impak yang lebih baik dalam memperbaiki pengawalan haba oleh sinaran solar dan meningkatkan cahaya siang di kawasan kajian. Tambahan itu, penambahbaikan ini diperolehi tanpa menjejaskan keterbukaan tingkap ke arah luar.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ASHRAE | - | The American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| BC | - | Base case |
| CIBSE | - | The Chartered Institution of Building Services Engineers |
| COSQC | - | Central Organization for Standardization and Quality Control (Iraq) |
| GCB | - | General Commission of Buildings (Iraq) |
| GDP | - | Gross domestic product |
| HSD | - | Horizontal shading device |
| HVAC | - | Heating, ventilation, and air conditioning |
| ICSO | - | Iraqi Central Statistical Organization |
| IEA | - | International Energy Agency |
| IESVE | - | Integrated Environmental Solutions-Virtual Environment |
| IBPSA-USA | - | The United States regional affiliate of the International Building Performance Simulation Association |
| LBNL | - | Lawrence Berkeley National Laboratory |
| LEED | - | Leadership in Energy and Environmental Design |
| MBE | - | Mean bias error |
| MRT | - | Mean radiant temperature |
| RA | - | Room area |
| RMSE | - | Root mean square error |
| SL50 | - | Glass slats layer tilted at 50° |
| SL60 | - | Glass slats layer tilted at 60° |
| SL70 | - | Glass slats layer tilted at 70° |
| SL80 | - | Glass slats layer tilted at 80° |
| UAE | - | United Arab Emirates |
| WA | - | Window area |
| WWR | - | Window-to-wall ratio |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | - | Absorptance (dimensionless) |
| AT | - | Air temperature (°C) |
| $A_{sl,wd}$ | - | Combined absorptance and reflectance of the slats and window (dimensionless) |
| $A_{total}$ | - | Absorptance after deduction of the slats' cosine law effect (dimensionless) |
| $b$ | - | Back surface |
| $d$ | - | Thickness (mm) |
| $E$ | - | Atmospheric extinction coefficient (dimensionless) |
| $f$ | - | Front surface |
| $I$ | - | Global solar radiation (W/m$^2$) |
| $I_0$ | - | Extraterrestrial radiant flux (W/m$^2$) |
| $I_D$ | - | Direct solar radiation from the sun (W/m$^2$) |
| $I_d$ | - | Diffuse solar radiation from the sky (W/m$^2$) |
| $I_{dH}$ | - | Diffuse horizontal radiation (W/m$^2$) |
| $I_{DN}$ | - | Direct normal radiation (W/m$^2$) |
| $I_{dS}$ | - | Diffuse radiation for inclined surface (W/m$^2$) |
| $I_{dv}$ | - | Diffuse radiation for vertical surface (W/m$^2$) |
| $I_R$ | - | The reflected solar radiation (W/m$^2$) |
| $I_{RS}$ | - | Reflected radiation for inclined surface (W/m$^2$) |
| $I_{sc}$ | - | Solar constant (W/m$^2$) |
| $k$ | - | Proportionality constant (dimensionless) |
| K | - | Kelvin |
| $L_{im}$ | - | i$^{th}$ measured value (unit of the variable) |
| $L_{is}$ | - | i$^{th}$ simulated value (unit of the variable) |
| lux | - | Lighting power density (lm/m$^2$) |
| $N$ | - | Total number of data pairs |

| | | |
|---|---|---|
| $n$ | - | Refractive index (dimensionless) |
| $p$ | - | Perpendicular polarisation of the solar wave |
| $R$ | - | Reflectance (dimensionless) |
| $R_{sl}$ | - | Reflectance of the slats (dimensionless) |
| $R_{sl,wd}$ | - | Combined reflectance of the slats and window (dimensionless) |
| $R_{total}$ | - | Reflectance in addition to transmittance and absorptance deducted by slats' cosine law effect (dimensionless) |
| $R_{wd}$ | - | Reflectance of the window (dimensionless) |
| $s$ | - | Parallel polarisation of the solar wave |
| $T$ | - | Transmittance (dimensionless) |
| $\mathrm{T_{out}}$ | - | Outdoor temperature (°C) |
| $T_{sl}$ | - | Transmittance of the slats (dimensionless) |
| $T_{sl,wd}$ | - | Combined transmittance and reflectance of the slats and window (dimensionless) |
| $T_{total}$ | - | Transmittance after deduction of the slats' cosine law effect (dimensionless) |
| $T_{wd}$ | - | Transmittance of window (dimensionless) |
| $x$ | - | Day of the year |
| $Z$ | - | Solar azimuth (°) |
| $Z_B$ | - | Wall normal in respect to the north |
| $\alpha$ | - | absorptivity (dimensionless) |
| $\beta$ | - | Solar altitude (°) |
| $\delta$ | - | Inclination angle of the surface to the horizontal (°) |
| $\theta$ | - | Angle of incidence (°) |
| $\theta_{sl}$ | - | Angle of incidence of the slats (°) |
| $\theta_{wd}$ | - | Angle of incidence of the window (°) |
| $\kappa$ | - | Glass extinction coefficient (dimensionless) |
| $\lambda$ | - | Wavelength (μm) |
| $\mu$ | - | Solar wave polarisation |
| $\rho$ | - | reflectivity (dimensionless) |
| $\rho_g$ | - | Reflectivity of surrounding surfaces (dimensionless) |
| $\tau$ | - | transmissivity (dimensionless) |
| $\varphi$ | - | Bearing angle (°) |
| $\varsigma$ | - | Refracted angle (°) |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Buildings consume substantial amounts of energy. The rise in world population associated with improvement in living standards leads to more energy demand. Energy savings in the building sector have high potentials in lowering carbon emissions and hence reducing the effects of global warming. By adapting technology along with energy efficiency policies in buildings, a global energy saving equivalent to the 2012 energy consumption of China, United States, Russia, Germany, France and the United Kingdom can be achieved by 2050 (IEA, 2015).

Iraq has significant growth in the gross domestic product (GDP) in recent years (World Bank, 2017). This growth, along with rising population, leads to more energy consumption as shown in Figure 1.1. Electrical appliances especially air conditioners are increasingly used with little attention to passive cooling design. Building sector is the largest consumer of the produced electric power in Iraq (Hashem, 2017). Increasing $CO_2$ emissions is expected because most of the electricity supplies in Iraq come from non-sustainable sources as shown in Figure 1.2 (Saeed *et al.*, 2016).

In most regions of Iraq, the cooling season extends from April until October. Summer harsh weather is featured with temperatures soaring to high levels that even exceed 50°C on some days which add huge demand for electricity (Kharrufa, 2008).

Adapting sustainability in buildings is crucial in lowering energy demand. The main goal in this aspect is heat mitigation to reduce the cooling load. This reduction could be achieved through preventing heat from solar radiation, as much as possible, from entering the buildings.

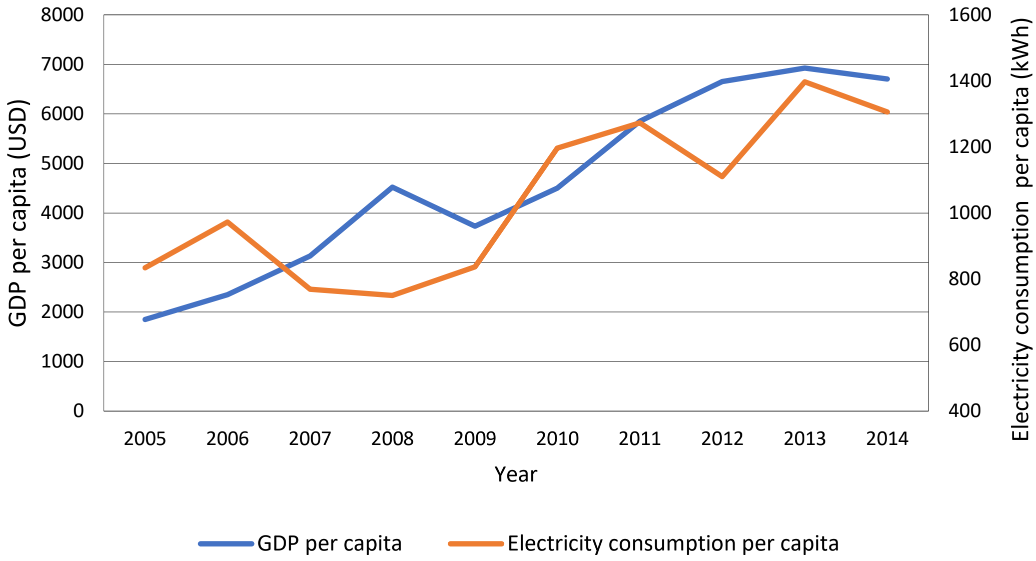


**Figure 1.1** Annual electricity consumption and GDP per capita in Iraq. Data source: World Bank (2017)

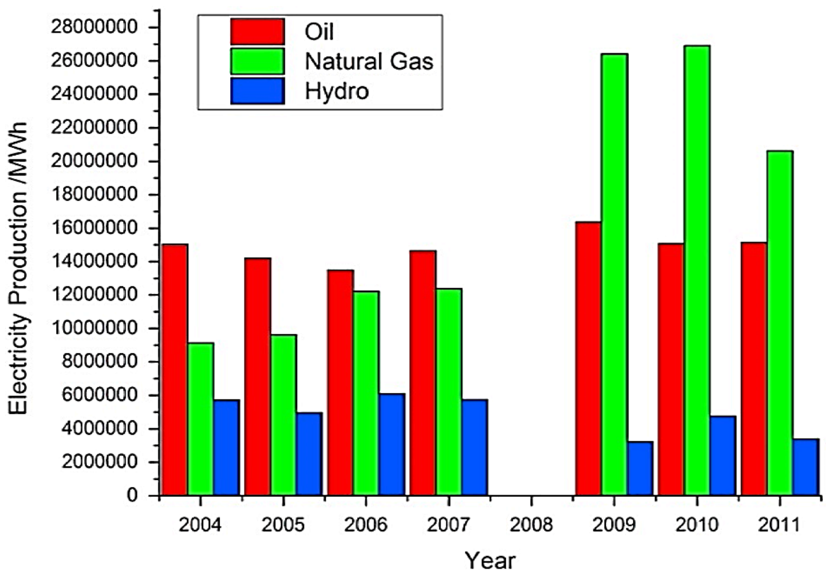


**Figure 1.2** Electricity production sources in Iraq. Source: Saeed *et al.* (2016)

## 1.2 Problem Background

Our thermal environment is determined mainly by the sun (Harkness and Mehta, 1978). According to Lechner (2014), the top climatic design priorities for desert climate is to keep heat out and achieve protection from the sun in summer. Figure 1.3 presents the three tiers approach for building design in hot and dry climates. The best way to avoid heat gain is not by eliminating undesirable heat but by excluding it in the first place (Olgyay, 1957).

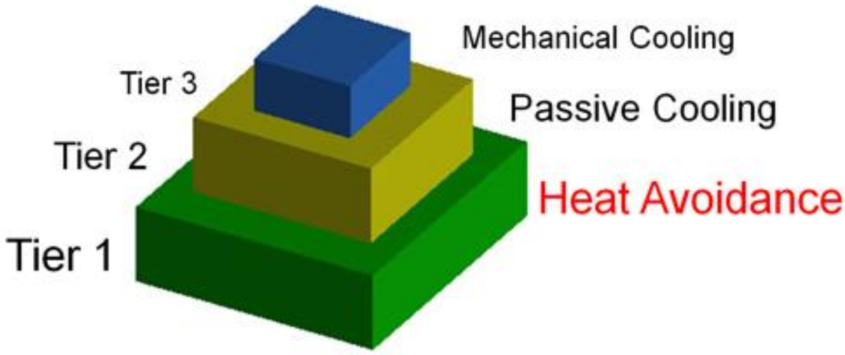


**Figure 1.3** Three-tier approach for sustainable building cooling. Source: Lechner (2014)

The long summer in Baghdad means that the building facades are exposed to lower sun angles in the periods far from the maximum solar altitude of the summer solstice. Further, the prevailing direction for main streets in Baghdad is northwest-southeast which makes the buildings located on their sides face southwest or northeast. The southwest buildings, in particular, are more exposed to lower sun angles that require deep shading to cover.

The shading depth is calculated for southwestern facades according to Olgyay (1957), Givoni (1998), Szokolay (2004) and Lechner (2014) from the sun path diagram (Figure 1.4). The last day of the cooling season was defined as October 31st when the sun faces the window directly at an altitude angle of 30° around 14:30. As shown in Figure 1.5, the intersection of the sun position at this altitude with window sill requires an overhang depth of around 3 m. Shading for lower sun angles requires even deeper shading.

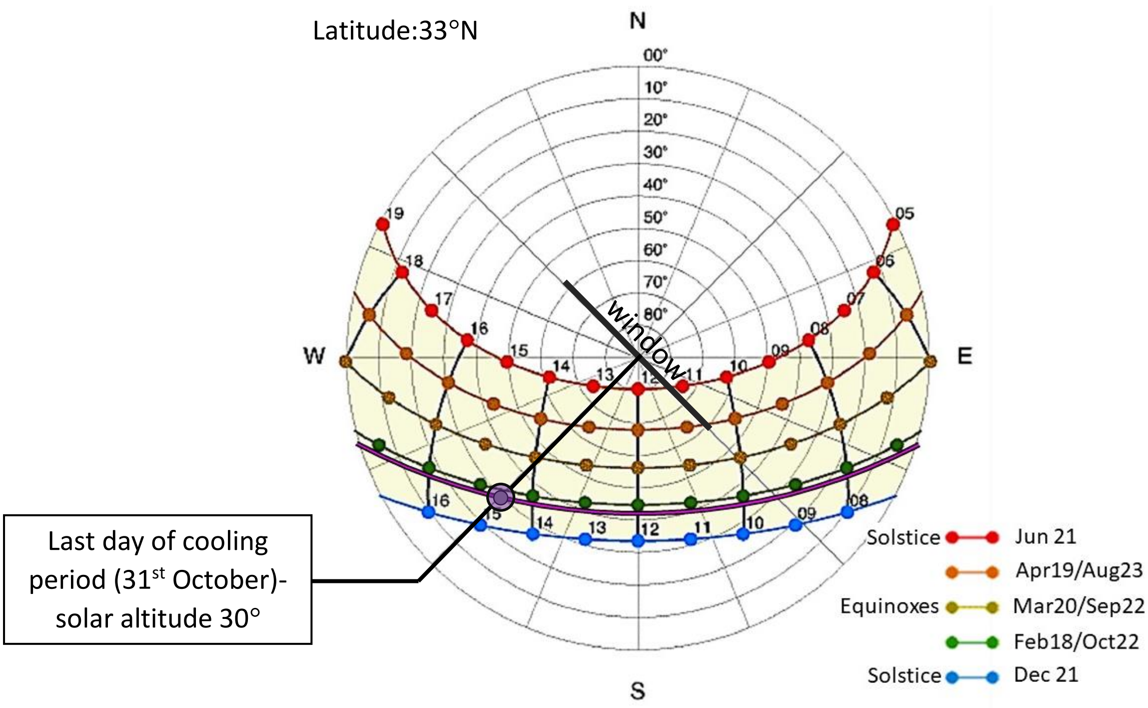


**Figure 1.4** Shading angle determination for southwest windows in Baghdad (Latitude 33°N) on the stereographic sun path diagram. Diagram source: adapted from University of British Columbia (2011)

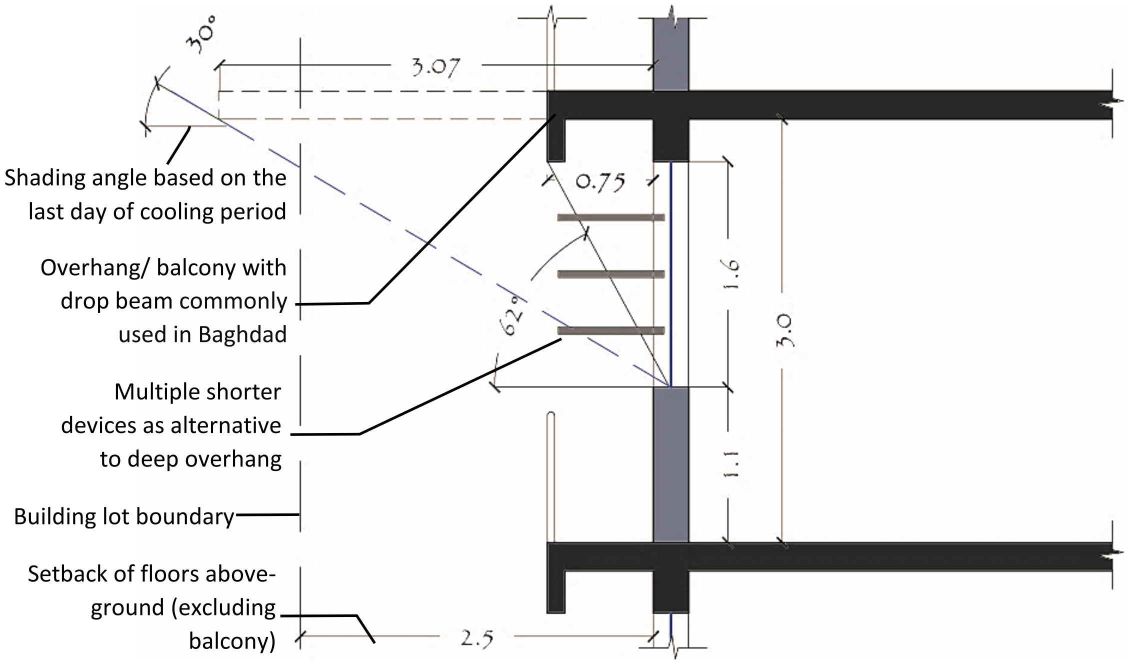


**Figure 1.5** Section through a typical room in commercial buildings in Baghdad

Obviously, the deep overhang is not practical due to its size that extends outside the building lot boundary as shown in Figure 1.5. On the other hand, this overhang does not match with the local regulations of Baghdad city for commercial buildings. The building regulations issued by Design Department in Baghdad Mayoralty allow only for 75 cm protrusion as open balconies on the floors above the ground floor (Baghdad Mayoralty, 2007).

The overhang/balcony (75 cm) can provide relatively adequate shading for a maximum solar altitude angle of 62º (Figure 1.5) which is efficient shading according to the stated method for the period from late April until the beginning of August when the sun faces the window directly. However, this shading is not sufficient when the sun moves to lower position towards the west during this period or the rest of the cooling season when the low sun faces the window particularly in September and October (Figure 1.4).

To overcome the architectural problem created by the deep overhang, alternatives of shorter shading devices can have the equivalent solar protection effect of larger devices (Lechner, 2014; Olgyay, 1957). This could be achieved for the case of southwestern facades in this study context by dividing the deep overhang to three horizontal devices of 75 cm that make, along with the commonly used overhang, a shading effect of one deep overhang. Although the horizontal shading device has the least obstruction to outside visibility due to its minimal impact on the horizontal view (Lechner, 2014), the deep shading still has a negative effect on the daylight availability whether it is a single large piece or smaller pieces with the same performance.

Apart from the horizontal shading, other adaptations are used in Baghdad to reduce the solar radiation and its excessive heat effect, for example, using small and recessed windows, vertical shading elements and solid shading screens. Other adaptations include hanging pieces of canvas/cloth, fixing the commercial signboards in front of the window, applying frosted films to the glass or adding a layer of reflective glass to the balcony. Appendix A presents photos of some of these adaptations.

One of the main functions of windows is the visual connection between outside and inside. This function is highly emphasised in modern architecture by having bigger areas of glazed facade to provide outside visibility and natural light (Kirimtat *et al.*, 2016). Menzies and Wherrett (2005) explained that besides the interaction with outside environment and allowing more daylight, bigger windows could have better psychological effect that leads to improved productivity in work spaces.

All the above-mentioned adaptations lead to outside visibility obstruction. A smaller window results also in less daylight and less connectivity to outside. The canvasses, solid screens, signboards and frosted films have the most damaging effect on outside visibility. Even in the case of reflective glass, though transparent, it cuts a substantial amount of useful daylight (Lechner, 2014) and it can have harmful solar reflection effect on the street. Although air conditioner can bring the internal temperature down, the required cooling energy is very high that makes these adaptations necessary, particularly with frequent power failure during the hottest days.

## 1.3 Problem Statement

Deep shading of 3 m or its equivalent is required for southwest facades in Baghdad to reduce direct solar radiation. However, this kind of shading can obstruct visibility and eliminate useful daylight when the sun is not facing the window directly as noticed in current shading practice in commercial buildings. There is a need to find shading alternative that may overcome this problem.

## 1.4 Hypothesis

This study hypothesises that tilted glass slats, when fixed in front of a window, can be an alternative to conventional opaque shading by utilising the optical properties of glass in its interaction with solar radiation to increase reflection due to bigger angles of incidence. Furthermore, the tilt effect decreases the solar exposure on the glass surface following the cosine law (Figure 1.6). The hypothesised effects of these glass slats are:

i. Reducing solar gain.
ii. Improving the daylight performance.

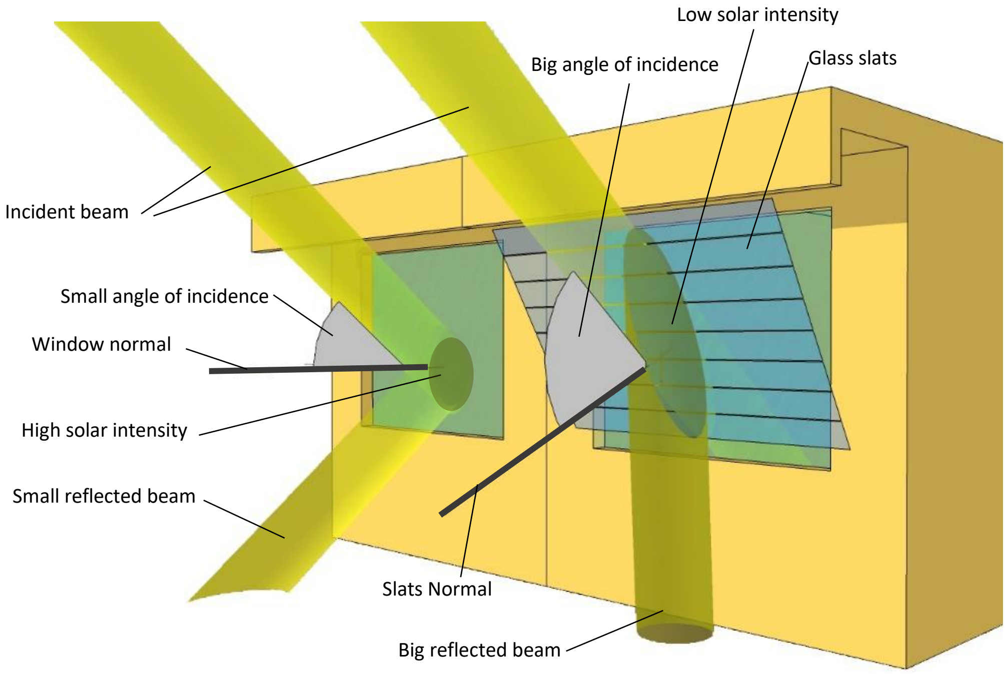


**Figure 1.6** Bigger angles of incidence maximise solar reflection and reduce solar intensity by distributing radiation over a wider area

## 1.5 Research Aim

This research aims to investigate the effects of using tilted glass slats as an alternative to conventional horizontal shading on thermal and daylight performances of southwest rooms in commercial buildings in Baghdad.

## 1.6 Research Objectives

In order to achieve the research aim, the following research objectives were formulated:

1. To analyse and compare the effects of enhancing the existing 75 cm overhang with multiple horizontal shading devices (equivalent to deep shading of 3 m) and tilted glass slats at 50°, 60°, 70° and 80° angles on the solar gain and indoor temperature.

2. To examine the effects of the above-mentioned horizontal shading devices and tilted glass slats on the daylight illuminance level and uniformity.

## 1.7 Research Questions

1. What are the effects of the horizontal shading devices and the tilted glass slats when added to the existing overhang on the solar gain and indoor temperature?

2. What are the effects of the horizontal shading devices and the tilted glass slats when added to the existing overhang on the daylight illuminance level and uniformity?

## 1.8 Research Scope and Limitations

This research was based on numerical simulation that was performed for the hot arid climate of the city of Baghdad, Iraq. A full-scale field experiment was not conducted due to resources and time limitations. However, validation experiment was conducted to check the reliability of the simulation tool in predicting the thermal performance while the prediction of daylight performance by the simulation tool was reviewed in previous studies in similar contexts. The research focuses on summer season only that requires a substantial cooling load to make buildings and spaces thermally tolerable due to the very high outdoor temperature.

The study scale is one generic room located in an above-ground floor in a commercial building. The selected orientation is the common southwest facade. Room and window dimensions, as well as the characteristics of construction materials were used as constant variables.

The glass type used for the tilted slats and the window was uncoated layer of 3 mm clear float glass fixed in front of the window at four angles with increments of 10° each. The size of the slats and the gaps between them were not calculated as ventilation is outside the scope of this research. The assumption of using smaller slats instead of one big piece of glass was to consider making the area between the glass and the window fully ventilated from the front in addition to the sides to avoid heat trap and neutralise the temperature in this area (Hashemi *et al.*, 2010). In any case, the slats were assumed to be overlapped in a way that does not allow for solar radiation to penetrate in between the slats. The suggested slats are assumed to reflect part of the radiation towards the overhang of the lower floor; the heating impact of such reflection on the room thermal performance was not considered in this study. The comparable tested shading device was the opaque horizontal type. Both of the slats and horizontal shading were external; the internal shading was not covered in this study.

The measured thermal performances were the solar gain, air temperature and mean radiant temperature in passive mode for 24 hours on one selected day of each month of the cooling season. Average illuminance and illuminance uniformity of daylight were measured in an area of interest in the middle of the room under clear sky condition. Daylight factor and glare analysis were not included in this research. The natural ventilation was not considered. Table 1.1 summarises the constant, dependent and independent variables of this research.

**Table 1.1** Constant, dependent and independent variables of the research

| **Type of variable** | **Variable** | **Details** |
|---|---|---|
| Constant variables | Climate | Hot dry climate of Baghdad |
| | Period | Cooling period (April–October) |
| | Orientation | Southwest |
| | Scale | Generic room |
| | Window-to-wall ratio | 36% |
| | Constructions | Common local materials (see Table 3.2) |
| | Glass (window and tilted slats) | 3 mm clear uncoated glass |
| Independent variables | Shading device | Overhang and horizontal shading devices |
| | Tilted glass slats angles | 50°, 60°, 70° and 80° |
| Dependent variables | Thermal performance | Solar gain, air temperature and mean radiant temperature |
| | Daylight performance | Illuminance levels, average illuminance and illuminance uniformity |

## 1.9 Research Significance

Heat gain avoidance is the primary challenge for the built environment in desert climates to achieve sustainability. A major approach in this aspect is done by controlling fenestration that can be achieved, for example, by reducing the window size or shading it densely. In both cases, this affects the building openness and the daylight potentials. In many other cases, bigger windows are associated with more solar gain and higher cooling loads. There are limited studies conducted on shading techniques specifically in Baghdad. This study is expected to give a better understanding of the effect of the commonly used overhang on building thermal and daylight performances.

This research attempts to test enhancing the overhang with tilted slats of clear glass as an alternative to opaque horizontal shading devices. In practice, the clear glass is the most affordable type of glazing that provides maximum visible transmittance. The suggested technique is passive and focuses more on fixing geometry rather than using complex systems or materials. These slats are retrofittable to the existing buildings in addition to their ability to be integrated in new buildings.

## 1.10 Thesis Organization

The thesis is arranged in five chapters as illustrated below.

Chapter 1 presents the background of this research and the problem addressed in this study. The research objectives and the research questions are set in this chapter along with the research scope, limitations and research significance.

Chapter 2 focuses on the literature review by presenting a theoretical background of solar radiation and geometry, and glass optical properties. Previous studies related to shading are also presented and discussed.

Chapter 3 provides an overview of the study context and an explanation of the followed methodology in conducting this study and analysing the results. It also presents the field experiment that was performed to validate the thermal simulation software and experiments that were used by other researchers to validate the daylight simulation software.

Chapter 4 presents the simulation results with analysis of the thermal and daylight performances of the different studied cases. Furthermore, it presents a discussion on the relation between the obtained findings and the solar behaviour of the study context.

Chapter 5 concludes the research by presenting a summary of the study findings along with recommendations and possible future studies in light of this study findings.

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