

# Determination of Heat Gain through Window Glass for Different Climates in KSA

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**ABSTRACT:** A numerical model based on the finite-volume method is presented for the determination of heat gain through window glass under time-dependent periodic conditions. The heat gain includes solar transmission and heat conduction to inner space. Model application is made to different climates in KSA; namely, Riyadh, Jeddah, and Abha. Different window orientations are considered using double-pane tinted window glass. Glass solar-optical properties for beam and diffuse radiation are determined as a function of solar incident angle. The ASHRAE clear-sky model is used to calculate the solar radiation. Results show that the peak heat gain in August pertains to the west-facing window with values of  $359.3 \text{ W/m}^2$ ,  $339.4 \text{ W/m}^2$ , and  $311.7 \text{ W/m}^2$  for Riyadh, Jeddah and Abha, respectively. Corresponding daily heat gains are  $7.67 \text{ MJ/m}^2\cdot\text{day}$ ,  $7.12 \text{ MJ/m}^2\cdot\text{day}$ , and  $4.39 \text{ MJ/m}^2\cdot\text{day}$ , respectively. The daily heat gain is found to be practically equal for the east and west orientations. The north-facing window has the lowest instantaneous and daily heat gain for all cities since the solar heat gain is the lowest for this orientation.

**KEYWORDS:** Heat gain; Double-pane glass; Solar radiation; Finite-volume method.

## NOMENCLATURE

$c_p$	specific heat [J/kg.K]
$h_{c,i}$	inside-surface convection coefficient [ $\text{W/m}^2 \text{ K}$ ]
$h_{c,o}$	outside-surface convection coefficient [ $\text{W/m}^2 \text{ K}$ ]
$h_i$	combined heat-transfer coefficient [ $\text{W/m}^2 \text{ K}$ ]
$I_b$	beam radiation [ $\text{W/m}^2$ ]
$I_d$	diffuse radiation [ $\text{W/m}^2$ ]
$I_s$	total solar radiation [ $\text{W/m}^2$ ]
$k$	thermal conductivity [ $\text{W/m K}$ ]
$k_{\text{eff}}$	effective air-gap conductivity [ $\text{W/m K}$ ]
$L$	glass thickness [m]
$L_a$	air-gap width [m]
$q$	heat flux [ $\text{W/m}^2$ ]
$\dot{q}$	heat generation per unit volume [ $\text{W/m}^3$ ]
$Q$	daily heat gain
$R$	overall resistance [ $\text{m}^2 \text{ K/W}$ ]
SHGC	solar heat gain coefficient
$t$	time [s]

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$T$	temperature [ $^{\circ}\text{C}$ or $\text{K}$ ]
$U$	overall transmittance [ $\text{W}/\text{m}^2 \text{K}$ ]
$x$	coordinate direction [ $\text{m}$ ]

## GREEK SYMBOLS

$\alpha$	thermal diffusivity [ $\text{m}^2/\text{s}$ ] or absorptivity
$\varepsilon$	emissivity
$\tau$	transmissivity
$\rho$	density [ $\text{kg}/\text{m}^3$ ]

## SUBSCRIPT

$b$	beam
$cond$	conduction
$conv$	convection
$d$	diffuse
$DP$	double pane
$g$	glass
$grd$	ground
$i$	inside
$o$	outside
$rad$	radiation
$sur$	surroundings
$trn$	transmitted

## I. INTRODUCTION

Glass fenestrations are glazed openings in buildings which consist of single- or multiple-pane glass that separate the indoor parts of the building from the outdoor environment. Glass fenestrations are the weakest parts in building envelopes with regard to controlling the transmission of thermal energy. The size of window glass, window orientation, type of glass used, and climatic conditions have substantial effects on the cooling and heating air-conditioning (AC) loads of buildings.

Heat transfer across a window glazing, as a result of a temperature difference between inside and outside ( $\Delta T$ ), has often a negative impact on building energy consumption. This heat transfer, called heat conduction gain, is proportional to  $\Delta T$  and the overall transmittance of the window glazing ( $U$ ). Therefore for a given  $\Delta T$ , as dictated by climatic conditions and indoor thermostat settings, means are sought to reduce  $U$  and hence reduce heat gain by conduction. This is often done through using multi-pane window glass which increases the overall thermal resistance ( $R$ ).

Unlike heat gain by conduction, solar heat gain through a window glass can be either advantageous or disadvantageous depending upon climatic conditions and season. However, in summer and in hot climates, solar heat gain has a negative impact on building energy consumption. The solar heat gain is proportional to solar radiation incident on the glass ( $I_s$ ) and solar heat gain coefficient (SHGC). In hot climates, therefore, means are sought to reduce the solar heat gain through reducing  $I_s$  and SHGC. The former parameter ( $I_s$ ) can be reduced through using shading devices and by properly orienting the window to receive the least solar radiation. The latter parameter (SHGC) can be reduced through using multi-pane window glass and by employing specially coated and tinted (heat absorbing) glass.

The heat gain through window glass ( $q_{\text{gain}}$ ) is the sum of the solar heat gain and the heat conduction gain. It is noted that  $q_{\text{gain}}$  is an instantaneous value that varies with time of day since both  $I_s$  and  $\Delta T$  vary with time. Also SHGC, which is

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frequently quoted as a single value for a given window glass material and configuration, is in reality a variable determined from varying solar-optical properties of glass. Indeed, SHGC depends on solar angle of incidence and, hence, depends on time of day and window orientation. The solar-optical properties of glass are often calculated at normal solar angle of incidence. This can lead to serious inaccuracy since the solar incident angle can deviate appreciably from being normal to glass surface.

In the present study, the solar-optical properties of glass are determined for both beam and diffuse radiation while accounting for effect of solar incident angle which, obviously, varies with time of day. In addition, the solar flux  $I_s$  is calculated using the ASHRAE clear-sky model. The heat gain  $q_{\text{gain}}$  is determined rigorously under dynamic conditions based on energy conservation principle which is inherently built in the finite-volume method. Thus, thermal energy storage is accounted for in addition to including longwave radiation exchange with the sky and ground. Instantaneous and peak heat gain through window glass as well as daily heat gain are presented for different window orientations and climates in KSA for representative days in January and August.

## II. RELATED WORK

A brief appraisal of previous studies is presented in view of their relevance to glass properties, solar radiation, and thermal analysis of heat gain through window glass. Calculation of solar-optical properties of window glass was reported in [1-3]. Rubin [1] presented a set of procedures for calculation of transmittance, absorbance, and reflectance of multiple glass layers for different incident angles. Results showed that properties remain fairly constant for incident angle up to  $45^\circ$ . The absorptance has a maximum value around  $65^\circ$  because bulk absorption increases at a faster rate than reflectance for incident angle up to  $65^\circ$ . Chandra [2] estimated optical properties of different types of glass. Solar radiation transmission through single and double-glazing were presented. Transmittance and reflectance were tabulated for single glass as a function of solar incident angle and extinction coefficient. Optical properties of advanced window glass were evaluated by Mohelnikova and Altan [3]. The authors focused on low-emissivity glass; glass properties were classified and compared with transmittance and reflectance of ordinary glasses.

Measurements and calculations of solar radiation are presented in, for example, [4-8]. The ASHRAE clear-sky model [4] is frequently used to calculate solar radiation for any geographic location at any time of day. Unlike measurements, this model does not account for local cloud and dust conditions. Adjustment factors for the ASHRAE clear-sky model based on solar radiation measurements in Riyadh over the years 1996-2000 were determined by Al-Sanea et al. [5]. These adjustments factors were needed to account for the effect of local cloud and dust conditions on solar radiation calculated by the model. The study showed that the ASHRAE model calculations generally over-predicted measurements for the months of October through May. El-Sebaili et al. [6] analyzed measured data of global solar radiation for Jeddah during the period 1996-2007. Correlations to estimate the diffuse radiation were developed. The total radiation on a tilted surface facing south was calculated using isotropic and anisotropic models. At optimum tilt angle, maximum daily total radiation in January was  $36 \text{ MJ/m}^2 \cdot \text{day}$ .

Al-Ghamdi et al. [7] measured and predicted global solar radiation for Al-Baha, KSA. Measured data showed that maximum radiation was  $11 \text{ KWh/m}^2$  in May whereas minimum was  $3 \text{ KWh/m}^2$  in January. Measured data and model results exhibited good agreement. Corrections of the ASHRAE clear-sky model parameters were reported by Alsadi and Nassar [8]. The authors used measured data in three different climates to compare with radiation calculated by the ASHARE model over a horizontal surface for validation purpose. It was found that the adjusted model was a good estimator for calculation of total solar radiation.

Studies focusing on  $U$ , SHGC, and heat gain through window glass are [9-16]. Net energy fluxes through windows of multiple layer of glazing were calculated by Rubin [9]. Numerical calculations were compared with measurements using a calibrated hot box. Bansal et al. [10] reported  $U$  and solar heat gain factor ( $g$ ) for sizing passive heating concepts. Four regions in India with different climates were selected to calculate heating loads in winter. Passive

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heating of a single zone building was calculated using steady-state analysis. Results showed that the comfortable room temperature was 18.3°C. Tinker and Al-Buijan [11] reported experimental and numerical results of heat transfer through glazing in hot climate of Dammam, KSA. Different double glass types were used: clear, low-e, reflective silver, and anti-sun bronze glass. Four test cells were constructed and calibrated with single glazing and then glazed with various control glasses.

Thermal analysis of single- and double-pane window glazing was carried out by Oliveti et al. [12]. A model based on effective absorption coefficient of the inside environment was used for calculation of solar heat gain. Yoo et al. [13] measured  $U$  of different glass types (low-e glazing and tempered glazed units) and analyzed its effect on energy consumption in different regions in South Korea. Energy performance of double-pane windows in different climates in Iran was examined by Banihashemi et al. [14]. Heating and cooling loads were determined using hot arid, hot humid, cold, and temperate climates. It was found that in hot arid and temperate climates, using double-pane windows was useful in both hot and cold months. However, in hot-humid and cold climates where cooling and heating loads were dominant, respectively, using double-pane windows was advantageous in only those dominant months.

Carlos and Corvacho [15] carried out experimental and analytical studies of heat transfer through ventilated double window using different types of glass and conditions. For single transparent glass, transmittance was 0.79 and absorptance was 0.14. For single reflective glass, transmittance was 0.44 and absorptance was 0.25. SHGC was 0.48 for single transparent glass while that for reflective glass was 0.18. Almogbel et al. [16] used ANSYS-Fluent to simulate heat transfer in Nano coated glass in KSA. Different glass coatings and thicknesses were used, and SHGC and  $U$  were calculated. It was found that the heat gain was reduced with increasing coating thickness.

In summary, detailed and systematic studies on effect of window orientation on heat gain through window glass under periodic conditions are lacking. The present study aims at filling this gap through using a rigorous finite-volume model that accounts for longwave radiation exchange with the surroundings and thermal energy storage effect. In addition, glass solar-optical properties for beam and diffuse radiation are determined based on solar incident angle which varies with time of day and window orientation. Model application is made to different climates in KSA using a double-pane tinted window glass.

## III. MATHEMATICAL FORMULATION

### Physical Situation

A schematic of a double-pane window glass showing heat transfer mechanisms is depicted in Fig. 1. The exterior glass surface is subjected to solar radiation (in which parts are reflected, transmitted, and absorbed by glass) as well as convection and longwave radiation. The interior glass surface is exposed to convection and longwave radiation. The window consists of two 6-mm-thick glass sheets enclosing a 12-mm air gap.

### Governing Equation

Heat transfer through a double-pane window glass is governed by the conduction equation. Under the assumptions of one-dimensional and constant properties, the governing equation for a typical layer  $j$  is given as:

$$\frac{\partial^2 T_j}{\partial x^2} + \frac{\dot{q}_j}{k_j} = \frac{1}{\alpha_j} \frac{\partial T_j}{\partial t} \quad (1)$$

where  $k_j$  is thermal conductivity of layer  $j$ ,  $\alpha_j$  is thermal diffusivity of layer  $j$  ( $\alpha = k / \rho c_p$ ), and  $\dot{q}$  is heat generation per unit volume due to solar radiation absorption in glass layers.

**Initial and Boundary Conditions**

**Initial condition**

At  $t = 0$ , the temperature is taken as uniform across glass thickness and is equal to mean outdoor air temperature, i.e.

$$T_{t=0} = T_{air,o,m} \quad (2)$$

It is noted that under periodic conditions and for small thermal mass, effect of the initial condition diminishes quickly with time. Therefore, the final periodic solution becomes independent of the initial temperature condition at large time.

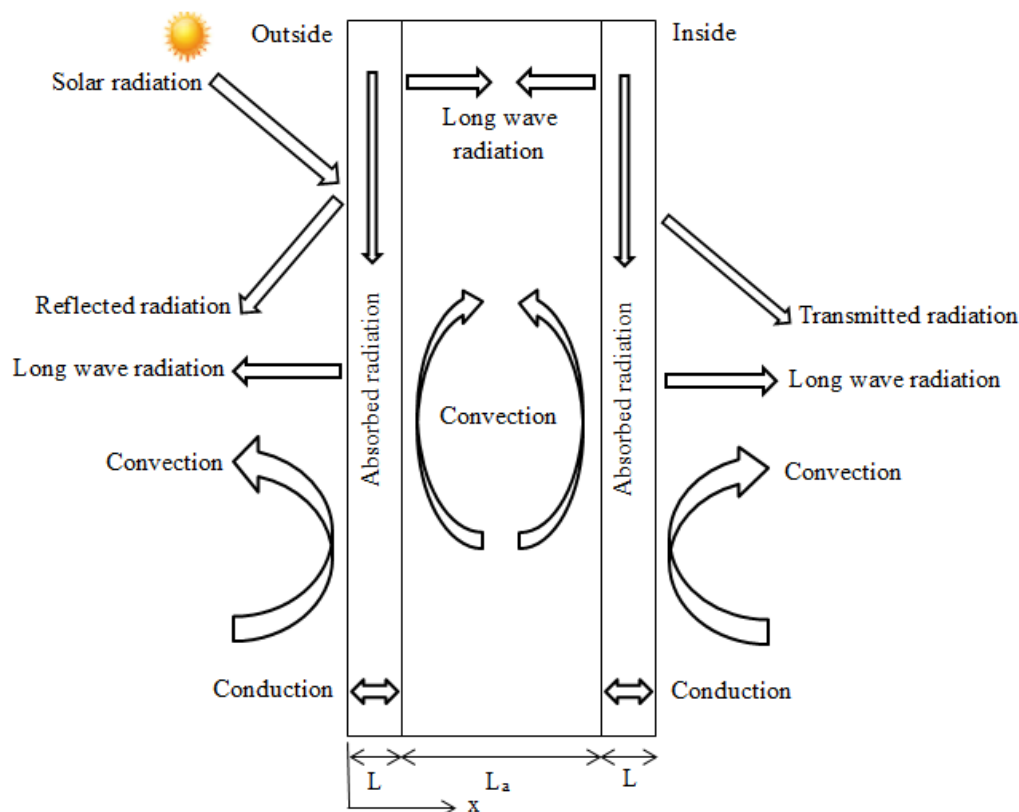


Fig. 1: Heat transfer mechanisms in double-pane window glass.

**Boundary conditions**

**Outside surface:**

The outside surface of glass is exposed to convection with outdoor air and radiation exchange with the sky and ground. Application of surface energy balance gives:

$$q_{cond} = q_{conv} + q_{rad} \quad (3a)$$

$$-k \frac{\partial T}{\partial x} = h_{c,o}(T_{air,o} - T_{g,o}) + 0.5 \epsilon \sigma (C T_{sky}^4 - T_{g,o}^4) + 0.5 \epsilon \sigma (T_{g,d}^4 - T_{g,o}^4) \quad (3b)$$

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where 0.5 is shape factor with sky and ground,  $h_{c,o}$  is outside-surface convection coefficient,  $T_{air,o}$  is outdoor air temperature,  $T_{g,o}$  is glass outside-surface temperature,  $\varepsilon$  is emissivity of glass surface,  $\sigma$  is Stefan–Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ ),  $T_{sky}$  is sky temperature,  $C$  is cloud-cover correction factor, and  $T_{grd}$  is ground temperature. Calculations of  $T_{sky}$  and  $C$  are described in [17] while  $h_{c,o}$  is calculated for a windward vertical surface [18]. It is noted that  $T_{air,o}$  is obtained from meteorological data,  $T_{grd}$  is often assumed equal to  $T_{air,o}$ , and  $T_{g,o}$  is determined by solution.

### Inside surface:

The inside surface of glass is exposed to convection with indoor air and radiation exchange with indoor surrounding surfaces. Surface energy balance gives:

$$-k \frac{\partial T}{\partial x} = h_{c,i}(T_{g,i} - T_{air,i}) + \varepsilon \sigma (T_{g,i}^4 - T_{sur,i}^4) \quad (3c)$$

where  $h_{c,i}$  is inside-surface convection coefficient,  $T_{g,i}$  is glass inside-surface temperature,  $T_{air,i}$  is indoor air temperature, and  $T_{sur,i}$  is indoor surroundings temperature.

When  $T_{sur,i}$  is equal to  $T_{air,i}$ , a combined convection-radiation coefficient ( $h_i$ ) is obtained, and Eq. (3c) can be written as:

$$-k \frac{\partial T}{\partial x} = h_i(T_{g,i} - T_{air,i}) \quad (3d)$$

In the present study,  $h_i = 8.3 \text{ W/m}^2 \cdot \text{K}$  which is based on ASHRAE value [19],  $T_{air,i}$  is fixed according to thermostat settings ( $22^\circ\text{C}$  in January and  $25^\circ\text{C}$  in August), and  $T_{g,i}$  is determined by solution.

### Overall Transmittance ( $U$ )

The overall transmittance ( $U$ ) in center of a double-pane glass is given as:

$$U = \frac{1}{\sum R} \quad (4a)$$

where  $\sum R$  is the overall thermal resistance ( $R$ ) given by:

$$\sum R = \frac{1}{h_{c,o}} + \frac{L}{k} + \frac{L_a}{k_{eff}} + \frac{L}{k} + \frac{1}{h_i} \quad (4b)$$

where  $L_a$  is air gap width, and  $k_{eff}$  is effective air-gap conductivity. The air gap is treated as a conductive layer with an empirical air-gap resistance of  $0.135 \text{ m}^2 \cdot \text{K/W}$  [19] accounting for convective and radiative effects. Based on this,  $k_{eff}$  is calculated to be  $0.089 \text{ W/m} \cdot \text{K}$ .

### Calculation of Heat Gain through Window Glass

The heat gain through window glass ( $q_{gain}$ ) is calculated using the numerical model as:

$$q_{gain} = q_{trn} + q_{cond} \quad (5a)$$

where  $q_{trn}$  is solar transmission, and  $q_{cond}$  is heat conduction through glass to inner space.

The solar transmission is given as:

$$q_{trn} = q_{trn,b} + q_{trn,d} = \tau_{DP,b} I_b + \tau_{DP,d} I_d \quad (5b)$$

where  $q_{trn,b}$  and  $q_{trn,d}$  are beam and diffuse solar transmission,  $\tau_{DP,b}$  and  $\tau_{DP,d}$  are beam and diffuse transmissivity of double-pane glass which are determined according to model described by Kusuda [20], and  $I_b$  and  $I_d$  are beam and diffuse radiation.

The heat conduction gain is calculated from:

$$q_{cond} = h_i(T_{g,i} - T_{air,i}) \quad (5c)$$

Hence, the total heat gain is:

$$q_{gain} = \tau_{DP,b} I_b + \tau_{DP,d} I_d + h_i(T_{g,i} - T_{air,i}) \quad (5d)$$

The above heat gain ( $q_{gain}$ ) is an instantaneous value, the daily total heat gain ( $Q_{gain}$ ) is obtained by integrating  $q_{gain}$  over a period of 24 hours.

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## IV. NUMERICAL SOLUTION PROCEDURE

The numerical solution procedure is based on the finite-volume method using the implicit formulation [21]. The double-pane glass is divided into discrete regions (control volumes or nodal points) by constructing a finite-volume grid. The finite-volume equations are derived by applying the overall energy balance over the control volume surrounding each nodal point. The nodal points comprise internal nodes, interior and exterior boundary nodes, and interface nodal points. The finite-volume equations are solved iteratively by the tri-diagonal matrix algorithm (TDMA). Details of the numerical solution procedure are given in [22].

## V. RESULTS AND DISCUSSION

The mathematical model outlined above is used to determine heat gain through the double-pane tinted glass depicted in Fig. 1. The model is applied to climatic conditions of Riyadh, Jeddah, and Abha. The application is made for the 21<sup>st</sup> day of each month. Results are presented for the months of January and August only in order to conserve space while focusing on effect of varying window orientation. January and August represent extreme winter and summer conditions, respectively.

It is noted that Riyadh, in central region, represents a hot-dry-climate in summer and a cold-dry-climate in winter. Jeddah, in western region by the Red Sea, represents a hot-humid-climate in summer and a temperate-humid-climate in winter. Abha, in south-western high inland region, represents a temperate-humid-climate in summer and a cold-humid-climate in winter. The air temperature, wind speed, and relative humidity are obtained using meteorological data averaged on an hourly basis over a number of years. The solar radiation is calculated using the ASHARE clear-sky model.

Thermal properties of double-pane tinted glass are supplied by glass manufacturer [23] and are summarized in Table 1. Longitude, latitude, and standard meridian pertinent to Riyadh, Jeddah, and Abha are presented in Table 2. Climatic data are presented next. These are followed by results in terms of heat gain variation with time, peak heat gain, and daily heat gain.

Table 1: Physical properties of glass [23].

$k$ (W/m.K)	$\rho$ (kg/m <sup>3</sup> )	$c_p$ (J/kg. K)	$\epsilon$ (-)
1.0	2500	720	0.84

Table 2: Longitude, latitude, and standard meridian pertinent to different cities in KSA.

City	$L_{loc}$	$\phi$	$L_{std}$
Riyadh	46.72°	24.93°	45°
Jeddah	39.18°	21.70°	45°
Abha	42.66°	18.24°	45°

The outdoor air temperature ( $T_{air,o}$ ) variations with time for Riyadh, Jeddah, and Abha are presented in Figs. 2a and b for the representative days of January and August, respectively. As observed,  $T_{air,o}$  follows cyclic variations over a period of 24 hours with minimum values at sunrise and maximum values in the afternoon. In January, Fig. 2a, Riyadh and Abha show close variations of  $T_{air,o}$  with time with Riyadh temperatures exceeding those of Abha by 2-3°C in the afternoon and evening. Jeddah, on the other hand, shows much higher temperatures with values exceeding 8-10°C those of Riyadh and Abha throughout the whole day. The average minimum temperature for Jeddah in January is about 20°C. With solar radiation adding to the total heat gain, overheating is expected for Jeddah even in winter. In August, Fig. 2b, Riyadh shows much higher temperatures than Jeddah, particularly during daytime, while Abha being a resort in summer shows much lower temperatures during the whole day.

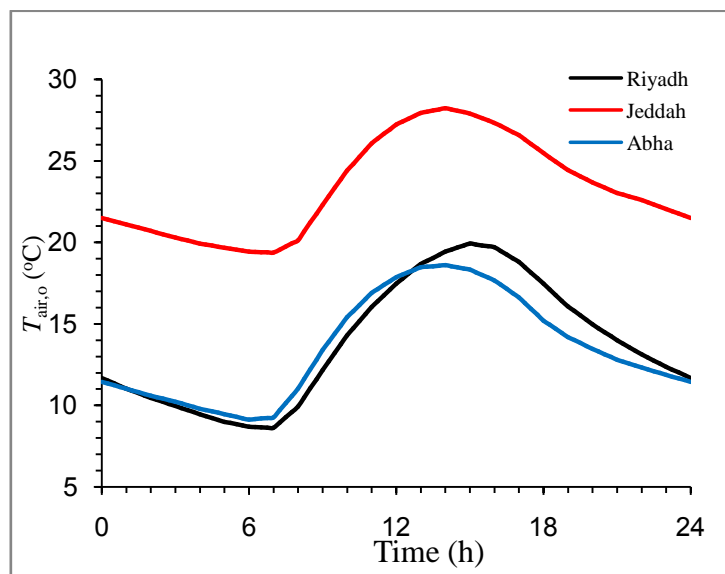
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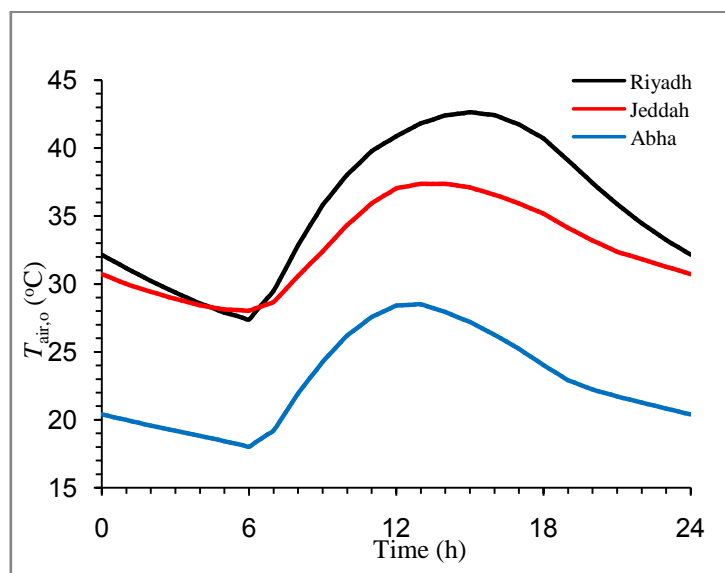
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It is important to note that the variations in  $T_{air,o}$  presented in Fig. 2 would reflect on the conduction heat gain which is part of the total heat gain through window glass.



(a) January



(b) August

Fig. 2: Outdoor air temperature variation with time for Riyadh, Jeddah, and Abha for the representative days of, (a) January and (b) August; data averaged over a number of years.

The solar radiation ( $I_s$ ) variations with time on vertical surface for the representative day in January are presented in Fig. 3a for the north and south orientations and in Fig. 3b for the east and west orientations. As observed in Fig. 3a,  $I_s$  is much greater for the south orientation as compared to the north orientation. This is because the south orientation is exposed to



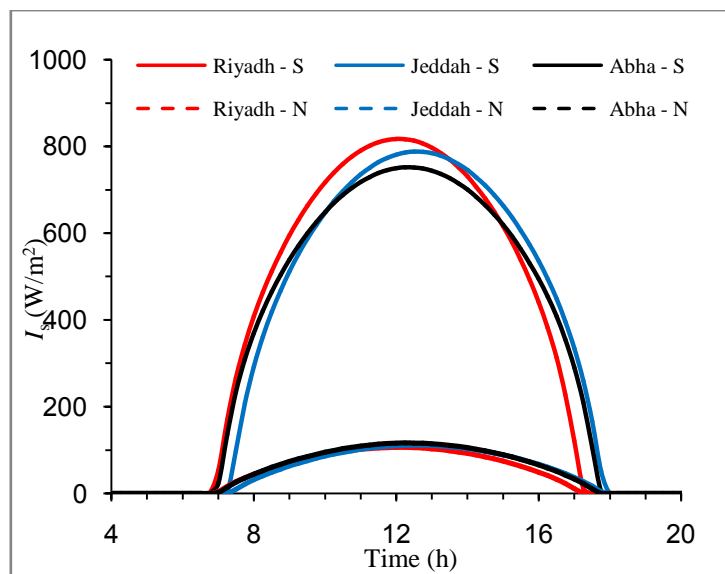
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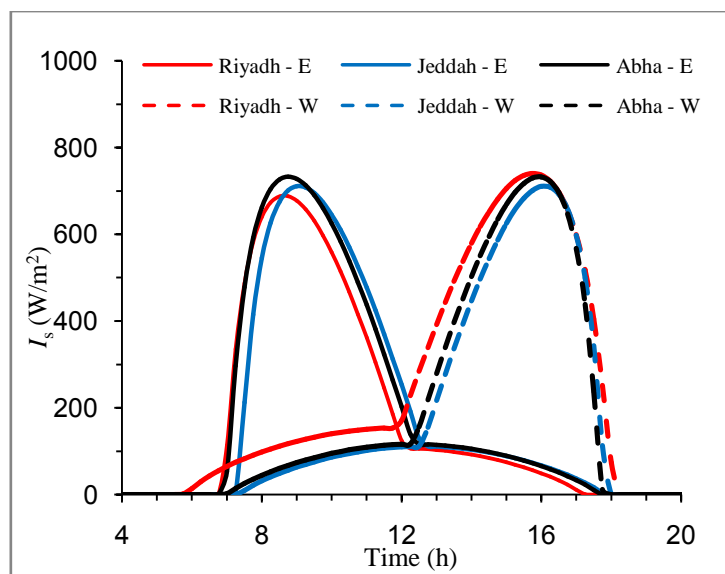
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both beam and diffuse radiation while the north orientation has diffuse radiation only in winter. Trends of  $I_s$  variations with time are similar for the three cities. For the east and west orientations, Fig. 3b, variations of  $I_s$  reflect the presence and absence of beam radiation during the day. For example,  $I_s$  for the east orientation is composed of beam and diffuse radiation from sunrise to midday. After midday,  $I_s$  is composed of diffuse radiation only. The trend reverses for the west orientation.



(a)



(b)

Fig. 3: Global solar radiation variation with time for representative day of January calculated by the ASHRAE clear-sky model, (a) N and S, and (b) E and W orientations.

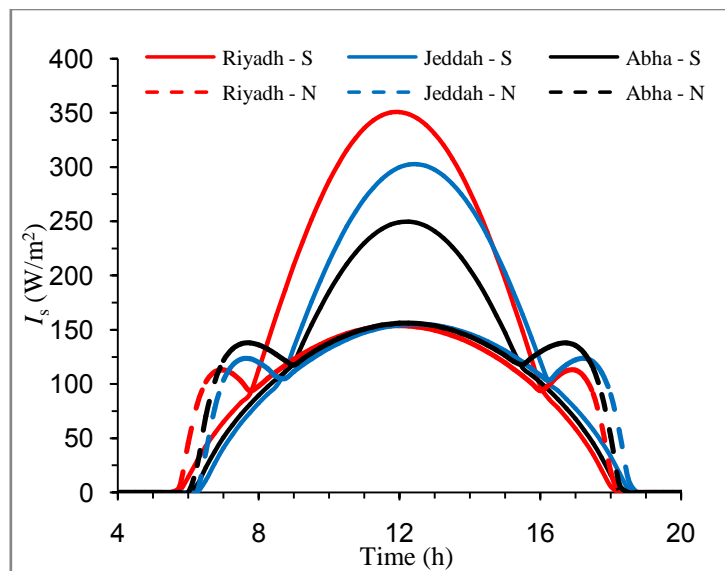
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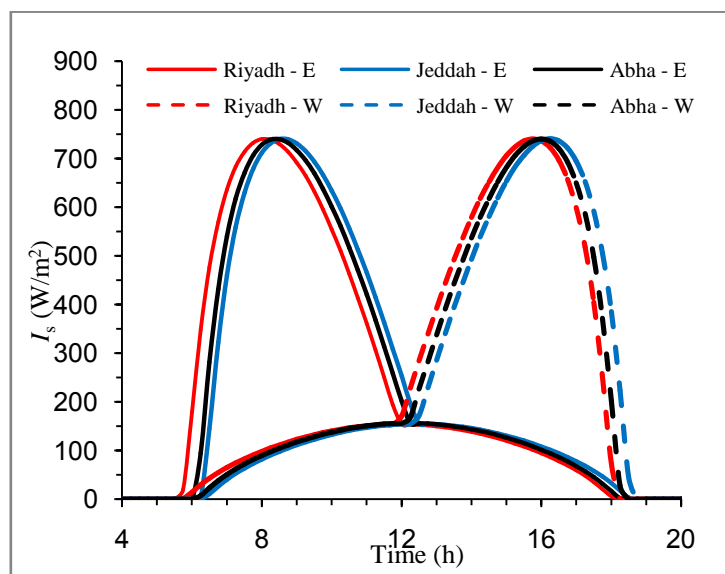
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Figs. 4a and b show variations of  $I_s$  with time for the representative day of August. For the south orientation, Fig. 4a,  $I_s$  is composed of diffuse radiation only in early hours of morning and late hours of afternoon. Outside these hours,  $I_s$  is composed of both diffuse and beam radiation. On the contrary,  $I_s$  for the north orientation is composed of both beam and diffuse radiation in early hours of morning and late hours of afternoon. Outside these hours,  $I_s$  is composed of diffuse radiation only. For the east and west orientations, Fig. 4b,  $I_s$  variations resemble those presented in Fig. 3b; however, differences are noticed in values of diffuse and beam radiation. It is important to note that the variations in  $I_s$  presented in Figs. 3 and 4 would reflect in a similar fashion on variations of heat gain as shown next.



(a)



(b)

Fig. 4: Global solar radiation variation with time for representative day of August calculated by the ASHRAE clear-sky model, (a) N and S, and (b) E and W orientations.

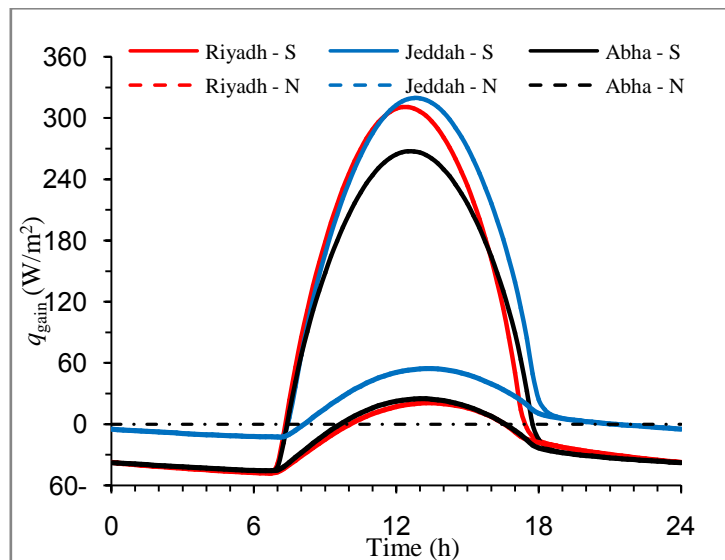
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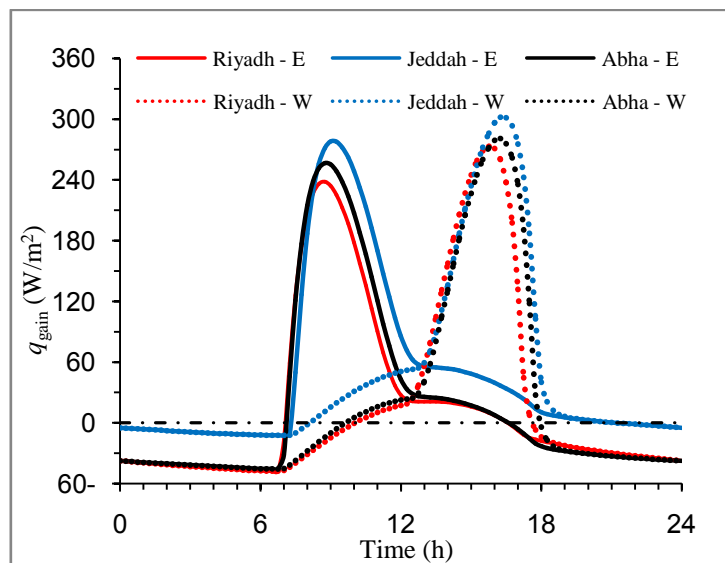
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Heat gain ( $q_{\text{gain}}$ ) variations with time for the representative day of January are presented in Figs. 5a and b for different window orientations. It is noted that positive values designate heat gain while negative values designate heat loss. The heat loss occurs mainly during nighttime when indoor temperature becomes greater than outdoor temperature. During most daytime,  $q_{\text{gain}}$  is positive as a result of solar radiation transmission as well as increase in glass temperature due to solar radiation absorption (heat conduction gain). It is interesting to note that, for a given city,  $q_{\text{gain}}$  are identical for all orientations during nighttime. Hence,  $q_{\text{gain}}$  is independent of orientation in absence of solar radiation. With regard to  $q_{\text{gain}}$  variations with time, the behavior shown in Figs. 5a and b reflects in general  $I_s$  variations presented in Figs. 3a and b. As a consequence, peak  $q_{\text{gain}}$  occurs at around midday for north and south orientations while it occurs at around 09:00 and 16:00 for east and west orientations, respectively. Peak  $q_{\text{gain}}$  are compared for different orientations and cities later.



(a)



(b)

Fig. 5: Heat gain variation with time for representative day of January, (a) N and S, and (b) E and W orientations.

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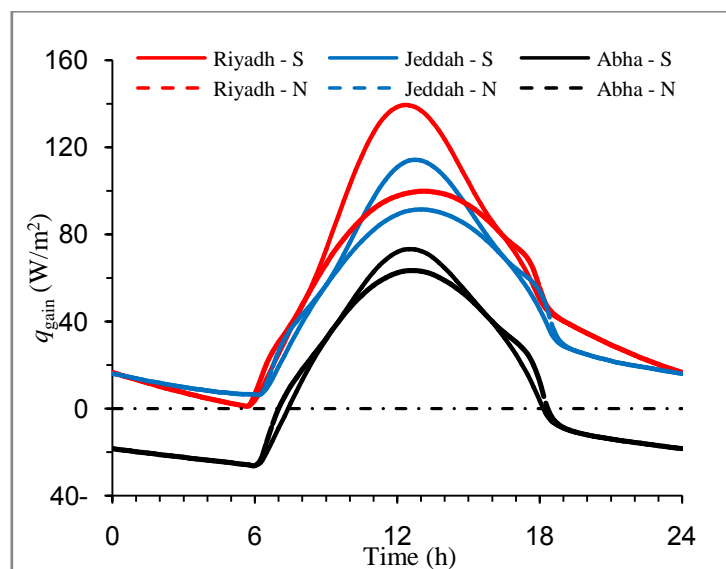
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Corresponding results in August are shown in Figs. 6a and b. For the south and north orientations, Fig. 6a,  $q_{\text{gain}}$  increases sharply after sunrise to reach peak value at noon and then decreases sharply till sunset. Gradual decrease in  $q_{\text{gain}}$  then follows during nighttime until sunrise. The general trends of variations of  $q_{\text{gain}}$  resemble those of  $I_s$  diurnal variations presented in Fig. 4a. The south orientation has larger  $q_{\text{gain}}$  than the north orientation for all cities. Values of  $q_{\text{gain}}$  for Abha are close for north and south orientations and are lowest compared to Riyadh and Jeddah because of Abha's temperate climate in summer. Riyadh has larger  $q_{\text{gain}}$  compared to Jeddah. It is noted that there is heat loss during nighttime for Abha, caused by cooler outdoor temperature, while  $q_{\text{gain}}$  persists for Riyadh and Jeddah over the whole day.

Fig. 6b presents  $q_{\text{gain}}$  for the east and west orientations in August. For the east orientation,  $q_{\text{gain}}$  increases sharply after sunrise to reach maximum at around 9:00 and then decreases sharply until noon in a manner that follows the beam solar radiation variation. For the west orientation, on the contrary,  $q_{\text{gain}}$  increases sharply from noon to reach maximum at 16:00 and then decreases sharply until evening. It is observed that the west orientation has noticeably higher  $q_{\text{gain}}$  than the east orientation for all cities. This is attributed to greater heat conducted to inner space caused by higher outdoor temperature during afternoon compared to lower temperature during morning hours. Abha has lowest  $q_{\text{gain}}$  for both east and west orientations.



(a)

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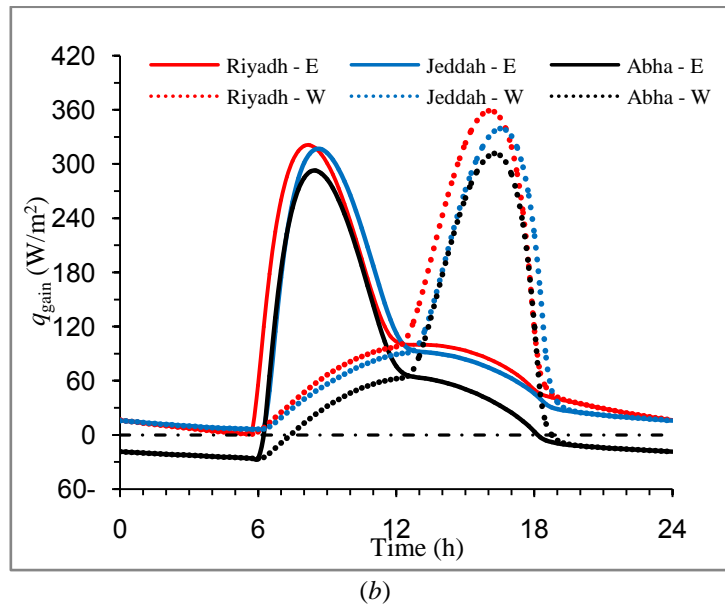


Fig. 6: Heat gain variation with time for representative day of August, (a) N and S, and (b) E and W orientations.

Peak values of  $q_{\text{gain}}$  ( $q_{\text{gain,max}}$ ) are compared for all orientations and cities in Figs. 7a and b for January and August, respectively. In January, Fig. 7a, it is observed that Jeddah has the highest  $q_{\text{gain,max}}$  for all orientations. The south orientation gives the highest  $q_{\text{gain,max}}$  for Riyadh and Jeddah. Abha has the highest  $q_{\text{gain,max}}$  for the west orientation. Therefore in winter, when heating is required, the south orientation is desirable for Riyadh while the west orientation is desirable for Abha. The north orientation gives the lowest  $q_{\text{gain,max}}$  for all cities and, hence, this orientation is the least desirable in winter for Riyadh and Abha.

In August, Fig. 7b, the west orientation gives the highest  $q_{\text{gain,max}}$  for all cities with values of  $359.3 \text{ W/m}^2$ ,  $339.4 \text{ W/m}^2$ , and  $311.7 \text{ W/m}^2$ , for Riyadh, Jeddah and Abha, respectively. This is followed closely by the east orientation. The south orientation gives much smaller  $q_{\text{gain,max}}$ . This is followed closely by the north orientation with the smallest  $q_{\text{gain,max}}$  for all cities with values of  $99.9 \text{ W/m}^2$ ,  $91.5 \text{ W/m}^2$ , and  $63.4 \text{ W/m}^2$ , for Riyadh, Jeddah and Abha, respectively. Riyadh has the highest  $q_{\text{gain,max}}$  for all orientations, this is followed by Jeddah then Abha. With regard to cooling requirement in summer, the west and east orientations are judged to be the worst, since  $q_{\text{gain,max}}$  are highest, while the south and north orientations are the most desirable for all cities.

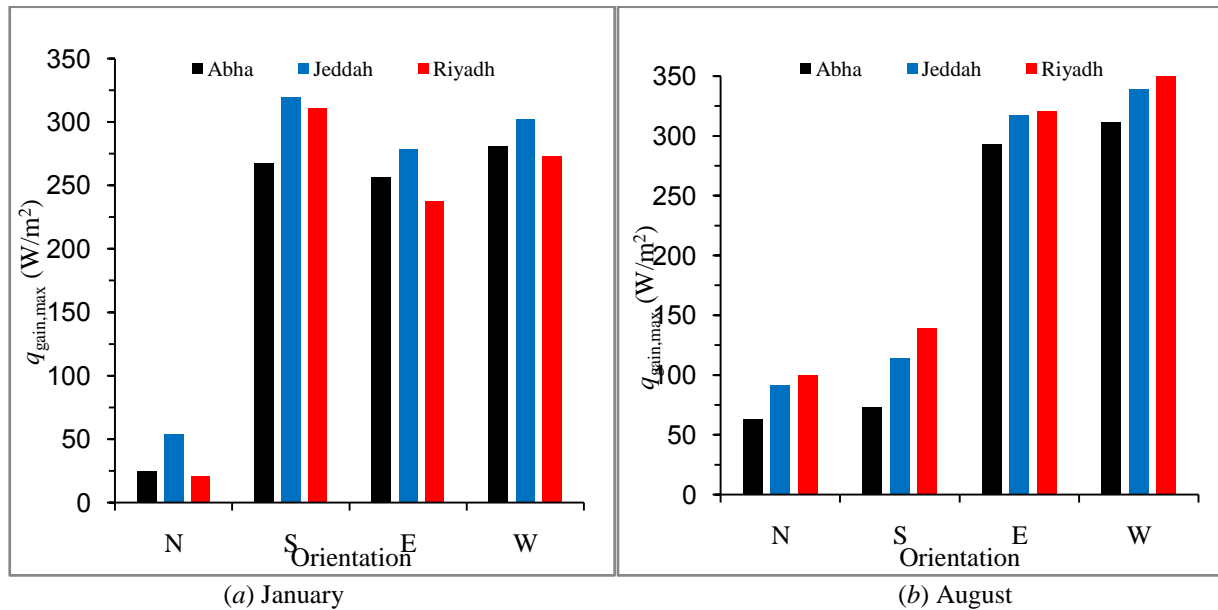


Fig. 7: Peak heat gain for representative days of (a) January, and (b) August.

Daily heat gain ( $Q_{gain}$ ) is calculated by integrating  $q_{gain}$  variation with time over 24 hours. Values of  $Q_{gain}$  are summarized in Table 3 for all cities and orientations for the representative days of January and August. While heat gain is welcome in January, apart from odd cases that could cause overheating, it is certainly not desired in August where it substantially increases the cooling demand of AC system. It is interesting to note that  $Q_{gain}$  are practically equal for east and west orientations. However, it is recalled that this is not the case with the peak heat gain in which  $q_{gain,max}$  is noticeably higher for the west orientation. In August,  $Q_{gain}$  is highest for east and west orientations. These are followed by south orientation while north orientation gives lowest  $Q_{gain}$  for all cities. In August, Riyadh has highest  $Q_{gain}$  for all orientations, this is followed by Jeddah while Abha has the lowest  $Q_{gain}$ . In January, Jeddah has highest  $Q_{gain}$  for all orientations while Riyadh and Abha exchange rankings according to window orientation.

Although bulk values of  $Q_{gain}$  in Table 3 are positive, two negative values are calculated for north orientation in January for Riyadh and Abha signifying daily heat loss. Unlike Jeddah, Riyadh and Abha have cold outdoor temperature in January. Since north orientation is not exposed to beam solar radiation in winter,  $Q_{gain}$  becomes negative as caused by dominant conduction heat loss. As observed in the table, Jeddah has the highest  $Q_{gain}$  of  $8.188 MJ/m^2.day$  for south orientation in January. This may well cause overheating for Jeddah in January depending upon window-to-wall area ratio.

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Table 3: Daily heat gain for Riyadh, Jeddah, and Abha for representative days of January and August for different window orientations.

Month	January			August		
City	Riyadh	Jeddah	Abha	Riyadh	Jeddah	Abha
Orientation	$Q_{gain}$	$Q_{gain}$	$Q_{gain}$	$Q_{gain}$	$Q_{gain}$	$Q_{gain}$
	MJ/m <sup>2</sup> .day	MJ/m <sup>2</sup> .day	MJ/m <sup>2</sup> .day	MJ/m <sup>2</sup> .day	MJ/m <sup>2</sup> .day	MJ/m <sup>2</sup> .day
N	-1.703	1.086	-1.616	4.077	3.642	0.8887
S	5.905	8.188	5.075	4.654	3.895	0.9057
E	1.180	4.055	1.515	7.684	7.130	4.391
W	1.171	4.050	1.511	7.671	7.124	4.386

## VI. SUMMARY AND CONCLUSIONS

A numerical model based on the finite-volume method was presented for the determination of heat gain through window glass under time-dependent periodic conditions. The model was applied for a double-pane tinted window glass using climatic conditions of Riyadh, Jeddah, and Abha. Different window orientations were considered and calculations were presented for representative days of January and August. Solar-optical properties of glass were determined for beam and diffuse radiation accounting for varying solar incident angle. The ASHRAE clear-sky model was used to calculate the solar radiation.

The results showed that the peak heat gain in August was obtained for the west-facing window with values of 359.3 W/m<sup>2</sup>, 339.4 W/m<sup>2</sup>, and 311.7 W/m<sup>2</sup> for Riyadh, Jeddah and Abha, respectively. Values of the corresponding daily heat gain were 7.67 MJ/m<sup>2</sup>.day, 7.12 MJ/m<sup>2</sup>.day, and 4.39 MJ/m<sup>2</sup>.day for Riyadh, Jeddah and Abha, respectively. The daily heat gain was found to be practically equal for the east and west orientations. The north-facing window had the lowest instantaneous and daily heat gain for all cities since the solar heat gain was the lowest for this orientation. Based on the peak heat gain, and with regard to cooling requirement in August, the south and north orientations were the most desirable for all cities.

Future work will investigate using different types of glass as well as different climatic conditions. SHGC will be determined, and measurements of glass temperature will be conducted.

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