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Energy Efficient Design Optimization of a Building Envelope in a Temperate and Humid Climate

N. Sadafi[1]*, N. Jamshidi[2], M. Zahedian[3]

[1] *Department of Art and Architecture, Payame Noor University (PNU), Tehran, Iran*
[2] *Department of Mechanical Engineering, Payame Noor University (PNU), Tehran, Iran*
[3] *Department of Art and Architecture, Mazandaran University, Babolsar, Iran*

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A B S T R A C T

A building envelope plays a key role in controlling the internal environmental conditions. The evaluation of façade designs for naturally ventilated residential buildings in the temperate and humid climate of Iran was carried out to optimize façade design for energy saving. Firstly, the common types of building materials were identified through a field study. In the next step, a computer simulation was conducted to investigate the impact of façade design parameters, including U- values, window to wall ratio (WWR), the open able part of the window, and the length of shading devices on buildings energy consumption. The simulation results indicate that the building envelopes constructed with Lightweight Steel Framed (LSF), 3D Panels, and Autoclaved Aerated Concrete (AAC) blocks are more effective than the other investigated materials, for reducing heating and cooling loads of the building. Using these materials can reduce the energy consumption for heating and cooling by 45%. Large and unprotected windows increase the building energy demands and require additional control devices. Therefore, 25%WWR, with 300mm horizontal shading devices in four steps, light opaque internal curtains, and windows with low emission glass parts that are closed during noon and afternoon hot hours were suggested and analyzed for the studied climate.

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INTRODUCTION

Consumption of energy in the building sector in Iran is higher than the world average. Therefore, actions should be taken to reduce heating and cooling energy used if the country has to play a part in moderating the global problem of climate change and preserving fossil fuel resources [1]. Building envelopes as the primary interfaces between the outside and inside space play a fundamental role in controlling the environmental conditions, providing comfort for occupants, and determining the heating and cooling loads of the building. Studies have indicated that external walls have the highest thermal waste (29.8 %) compared to the other parts of a building [2]. Envelope performance containing windows, walls, and shadings, which affects the energy demands and electric lighting as well as daylight [3]. Therefore, to control the heat transfer, the selection of building materials, windows, and opening design are essential factors.

Several studies have calculated the thermal performance of materials in various conditions. The application of materials should consider the fact that location, weather, and user behaviour affect the energy performance of a building as well as the façade properties and design factors (building shape, volume and window configuration). The main façade features associated with energy performance are thermal quantities (e.g., u-value) and solar heat gain quantities. The main concerns of previous studies were either on particular building shape or a specific climatic condition [4, 5].

Considering the design factors, building configuration has been investigated as a factor affecting the annual energy demands of a residential area in Malaysia [6]. The

*Corresponding Author Email: *nsadafi@pnu.ac.ir* (N. Sadafi)

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findings emphasized the effects of a building envelope configuration such as shading and Window to Wall Ratio (WWR) on annual energy demands. As an example of considering the façade properties, the impact of external envelope insulation on minimizing the energy requirements have also been discussed in not only semi-arid continental regions such as Iran, but also cold regions such as Estonia [3, 7]. According to the results, well-insulated walls often reduce the building heating and cooling loads, while they tend to increase construction costs.

Naiji and Klaus [8] conducted residential building energy simulations studying the effect of thermal mass, total thickness, and weight of the wall surface unit on the maximum heating and cooling loads of buildings located in Tehran. They showed that thermal mass has higher effects on reducing the heating and cooling loads of the building in hot and dry climates. Sekhavatmand et al. [9] evaluated multiple types of materials for the external walls of buildings in Tehran using Energy Plus Software. The results indicated that changing the materials from the brick to the heblex, or three-dimensional (3D) panels can reduce the thermal loads to about 35% and 44%, respectively. Rezazadeh and Medi [10] studied the effects of double skin facades on the thermal comfort of the occupants in moderate and humid climate of north of Iran. The findings showed that these facades are more appropriate for cold seasons, and it is essential to consider a combination of natural ventilation and mechanical systems to increase thermal comfort inside the building.

Windows also distinguish energy use and visual comfort patterns in buildings. Choosing their material and proportions is a part of a fundamental early design stage decision, which is challenging to modify afterward. Therefore, window design is a crucial process and must be a part of an integral investigation process, considering various aspects at the same time. The desired WWR has been investigated to reduce the cooling, heating, and lighting energy demands of an office building in the Netherlands and Germany [11, 12]. The results indicated that WWR between 35% and 45% could achieve optimum configuration. At the same time, additional control devices, including solar shading systems, should be considered to achieve low energy consumption and visual comfort. Poirazis et al. [13] studied the effects of WWR, glazing type, shading, and orientation on buildings' energy consumption. They concluded that a lower WWR would decrease the energy demands of the building. A similar analysis was made by Motuzeine and Joudis [14], and it was found that the optimal WWR was between 20% and 40%, while in the cases with smaller WWRs, there will be issues to fulfil daylight requirements. Transparency is also an essential factor in improving the utilization of daytime lighting [15]. Nasrollahi [1] simulated office buildings, studying WWR, and different orientations and shadings in the hot and dry climate of Iran. Based on the results, the optimal WWR for windows with and without external shadings were 60 and 50%, respectively. The optimum length for the shading was one-ninth of the window's height.

Kosir et al. [16] studied optimizing building envelop configuration in the European temperate climate. Design parameters including building form, orientation, WWR, and shading were investigated. According to the simulation results, elongated building forms with larger glazing portion and appropriate shading are more energy-efficient than compact buildings with small or medium glazing portion. In the countries with higher mean daily temperatures, a decrease in windows U-value maximizes the cooling energy requirements of a simulated room [17]. On the contrary, investigations in some regions of the warm parts of Asia, have shown the close relationship between the low windows U-value and building energy savings [18]. Studies by Thalfeldt et al. [3] and Skarning et al. [19] considered both the thermal performance of solar shading and the effect of the shading on daylighting, visual comfort, or electricity usage for lighting in residential buildings. Although the conducted studies have shown that lowering WWR improves energy efficiency, it reduces natural light. Therefore, it is critical to set lower limits for window sizes.

Moolavi Sanzighi et al. [20] investigated the impacts of design variants, on the indoor thermal comfort for case studies in the temperate and humid climate of Iran. The results showed that contemporary residential buildings are not designed as efficient as traditional houses in this area, in terms of passive energy-saving techniques. There is a gap in detailded investigations about buildings' thermal behavior and energy performance in the humid and moderate climates of Iran. According to the importance of sustainability issues in developing countries, energy conservation should be considered more seriously in all stages of construction development. Therefore, this article investigated different assessments and factors for building façade design to evaluate the influence on the heating and cooling energy requirements of buildings via simulation. The aim is to evaluate the most common available facade materials and openings design in this region.

METHODS

To discuss the implications of a facade configuration on the energy consumption of a residential building located in a temperate and humid climate, a three-step method has been developed.

The first step consisted of a field study and analysis of the local expert's opinions about the characteristics of common building materials. Second, a basic simulation model was designed and tested within a specific built environment. Third, the study of the energy performance for curtain walls of the base model is performed. To this end, the effects of façade common materials, dimensions and configuration of windows and design of shading devices on total heating and cooling demands are assessed.

Field study

A survey was conducted to identify and evaluate different types of materials used in building envelopes in the North of Iran. 52 experts participated in the survey, from which 30% were civil engineers, 20.3% architects, 20% building developers, 23% structural engineers, and 6.7% mechanical or electrical engineers. As far as their education is concerned, 3% had a diploma, 3.3% held an associate degree, 77.1% obtained a Bachelor's degree, and 16.6% completed postgraduate studies. In terms of experience, 43.3% had one to five years of work experience, 40% five to ten years, and 16.7% had more than ten years of work experience. The questions of the questionnaires were designed to collect the respondents' assessment of the common materials concerning cost efficiency, ease of application, accessibility, and quality.

According to the results, the hollow clay block was introduced as the most popular material, by 60% of the experts. The existence of factories in the studied area provided cost efficiency and easy access to this material. Autoclaved Aerated Concrete blocks (AAC) were in the second place of popularity, according to 46.6% of the respondents. The principal mentioned positive features were ease of implementation and structural style. In addition, its porous structure had adequate thermal and sound insulation after building construction. Three Dimension (3D) panels had 43.3% of the expert's acceptance. The acoustic insulation caused by the middle polystyrene layer reduces the weight of the panels. Furthermore, they are easily accessible and cost-effective thanks to the local factories. The Lightweight Steel Frame (LSF) construction system is less popular among the constructors despite the lightweight and efficient struructure. The reasons were the absence of domestic manufacturers and professional workforces that increases the final cost of the construction projects.

Table 1. The results from field study and priorities of the respondents

Priority	Envelope material	Reasons
1	Hollow clay block	- Cost efficiency - Ease of access
2	AAC	- Ease of implementation - Structural style - Acceptable thermal and sound insulation
3	3D Panel	- Decreasing building's dead load - Cost efficiency - Ease of access
4	LSF	- Abcence of local manufacturers - Limited professional workforces - Incresed final cost

Simulation

In the next step, a five-storey residential building, which is a common type in the studied area, was simulated (Figure 1). The third floor in the residential model was chosen to study the effects of the envelope materials and opening design on the energy usage pattern of the building. The selected model was attached to other buildings from two directions (East and West) and free from the other two (North and South), i.e., only had two facades. The total area of the model was 193 m^2 (11.3 × 17.1), with a floor to ceiling height of 2.70m.

For simulation, Design Builder interface version 5 for Energy Plus was used as a building energy performance tool to create the model. DesignBuilder is a validated tool according to the EN ISO 13790 standard [21] for the calculation of energy used for space heating and cooling and fabric loads.

The real building properties and climate data were used for making the simulation model. The settings used for the base model are summarised in Table 2. The factors such as wall materials, WWR, glass types, curtain materials, shading devices and the windows openability percentage were assessed in the case of the residential base model for the best achievable energy performance. The weather data was used for the climate of Sari, Iran (36.0°N, 53.4°E), adopting IWEC file between 2017 and 2018 [22]. This region's altitude is 40m above sea level and has a temperate and humid climate characterized by limited temperature range, high relative humidity, and a large number of cloudy days. According to the recorded climatic data, the summer dry bulb temperature is 33.6 °C, and relative humidity is 55.89% while, the winter dry bulb temperature is -3 °C and relative humidity is 92% [23].

Envelope materials

Different types of common envelope materials in the region, were considered for the simulated building, while the properties of other parts were deemed to be constant. Table 3 represents the properties of the selected elements for the envelopes. Physical properties of the materials were adopted from previous researches.

Figure 1. 3D model of the simulated residential building in design Builder

RESULTS AND DISCUSSION

The effects of envelope materials on building loads

Heating load is the amount of energy required to reach comfort temperature inside the building during cold seasons. The heating load evaluated for one year is shown in Figure 2. According to the results, the highest heating energy demands in the building appear between December and February for the cases with less thermal insulation, such as brick walls (19747 Btu/h) and clay air brick without polystyrene insulation (16868 Btu/h). In buildings with external walls made of air brick with polystyrene layer, AAC blocks, and 3D panels, the consumption of heating energy decreases during that period. However, the lowest heating energy demand occurs in LSF buildings for the whole year, while the highest ammount is 8296 Btu/h.

On the other hand, the results from analyzing the required cooling load during one-year period shows that the building with the LSF external walls has the highest. Whereas during summer months, when the higher daily mean temperatures reach up to 27°C, the buildings with brick walls and clay air brick without polystyrene insulation will have the highest cooling loads compared to the other material types. According to the temperate and humid climate of Sari during autumn and spring months, increasing natural ventilation is vital to improve the internal air quality, while in summer, less interaction with the outside environment are preferable [24].

Table 2. Simulation settings of the base model

Building	Properties
Type of building	Residential
Orientation	North to south
Set temperature	Heating 18 cooling 25
Floor and ceiling	ceramic glazed 0.005m, Mortar 0.03m, Concrete Reinforced 0.3m, plaster sand aggregated 0.03m, plaster light weight 0.01m U-value: 1.261 W/m^2-K
Roof	Clay tile (roofing) 0.03m, Mortar 0.03m, Bitumen felt layer 0.01m, Concrete Reinforced 0.3m, mortar 0.01m, plaster sand aggregated 0.02m, plaster light weight 0.01m U-value :2.261 W/m^2-K
Windows	double glaze clear glass 6mm
Solar Heat Gain Coefficient (SHGC)	0.703
Window frame	UPVC U-value: 3.476 W/m^2-K
Shading	External steel shading 0.002m thickness
HVAC	Cooling: electricity, Heating: Natural Gas
Airtightness	0.5 ac/h
Lighting system	LED lighting system with linear light control

The effects of window to wall ratio (WWR) on building loads

Simulation cases with several WWRs of 15, 25, 35, and 45% were generated for each facade to find the optimal size of the windows, decreasing building energy usage and natural lighting exploitation. Figure 3 compares the variation of the received solar energy from widows with different sizes throughout the year. Larger windows cause higher solar gains, however, a 10% increase of the windows from 15% WWR to 25% WWR leads to a larger solar gain, from 19000 to 40000 Btu/h in April, compare with those of from 25 to 35% WWR (from 40000 to 55000 Btu/h in April) and 35 to 45% WWR (from 55000

Table 3. Element properties used in the simulation

Envelope material	Thickness (mm)	Conductivity (W/m.K)	U-Value (w/m^2.k)	Ref.
Brick	220	0.78	3.5	[25]
AAC concrete block	280	0.19	0.71	[7]
LSF with a middle layer of mineral fiber insulation	295	0.052	0.3	[26-28]
Clay air brick with an air layer insulation	230	0.51	2.4	[25]
Clay air brick with Polystyrene insulation	230	0.24	1.08	[7]
3D panel	150	0.53	0.53	[29]

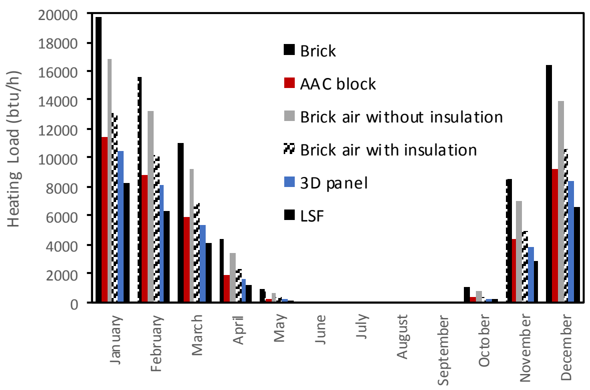

Figure 2. Comparing the effects of external walls material on annual heating load

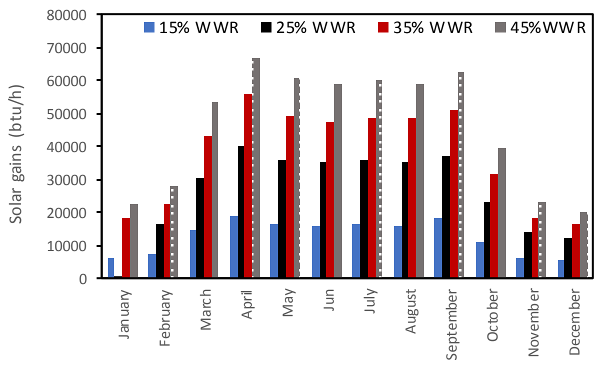

Figure 3. Comparison of building's solar gain with different window sizes

to 65000 Btu/h in April). Besides, the primary heat gains are happening during the early spring and the late summer days because the angle of sunbeams during these periods penetrates inside the house more than other times of a year.

It is observed that increasing the size of the windows improves the utilization of solar energy inside the building and decreases the use of electricity for lighting. Therefore, it will reduce the heating load of the building, especially during spring. According to the results, penetration of the sunbeams during the hot months of summer increases the cooling loads of the building.

According to the results, considering WWR of 25% for envelopes optimises the building loads throughout the year. The variation of energy consumption demonstrates that in a temperate climate, using larger windows becomes counterproductive, because it provides larger areas for heat transfer during both winter and summer. It is shown that enlarging window size for South orientation results in higher cooling demands, while larger window sizes for North orientation will increase the heating loads. Though, the window size cannot be reduced inconsistently because the consumption of electricity for illumination becomes an issue, as well as visual comfort. The highest energy consumption was observed for 45% WWR, (413000 Btu/h in July and Auguest), while for 15% WWR, the heating load will increase in 9 months of the year . Conversely, solutions with lower energy consumption, have the most inferior visual performance. It can be perceived that decreasing the complexity of the studied system shows the difficulties in fulfilling all the criteria. Therefore, additional building elements such as blinds, shades, and improved glazing must be considered to control solar radiation, light amounts, and glare. Generally, our findings are in good agreement with the results reported by Moolavi Sanzighi et al. [20]. They found that the building with the optimum WWR of 24% consumes the minimum energy in a temperate climate. From the described situation, it becomes evident that at large glazing areas, shading of windows becomes essential. It can help to analyze the cases in which shading can improve critical conditions.

Evaluating the effects of solar shading on building energy usage

In this step, to investigate the effects of shape and length of the shading devices on the energy usage of the building, an optimal size of 25% WWR was considered for the windows, and different types of shading devices were applied. Figure 4 shows the amount of solar heat gains through the windows after installing the shading devices. According to the width of the shading devices, the amount of received energy during summer months has a substantial decrease. Increasing the depth of the horizontal canopies from 300 mm to 600 and 900 mm, decreases the heat absorption considerably. However, the lowest cooling load of the building is perceivable when four 300 mm horizontal shading devices along with the height of the windows were applied. Besides, during the hottest months of the year (May to July) 600 mm overhang with side fins seemed more practical. The study conducted by Ramli [30] also showed that devided shadings are more suitable during the afternoon in order to reduce heat from direct sunlight as well as to avoid glare for the occupants.

Evidence suggests that the effect of horizontal shading devices on the prevention of solar penetration in hot seasons and the possibility of heat and radiation absorption in cold seasons are more suitable than vertical shading devices. Because the wider fixed shading devices will decrease the penetration of sunbeams in cold seasons, the total heating load of the building does not change considerably after installing the shading devices. Obviously, applying moveable shading devices can improve the conditions.

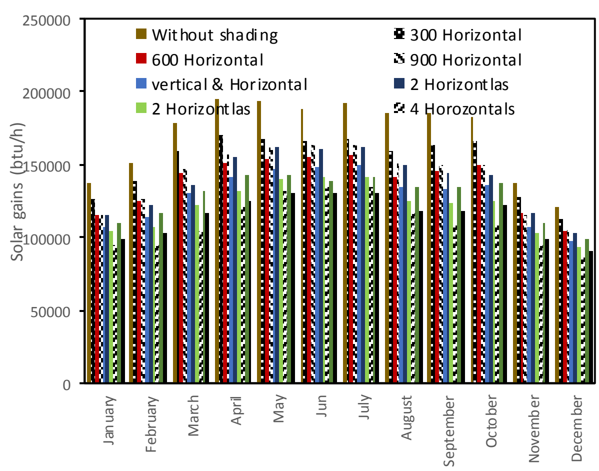

Figure 4. Comparison of the amount of windows solar absorption in case of different shading devices application

The effects of windows glass material on building loads

Five types of glass materials were applied for the windows: single glaze, double glaze, absorptive, reflective, and Low Emission (Low-E). It was perceived that the reflective glasses reduce the cooling loads of the building during summer months, from 400000 to 350000 Btu/h. However, due to the decrease in the absorption of lighting and heating energy of the sun, it will increase the heating load of the building during the cold months considerably from 18000 to 2000 Btu/h in January (Figure 5).

According to the variation in cooling and heating loads of the building with a different choice of window's glass material, the Low-E glasses will improve the heating and cooling loads of the building more effectively through the year. The Nano cover on these glasses reduce the total u-value from 3.1 to 2.5 W/m^2-K, and provides better UV protection [25]. Increasing the size of the windows to 35%WWR and 45%WWR have also resulted in the same conditions with a higher increase in heating and cooling loads differences. Results reported by Abdoly Naser et al. [31] also showed glazing with low emission coating will decrease, heat loss decreased and annual gas consumption. While reflective coatings on the surface of the glass reduce the receipt of solar energy by 90.86% and therefore this type of glazing is not suitable in cold seasons.

The effects of internal curtains on building loads

Five different types of curtains were applied on the inner side of the windows: closed weave dark drapes, closed weave medium drapes, closed weave light drapes, shade roll-light opaque, semi-open medium drapes. According to the evaluations, the dark and closed wave drapes increase the cooling load of the building due to the higher heat absorption rate in hot seasons (from 320000 to 380000 Btu/h in August). On the other hand, they decrease the heat transfer in cold seasons, and thus reduce the heating load of the building. However, due to the reduction in the penetration of natural lighting, from 11000 to 10000 Btu/h in March, the use of electricity for illumination will increase (Figure 6).

Light opaque shade roll and closed weave light drapes reduce the heat absorption during the day, and consequently decrease the building's cooling loads in hot months of the year. All in all, they show an improved performance regarding reducing building loads and natural lighting absorption.

The effects of natural ventilation on the building's heating and cooling loads

In this step, the window control was set up, and partially opened windows were defined in different times of the day to monitor the effects of natural ventilation on the cooling loads of the building during the hot months. The operation time was 24 hours on weekdays with various open factors between 25 and 100%. The evaluated cases are summarized in Table 4.

The simulations' results showed that the building experienced lower cooling loads when the windows were closed in hot hours of the day (12 pm to 4 pm) and partially opened at other times (Figure 7). On the other hand, the highest amount of cooling load was perceived when 25% of the window was opened from 7 pm to 7 am and closed from 7 am to 7 pm. The second highest amount was experienced when the windows were opened 25% all the time to meet the requirement of minimum fresh air and velocity.

According to the results, it is perceivable that increasing the percentage of windows' open parts have improved natural ventilation inside the building, and night cooling has a great impact on cooling load of the building in summer. Hence, for the conditions that the windows were opened 100% from 12 am to 8 am the lowest values of cooling loads were perceived.

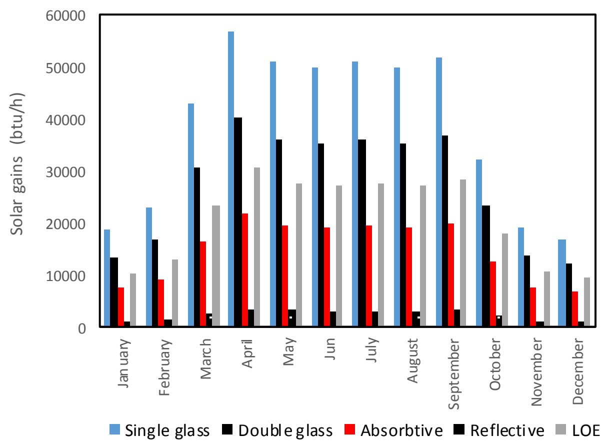

Figure 5. Windows solar gains with different glass materials

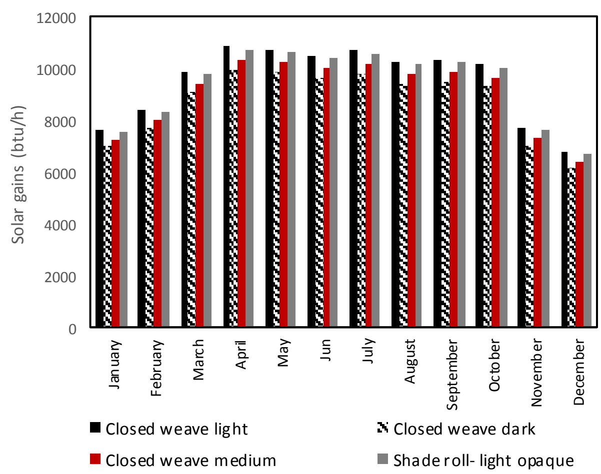

Figure 6. Building solar gains with different materials for internal curtains

Table 4. Evaluated cases with different open factors for windows

Condition	Time	Open factor	Condition	Time	Open factor
1	Day and night	25%	9	8 am to 12 pm	25%
2	Day and night	50%		12 pm to 4 pm	-
3	Day and night	75%		4 pm to 12 am	25%
4	Day and night	100%		12 am to 8 am	100%
5	7 pm to 7 am	25%	10	8 am to 12 pm	50%
	7 am to 7 pm	-		12 pm to 4 pm	-
6	7 pm to 7 am	50%		4 pm to 12 am	50%
	7 am to 7 pm	-		12 am to 8 am	100%
7	7 pm to 7 am	75%	11	8 am to 12 pm	75%
	7 am to 7 pm	-		12 pm to 4 pm	-
8	7 pm to 7 am	100%		4 pm to 12 am	75%
	7 am to 7 pm	-		12 am to 8 am	100%

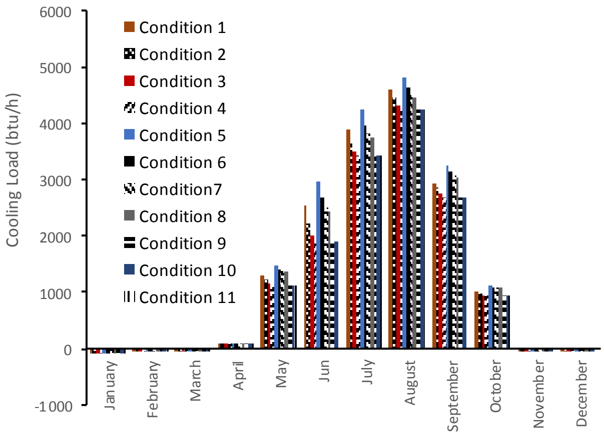

Figure 7. Comparison of building cooling load with different percentage for open able part of the window

CONCLUSION

The reduction of energy consumption in the residential sector is among the top priorities of the Iranian government. Adopting suitable envelope materials and windows design, can significantly contribute to reducing residential energy demand. This study identified the building with LSF structure with the lowest energy usage followed by 3D panels and AAC cement blocks in temperate and humid climate of Iran. The window size has to be optimized for more than one objective, because of its influences on energy consumption and visual comfort. The larger WWRs improve factors such as view and natural lighting. On the other hand, the smaller WWRs, address privacy and energy saving. According to the findings, such objectives can be satisfied by a 25% WWR window size. It was observed that external shading devices are more effective than internal curtains since the internal devices absorb solar heat and radiate inside the building. In addition, horizontal shadings provide better energy performance in cold and hot seasons compare to the vertical fins. Since wider horizontal shadings cause lower cooling loads in warm seasons, the adjustable shadings would improve the absorption of solar radiation in cold seasons. The evaluated materials for curtains and windows glasses considering the quality of luminosity as well as energy usage throughout the year suggested that light-wave and opaque curtains and low emission glasses are suitable in this climate. Furthermore, it is more appropriate to close the windows during hot hours of the day (12 pm to 4 pm), open them during the night (12 am to 8 am), and make them partially opened during the other times to optimize the natural ventilation and reducing cooling loads in summer months.

The approach for designing energy-efficient building facades requires systematic investigations of different design options, and an ideal solution is based on the building's location, climate, building type, etc. This study can be extended to other types of buildings in moderate and humid climate, additional building components, and shadings.

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Persian Abstract

چکیده

پوسته ساختمان نقشی اساسی در کنترل شرایط محیطی داخلی دارد. ارزیابی طراحی نما برای ساختمانهای مسکونی در آب و هوای معتدل و مرطوب ایران به منظور بهینه‌سازی مصرف انرژی در این اقلیم مورد توجه قرار گرفته است. ابتدا، انواع متداول مصالح ساختمانی از طریق یک بررسی میدانی شناسایی گردید. در مرحله بعدی، شبیه‌سازی کامپیوتری جهت رسیدن به یک مدل بهینه از کاربرد مصالح انجام شد. تأثیر پارامترهای طراحی نما از جمله مقادیر هدایت حرارتی، نسبت ابعاد پنجره به دیوار، قسمت بازشوی پنجره و طول سایه‌انداز بر مصرف انرژی ساختمان بررسی گردید. نتایج شبیه‌سازی نشان می‌دهد که پوسته‌های ساخته شده با اسکلت فلزی سبک، پانل‌های سه‌بعدی و بلوک‌های بتن هوادهی اتوکلاو برای کاهش بارهای گرمایش و سرمایش ساختمان از سایر مواد بررسی شده در این اقلیم موثرتر می‌باشند. استفاده از این مصالح می‌تواند مصرف انرژی را برای گرمایش و سرمایش تا ۴۵٪ کاهش دهد. پنجره‌های بزرگ و محافظت نشده انرژی مورد نیاز ساختمان را افزایش می‌دهند؛ بنابراین نسبت ۲۵٪ سطح پنجره به دیوار همراه با سایه‌بان افقی ۳۰۰ میلی‌متری در چهار قسمت پنجره، پرده‌های داخلی مات سبک و پنجره‌هایی با قطعات شیشه‌ای با انتشار کم که در ساعات گرم ظهر و بعد از ظهر مسدود هستند، برای آب و هوای مورد مطالعه تحلیل و پیشنهاد گردید.