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Investigating the Impact of Exterior Window Shutters on Indoor Climate Conditions in Humid and Temperate Climate

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ABSTRACT: Improving the thermal comfort of occupants in indoor spaces is one of the objectives of improving building construction techniques. In temperate and humid climates, window shutters are utilized as a protective shield during storms. They can also block the view from the outside environment into the room. In this study, we looked into how the inner climate condition was affected by various design patterns of these flexible envelopes. Vernacular architecture in humid and temperate climates can be used to describe different window shutter sizes and shapes. These shutters include both entirely rigid or perforated types. Window shutters are utilized as adjustable enclosures outside building windows that allow occupants to adjust their position or location. Occupants in this area frequently open windows during extreme heat to ventilate the building and enhance the inner climate.

In this regard, while using natural ventilation, we compared the twelve sample models with window shutters with various opening inlets to those without these flexible envelopes. We concluded after looking at several variables that flexible envelopes with an inlet area of 12.5% to 25% of the flexible envelopes produce better inner climate conditions.

Keywords: *Hygrothermal Performance, Vernacular Architecture, Building Envelope, Window Shutter.*

INTRODUCTION

The building envelope acts as a barrier between the exterior and interior spaces. The building's envelope is subjected to various climatic conditions, and it must consider aesthetic and socio-cultural factors in addition to security and environmental protection. It should be noted that there are two types of building envelopes: static and flexible. A structure that can be repositioned or deformed is called a flexible envelope. According to the definition of flexible automatic envelopes, these are described as building skin that can change its properties and control the various parameters of building skin. These adjustments are made in response to changes in climatic loads or indoor environments to improve the comfort of the occupants (Shahin, 2019). A good example of Adaptive Buildings envelope application in traditional architecture is the Japanese house, which exhibits high envelope adaptability due to its movable "shoji" screens and "Amado" shutters. The main difference between traditional and modern Adaptive Building envelope systems is in the level of control, whereas traditional solutions rely on manual control with high margins of error. In contrast, modern solutions must be automated to satisfy the increasingly high demands of users regarding accuracy (Košir, 2016). Due to the ever-changing boundary conditions around building envelopes, the use of flexible envelopes such as shutters, curtains, vegetation, or even modern, flexible envelopes can provide the occupants of space with thermal comfort (Golabchi et al., 2012).

Window shutters can also be defined as flexible envelopes operated by users. The inhabitants of the space use natural ventilation to improve the indoor climate condition. Due to temperatures above 33°c at certain times of the year and the high relative humidity, we believe using natural ventilation without window shutters can't improve the inner thermal condition. It seemed that in such conditions, the high air flow would create conditions similar to the outdoor space in the indoor space. By investigating all of the factors influencing the indoor environment and monitoring the hygrothermal performance of building envelopes in such conditions, a suitable model for developing flexible envelopes that improve inner climatic conditions during thermal peak conditions can

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be introduced. Research on the effect of the hygrothermal performance of building envelopes on indoor climate has been undertaken.

Hygrothermal envelope properties on a material level determine how the envelope will perform under given boundary conditions in heat and moisture transport. The hygrothermal performance of building elements or the building cannot be described solely based on the hygrothermal behavior of individual materials (Bagarić et al., 2020). The hygrothermal performance of building envelope systems (walls, roofs & floors) exposed to outdoor climate is affected by the initial moisture content, intentional and unintentional moisture leaks, diffusion of indoor air, and air infiltration/exfiltration between indoor air and the structure (Salonvaara & Ojanen, 2003). The building envelope's hygrothermal performance influences the service life of the building, energy needs, indoor comfort, and indoor air quality, which is directly related to the health of occupants (Bagarić et al., 2020).

A simulation should be done to investigate the hygrothermal behavior of the building envelope because it is cheaper and more detailed than the test in situ. For this to be done, many simulation tools have been developed. Hygrothermal properties are required for all Heat, Air, and Moisture transfer (HAM) models (Le et al., 2015). Due to the transient conditions of the environment, accurate and appropriate simulation software should be used to investigate the hygrothermal performance of the wall, and its validation should be performed. Several studies have been conducted on the hygrothermal performance of building envelopes in indoor climates (Glass et al., 2013). WUFI is well-known as one of the most popular software for calculating a building's hygrothermal performance, and it has been used in numerous studies (Parker & Lozinsky, 2010). Holm and Künzel used WUFI, a computer program that calculates the transient heat and moisture transport in building components, to predict, under natural climatic conditions, the moisture and temperature strains that act on an ETICS with mineral wool insulation (Tadeu et al., 2018).

Karagiozis and Salonvaara evaluated the full-house hygrothermal performance of an aerated concrete wall system (Karagiozis & Salonvaara, 2001). Karagiozis evaluated the influence of airflow on the moisture performance of a residential building envelope system. It showed that air leakage through the building wall system significantly affects the wall's hygrothermal performance (Karagiozis, 2020). Pozas and González used Design Builder to diagnose the hygrothermal behavior inside the vernacular housings of the Jerte Valley showed. They provided various conditions to improve thermal comfort in different building parts based on Givoni's chart (Montalbán Pozas & Neila González, 2016). Steeman et al. research focused on accurately modeling the hygrothermal interaction between the building and its hygroscopic content to assess the indoor climate (Steeman et al., 2010). Desta et al. research report experimental studies on heat, air, and moisture (HAM) transfer through a full-scale lightweight building envelope wall under real atmospheric boundary conditions (Desta et al., 2011). Much research has been conducted about the effect of natural ventilation on inner thermal conditions. For example, Kasmai has discussed the effect of breezes on inner climate conditions in temperate and humid areas (Kasmai, 2003) and Ghiabaklou has discussed the effect of different openings on indoor airflow (Ghiabaklou, 2013). Gao and Lee (2011) evaluated the influence of opening configuration on the natural ventilation performance of residential units in Hong Kong. They stated that the relative position of the two window opening groups (bedroom windows and living room windows) was the most affecting parameter (Gao & Lee, 2011). However, research on the effectiveness of natural ventilation in extreme heat and humidity conditions in such a climate (mountainous part of Golestan) concerning the hygrothermal performance of the building has not been done.

The effect of flexible building envelopes (window shutters) on the inner climate condition of the building when inhabitants open windows to provide natural ventilation through their space was investigated. Golestan in Iran was chosen as a temperate and humid region with a mountainous climate that differs from other temperate and humid regions for this study. The main question of this research is whether it is possible to improve the internal climate conditions while using natural ventilation through external window shutters with a design pattern similar to those in vernacular architecture.

The purpose of this research is to Investigate the impact of window shutters on the hygrothermal performance of buildings to investigate the comfort that the building provides for residents during overheating.

During extreme heat and humidity conditions, residents use natural ventilation by using building openings to improve indoor climate conditions. At such times, the effect of natural ventilation on internal climate conditions can be investigated due to the presence of such external elements on the openings concerning the thermal performance of all the walls of the building.

Climate and Architecture

Golestan fits into the moderate and humid areas of Caspian Sea shores among Iran's four climatic divisions. The more we go towards the east on the southern shores of the Caspian Sea, the less humidity and rainfall there is. In this area, the average temperature is between 25 to 30°C in summer and 0 to 5°C in winter (Kasmai, 2003).

Golestan is located southeast of the Caspian Sea between the northern ranges of the east Alborz mountains and the Atrak river. According to the research of Soltanzadeh and Ghaseminia, the Golestan climate can be divided into three regions. The plain of Gorgan has cold winters and warm and very humid summers. The average minimum temperature is 9/67°C from December- January, and the average maximum

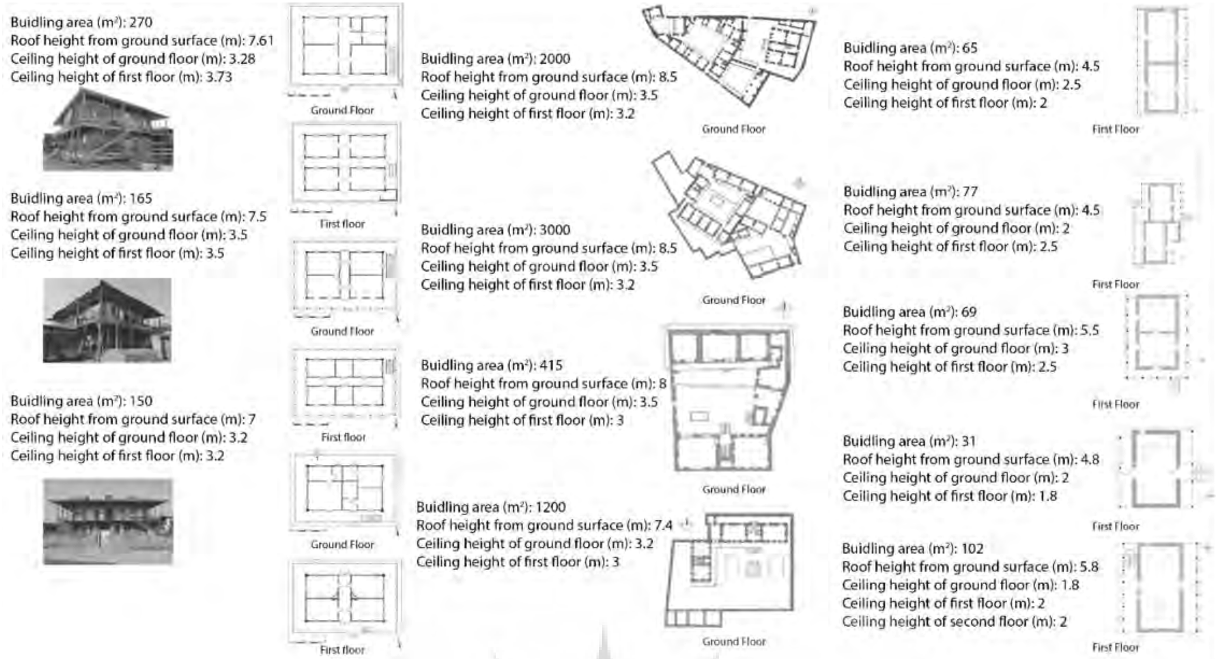


Fig. 1: Vernacular architecture type in Golestan (from left to right: Gomishan, Gorgan and mountainous area (Soltanzadeh & Ghaseminia, 2016, 56-59)

temperature is 28/95°C from July-August. The prevailing wind is from west to east (Soltanzadeh & Ghaseminia, 2016). The vernacular architecture types in this zone (Gomishan) are shown in Fig 1.

Hillside areas have moderate and humid climates. This area is located in the south and the east of the province and at the foot of the mountains. According to the statistics report of 12 consecutive years from the Synoptic weather station in Hashem Abad, the maximum temperature in Gorgan is 33/1°C and the average of its minimum is 4/1°C. The vernacular architecture types in this zone (Gorgan) are shown in Fig 1.

The mountainous area is located at the extension of the east Alborz mountains from the west to the east and gradually tends towards the north, wherever the height is low. These areas, with less than 1000-meter altitude, have moderate and humid weather surrounded by jungles. In areas with 1000-meter Hight and more, the density of jungle and humidity of weather gradually reduce. In winter, due to the blowing of Siberian winds in the mountains, the density of clouds amount of snow and rain in this climate increases, and the weather becomes very cold, while it is moderate in summer (Soltanzadeh & Ghaseminia, 2016). The vernacular architecture types in this zone are shown in Fig 1.

Vernacular architecture of the humid climate in Iran includes a large part of lands south of the Caspian Sea that have been neglected over time. In most traditional areas of local and modern architecture, architects in these regions should study the climatic conditions to develop appropriate and useful ideas and provide solutions suited to the climate (Galogahi et al., 2016). During recent years, construction to construct rather than living has left no opportunity to focus on important issues such as taking advantage of natural conditions and building consistency with climatic conditions. Due to high humidity and rainfall, especially in rural areas, most buildings are made apart and away from each other, and due to the abundance of wood in this area, the buildings are mainly built of wood or light materials and then covered by steep rooftops (Galogahi et al., 2016). Ventilation has been an inseparable part of vernacular architecture; however, due to building density and modern architecture, optimal use of wind energy is no longer considered an internal ventilation factor. Though, regarding the high humidity of moderate and wet climates required for creating a natural draft, natural ventilation can be helpful in buildings (Galogahi et al., 2016). Protection of the openings from solar radiation during summer, especially in the plain zone and mountain foot region, is provided by using movable shades such as external wooden shutters that permit the dwelling to be fully shaded during the summer but fully exposed to solar radiation in the winter (Soltanzadeh & Ghaseminia, 2016). Examples of window vernacular shutters and openings are shown in Fig 2.

The height of buildings is lower and more emphasis is placed on massive structures and materials with better thermal capacities in studied examples of mountainous regions, where temperatures are lower, and winters are colder. In these units, the proportion of length to width has been increased. On the

Fig. 2: Examples vernacular window shutters and openings in the climate

other hand, the width of the shade and verandas and also areas of the openings have been reduced to a great extent. Besides, the orientation of openings on the northern and eastern sides and the status of residential parts on the upper ground floor provide the possibility of better ventilation in warm seasons (Soltanzadeh & Ghaseminia, 2016).

The materials used in building envelopes can generally be divided into massive and lightweight. Examples of massive wall construction materials include rubble and earth, wood covered with packed earth, rammed earth, adobe bricks, large wood timbers, and a large stone with earth or mortar as the binding agent. On the contrary, non-massive, lightweight structures are made with thatch, wood, bark, or bamboo. It should be noted that many vernacular dwellings observed combine massive walls with lightweight roofs, most frequently thatch roofs. When the climate becomes warmer and more humid, lightweight building envelopes and materials become more prevalent (Soltanzadeh & Ghaseminia, 2016).

Aliabad Katoul region with CS climate was chosen for experimental studies based on climatic conditions in the Golestan. The houses in this area are two stories tall, with the lower floor dedicated to warehouses and the upper floor dedicated to living. Figures 3 and 4 illustrate two different building types in this area.

Most of the buildings in this area have plenty of openings. The plans for these houses were linear, and the rooms were arranged linearly, with wide porches on the southern side. In addition to the high humidity in this area, the temperature rises above 33oC during the summer, causing discomfort to those accustomed to the climatic conditions.

Removing the extremely high humidity from people's bodies by the mountain generates thermal comfort in this climate. When these breezes are absent, people experience thermal dissatisfaction. This study aims to assess the effects of different window shutter types when using natural ventilation to enhance indoor climate conditions.

Fig. 3: Examples of vernacular buildings in the climate\

Fig. 4: Examples of vernacular buildings in the climate

MATERIALS AND METHODS

The paper is built on a mix of research methods, including field research, archival research, and simulation. After reviewing the relevant literature, a building in the desired climate was chosen to simulate hygrothermal performance and software validation.

To more accurately simulate the building and validate the software, we recorded environmental data in the building. This study collected the relative humidity and air temperature intensity to measure the building's environmental factors during the intense summer heat periods for a week in July. Two UNI-T UT333 BT data loggers were used to collect relative humidity and air temperature, with an accuracy of ± 5% for relative humidity and ±1 ° C for air temperature. The instruments were calibrated and used for the first time in this study. Therefore, factory calibration is considered appropriate for this study. Bluetooth connection to the smart device (data logger software) was used to record the data, and the data recording rate was once every minute. For one week in July, data loggers monitor and record environmental factors from 10:00 a.m. to 6:00 p.m. The reason for choosing July is the warmest period of the year this month when the need for cooling strategies is felt more and more. The location of the data loggers is in the outdoor space (porch) in the northern part and the shade at the height of 1.2 meters; the other is inside the residential space in the middle of the space at the height of 1.2 meters above the ground. The information obtained from this step was used to validate the software and modify a weather file for the simulation software. Data were recorded when the building windows were open to investigating air flow intensity's effect on relative humidity and indoor air temperature when the air flow was equal for two consecutive hours. As shown in Fig 5, the values recorded for one day at the site for the external environment were as follows.

After the field study stage, we modeled our sample building in Sketchup. We used WUFI Plus 3.2 and imported our model to simulate the hygrothermal performance of sample buildings in the relevant climate. WUFI Plus is a whole building simulation software that can simulate the indoor environment and is thus appropriate for addressing building comfort and energy consumption.

This software's essential input data includes different layers of the building walls, building orientation, initial temperature humidity conditions, and the desired time. Materials and weather conditions can be chosen from pre-existing databases in WUFI® software or other sources.

Furthermore, to analyze the impact of the envelope's hygrothermal performance on the inner climate condition, we needed to model the entire building with all its components and input a large amount of data. We compared our on-site recorded building components to the WUFI library and edited some of their properties. For the initial condition of the software, we used the site's recorded temperature and relative humidity. Weather file information was created using information from the regional meteorological organization and Meteonorm 7.3, and it was verified using data recorded in the environment. The simulation ran during the warm months of the year due to the occurrence of very harsh conditions in this climate during these months. The building was initially modeled with existing conditions without flexible envelopes to compare different conditions. These simulations were carried out for a variety of circumstances.

- Natural ventilation + wind-driven rain
- No natural ventilation + wind-driven rain

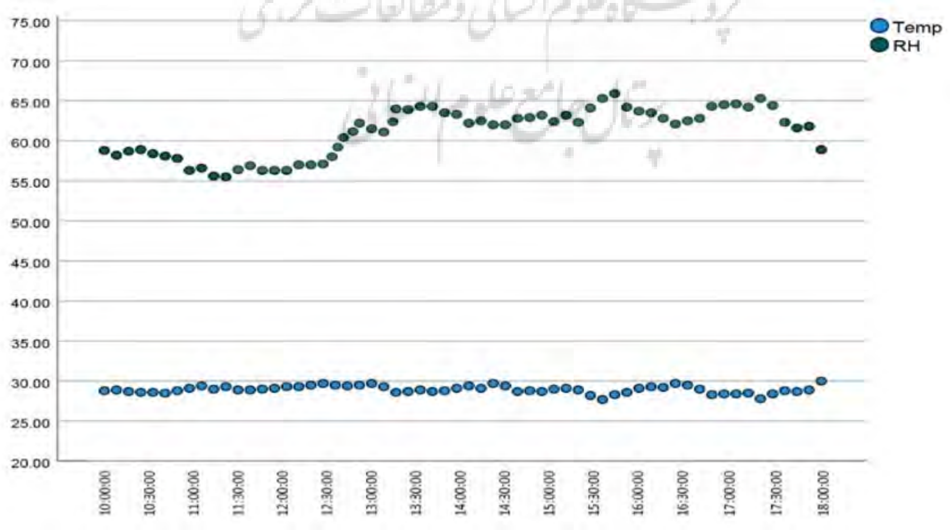


Fig. 5: Data recorded by Datalogger for one day

- Use of natural ventilation + absence of wind-driven rain
- Absence of natural ventilation + absence of wind-driven rain

Following the previous step, standard conditions for new simulations were chosen based on the results, and the building with different flexible envelopes was used in hygrothermal simulations. These flexible envelopes have variable-area inlets. The other input data for the software includes the rate of metabolism and clothing resistance of the residents, their hours of presence in space, and their daily work schedule.

Finally, the results of this stage and the previous stage were compared, and the best option was chosen based on the adaptive thermal comfort conditions. We used the empirical validation method to validate the software, comparing recorded data from the sample building to calculated results from WUFI. The software produced similar results with a small percentage difference.

Description of the Case Study

In this study, we chose a building with a common construction method in Golestan's mountainous area (in Aliabad Katoul villages with a climatic classification of Cs). We investigated the impact of exterior window shutter shapes on the inner climate of the building when windows were opened during overheating. We used a whole-building hygrothermal simulation tool for this purpose. The chosen building was located next to three similar buildings in Aliabad Katoul's Rig Cheshme in the mountainous terrain of Golestan. Given that the new buildings in this region were substantially equivalent to this building in terms of construction methods and materials and that most of these structures had nearly identical floor plans, we chose this building as our case study. The sample building has two floors. The lower floor is a warehouse in this climate's vernacular architecture. The building has a large nourth porch with a width of 3 meters and a length of 10 meters, and most of the unit's windows open to this space. The unit's entrance is provided by a staircase leading. Because the living space in all vernacular buildings in the climate is on the second floor, this study was conducted on that floor. During the warm days, most residents interact. Figure 6 shows the sample building as well as the assembly of surrounding buildings. The structure has a double-sided sloping roof made of galvanized sheets.

This unit has two entrance doors, two interior doors, and six windows, one of which is in the restroom, and all windows can be opened during hot summer days. The other five (except the restroom window) are all the same size and have an area of 0.912 m^2. There is only a ceiling fan in the living room. The window frames are made of wood and have single uncoated glazing, but the building does not have window shutters. As shown in Fig 7, this unit has one bedroom, a total area of 43.66 m^2, and the second floor is located at the height of 3.55 m above ground.

After all the data related to the building was recorded, the model was developed in Sketchup and then prepared according to the requirements of WUFI Plus. Fig 8 shows the initial Sketchup model (left figure) and the final WUFI Plus model (right figure). To transfer the file to WUFI Plus, the depth of all surfaces and unnecessary elements in the model must be removed. The stairs were removed in the final modeling to properly simulate and reduce heavy calculations, and the fences around the porch were removed due to their minimal impact on airflow. The thermal zones were also defined in the model. This building has three thermal zones: interior space on the first floor, unheated attic space, and ground floor space. The modeling was completed by defining the thermal spaces on each surface side, and the components' various functions were determined and then transferred to WUFI Plus.

Fig. 6: The sample building and its surroundings in the climate

Fig. 7: First-floor plan of the building

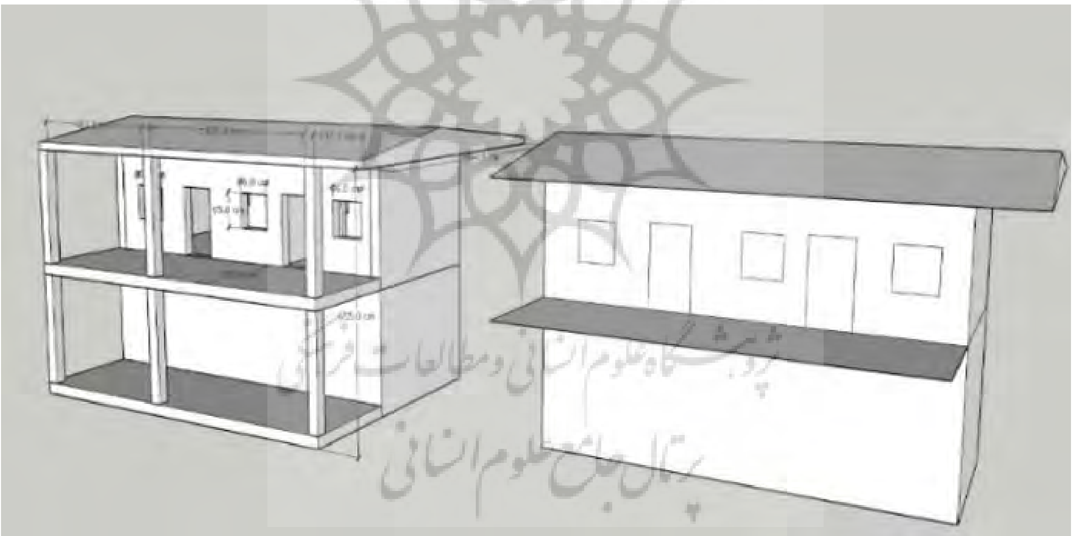


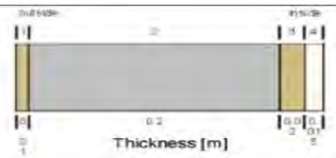
Fig. 8: Simulated models in SketchUp and final model based on WUFI Plus requirements

Figure 9 illustrates the building's exterior walls. This envelope had a total thickness of 24.5 cm and a U-Value of 1.758 W/m2k. For this component, the short-wave radiation absorption is set to 0.4, and the long-wave emissivity, surface to the outer air, is set to 0.9 using the WUFI library. The constant related shading factor is set to 1 (no shading), while the solar radiation on the inner surface is set to 0.42. We used Wufi Library for Sd-Value and rain load coefficients for each component. For each component, we calculated heat and moisture transport. These walls have not been painted on any sides.

Figure 10 also illustrates the ceiling and floor components of the unit. The key point is that the floor in the case study building has no flooring, and only the concrete layer is used. A hollow space in the attic (above the conditioned zone) protects the horizontal ceiling from rain. This layer includes a concrete core with a thickness of 25 cm and a layer of concrete screed with a thickness of 5 cm on the top layer with mud plaster and interior plaster on the inside layer (bottom layer). The solar radiation on the inner surface of this component is set to 0.226.

In addition to the main exterior walls, this building has interior

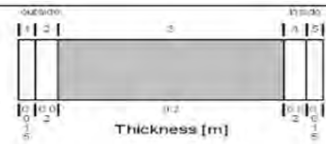
Homogenous layers
Thermal resistance: 0.399 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 1.758 W/m²K
Thickness: 0.245 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Mud Plaster	1514	1000	0.59	0.01	
2	Concrete Brick	2315	800	0.733	0.2	
3	Mud Plaster	1514	1000	0.59	0.02	
4	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.015	

Fig 9. Exterior wall layers

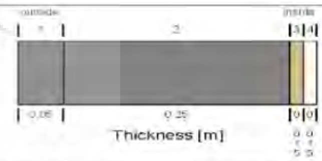
Homogenous layers
Thermal resistance: 0.623 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 1.133 W/m²K
Thickness: 0.27 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.015	
2	Gypsum Plaster	1721	850	0.2	0.02	
3	Concrete Brick	2315	800	0.733	0.2	
4	Gypsum Plaster	1721	850	0.2	0.02	
5	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.015	

Fig 10. Ceiling and floor layers

Homogenous layers
Thermal resistance: 0.314 m²K/W (without Rsi, Rse)
Heat transfer coefficient (U-value): 1.946 W/m²K
Thickness: 0.33 m



Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Concrete Screed, top layer	1890	850	1.6	0.05	
2	Concrete	2104	776	1.373	0.25	
3	Mud Plaster	1514	1000	0.59	0.015	
4	Interior Plaster (Gypsum Plaster)	850	850	0.2	0.015	

Fig 11. Interior wall layers

partition walls, the specifications of which are shown in Figure 11. Their total area inside the space is equal to 10 m2. Because the internal restroom wall was not used in the simulation, the details of that part were not included. Solar radiation on the inner surface is set to 0.052 for this combination. The inner surface Sd-value (material resistance to vapor diffusion) was set to 0.1 (m) for inner and outer surfaces based on its final surface coating.

The window frames are wood, and the glazing is a single layer. The structure has five windows with a total area of 4.7 m² and is located 4.45 m above ground. They don't have any solar protection, and the overall insulation properties (Uw-value) for these windows, including all their components, are 5.05 W/m2k. The depth of the window reveals were 5 cm.

We utilized the WUFI library to input data for each layers of building envelopes. Some of the specifications of layers were modified based on article 19 of Iran's National Building code. In this simulation, the discharge coefficient of the opening is equal to 0.6, and the width and height of the openings are equal to 0.96 m and 0.95 m, respectively (the openings have the same dimensions). To simulate different modes and compare the effect of different flexible envelopes shape on inner climate condition, we first simulated the building in four different modes with the existing conditions. We investigated the simulation with and without natural ventilation in these cases and in two cases with and without the effect of wind-driven rain.

Next, we simulated building with different window shutter shapes based on our previous simulations with natural ventilation. Finally, we summarized the findings of these 16 simulations. The shutters were made of wood with a thermal resistance of 0.556 m2K/W and a thickness of 5 cm. The short-wave radiation absorption and long-wave emissivity were set to 0.4 and 0.9, respectively. The frames had not any coating. Fig 12 illustrates the window shutters used in the second series of simulations. We set out design condition minimum and maximum values to 22°C ad 27°C, respectively, and the relative humidity is set to 30% for minimum value and 60% for maximum value.

Based on field data, the initial temperature and humidity for the room conditions were set to 30°C and 60%, respectively. Thermal bridge modeling was avoided due to the building's lack of thermal insulation. The heat load of the interior space was determined by the people who lived in the building. For this unit, a life plan was developed for four people who were not at home from 8 a.m. to 6 p.m., and heat and humidity loads were selected and adjusted based on the software library. Based on environmental observations, the average resistance of clothing is 0.48 Clo, and the airflow is 1 m/s. Due to the lack of air conditioning, no related simulations were performed. For airflow calculations, the openings opened during overheating.

The data collected in the environment were used to modify the software's daily thermal and humidity profiles to simulate more accurately. Thermal area specifications, such as distance from the ground, area, volume, orientation, and slope relative to the horizon, were also added to the model. Other information, such as different people's activities, was chosen based on the software library and modified or deleted based on the adjustments recorded in the environment.

The maximal time step results in the calculation were set to 1 hour, the simulation duration was set to one year, and graphs from June to October (the year's warm months) were extracted. All climatic factors and factors influencing them have been considered for climatic conditions.

Hygrothermal Simulations

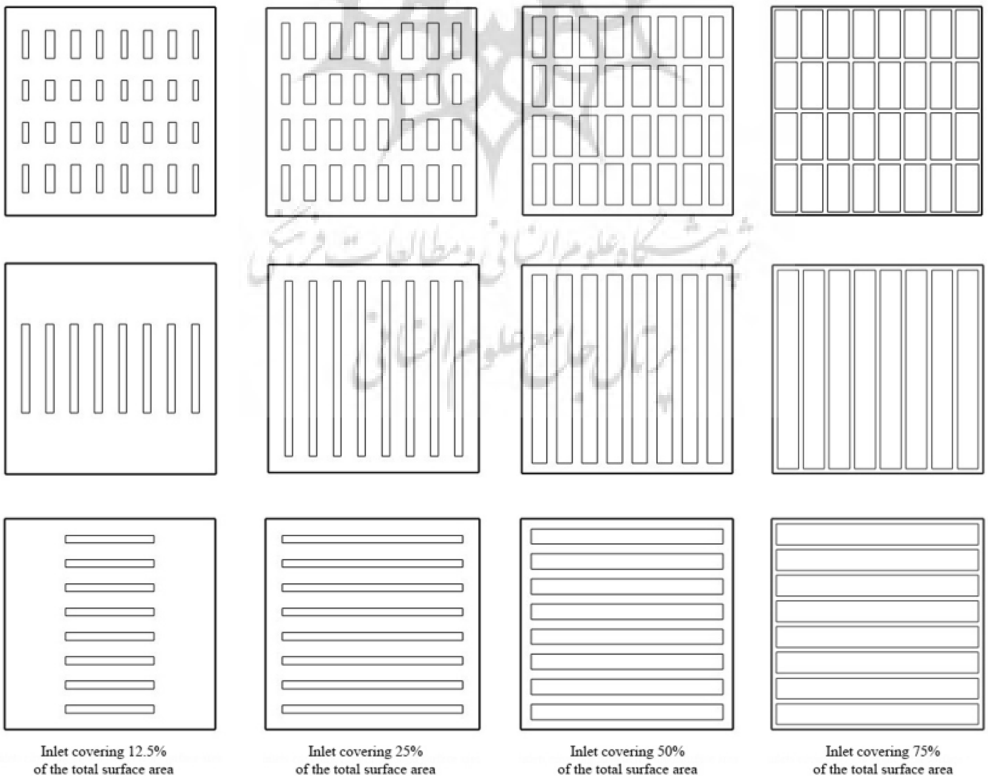


Fig. 12: Sample flexible envelopes for simulations

These simulations were carried out in three stages, and the first involved subjecting the sample building (without any window shutters) to hygrothermal simulations in four different conditions.

A- in the absence of natural ventilation and the presence of wind-driven rain

B- There is no natural ventilation and no wind-driven rain.

C- Using natural ventilation and wind-driven rain.

D- if there is natural ventilation and no wind-driven rain.

These studies were carried out to investigate the effect of natural ventilation and wind-driven rain on the internal conditions of the space and the hygrothermal performance of the envelope To have information about the impact of various factors on the internal climate condition.

According to the results of these simulations (Fig 13), it can be concluded that wind-driven rain has no significant effect on the results of this simulation. In this figure, the first row's graphs compare the outside air temperature with the inside air temperature, where the red lines are for the outside air temperature. In the second row, the comparison of external and internal relative humidity is shown, and the blue lines represent the relative humidity of the external space. (Figures 13-16)

As shown in Table 1, natural ventilation has increased the average and maximum temperature of indoor air (both air and surfaces) but reduced the inner space's relative humidity. Although the use of natural ventilation improves the humidity conditions of the indoor space but increases the operative temperature after examining the standard conditions without flexible envelopes, we investigate the impact of window shutters on the indoor climate by modeling flexible envelopes and modifying the structure of existing models in the environment. In this section, we modeled three categories of flexible envelopes (based on the samples from vernacular architecture). The inlets on the envelope in the first category are grids I, similar to the traditional grid window shutters in the climate. Flexible envelopes in the second group have vertical linear inlets, and horizontal linear inlets in the third group. In each category, the ratio of inlets to the total area of the flexible envelope is 75%, 50%, 25%, and 12.5% of the total envelope area (Fig 12). The comparisons between outer and inner temperature and outer and inner relative humidity for flexible envelopes are shown in Figures 14, 15, and 16.

In temperature diagrams, it can be seen that with increasing the area of the inlets, the fluctuation of indoor air temperature has become more similar to the fluctuation of external temperature; also, the fluctuation of relative humidity increases with increasing the area of the inlets in the envelope. The type of fluctuations of samples with horizontal and vertical inlets are similar. To compare the results of the simulations, we use bar charts. To better represent the comparative figures, a number is considered for each simulation (Table 2).

For a better comparison between simulation results, in Fig 17, the air temperature of all 16 modes is compared. As can be seen, using the flexible envelope, the maximum values and the average air temperature take a decreasing trend. By reducing the area of the inlets, these values are reduced. Almost all three series of flexible envelopes act similarly in this factor. Fig 18 illustrates a comparison of the relative humidity of indoor air in each of the 16 models. As can be seen, the variations between these 16 samples are far greater than the temperature factor. The maximum and minimum humidity levels are higher when a window shutter is not used. However, flexible envelopes with inlets that have an area of 75% of the total envelope area perform better. The results of the flexible envelope models are

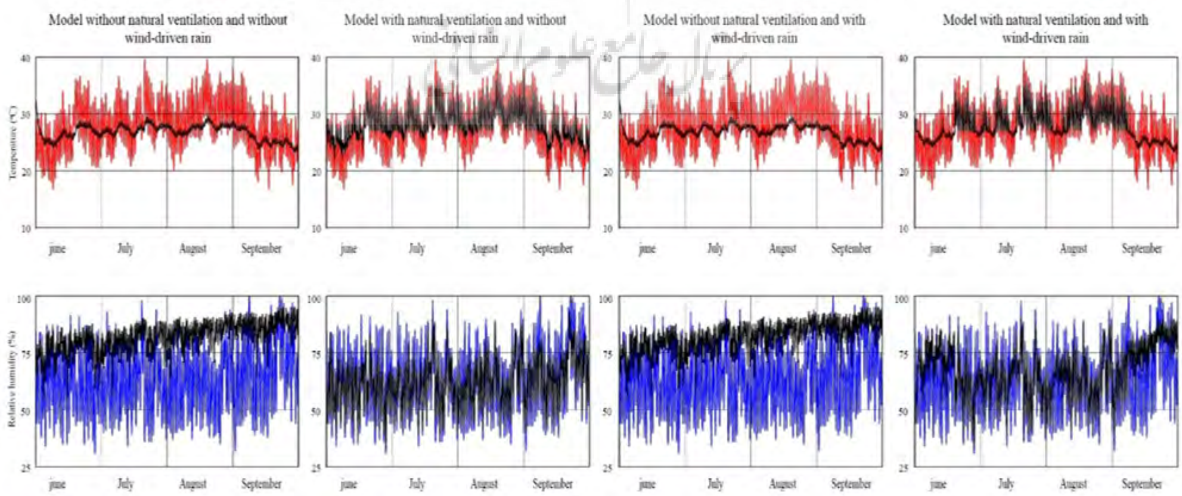


Fig. 13: T and RH in models withot shutters

Table 1: Numerical results of simulation without shutter

	Unit	With natural ventilation and without wind-driven rain			With natural ventilation and wind-driven rain			Without natural ventilation and wind-driven rain			Without natural ventilation and with wind-driven rain		
		min	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**	**mean**
The temperature of interior air	^{0}C	22	37.5	28.3	23.3	37.5	27.8	23.2	32.4	26.8	23.2	32.4	26.8
Rel humidity of inner air	%	5.3	93	61.8	5.3	91.1	66.9	54	95.5	81.5	54	95.5	81.5
Mean surface temperature	^{0}C	22.9	34.7	28	23.2	34.7	27.6	23.2	32.4	26.8	23.2	32.4	26.8
Mean floor temperature	^{0}C	22.9	34.7	28	23.2	31.7	27.6	23.2	32.4	26.8	23.2	32.4	26.8
Mean ceiling temperature	^{0}C	22.3	32.9	26.9	22.8	32.9	26.6	22.8	32.6	25.7	22.8	32.6	25.7
Operative temperature	^{0}C	22.5	36.1	28.1	23.2	36.1	27.7	23.2	32.4	26.8	23.2	32.4	26.8
Mean window's inner surface temperature	^{0}C	19.7	38.8	28.1	19.7	38.8	27.9	19.7	35.7	27.5	19.7	35.7	27.5

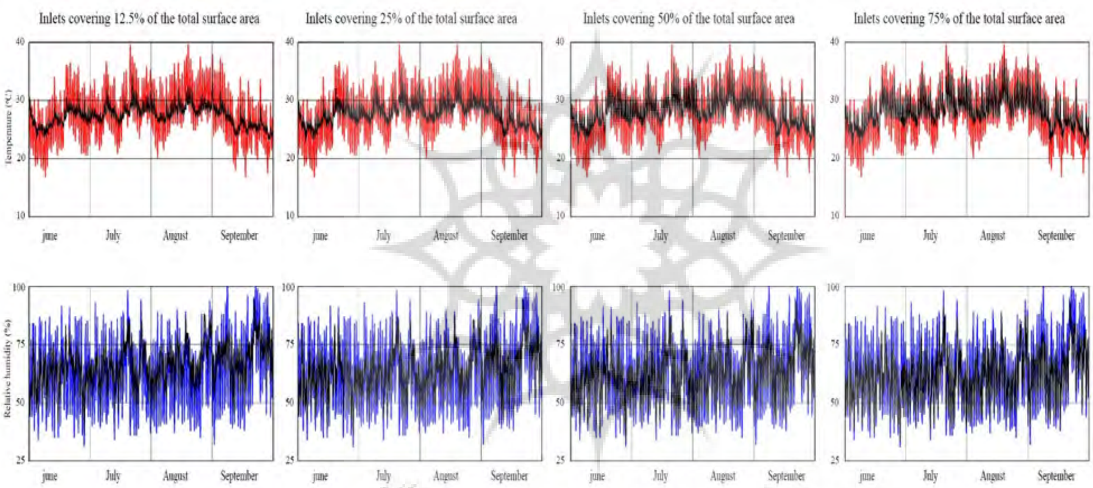


Fig. 14: T and RH in models with grid inlets

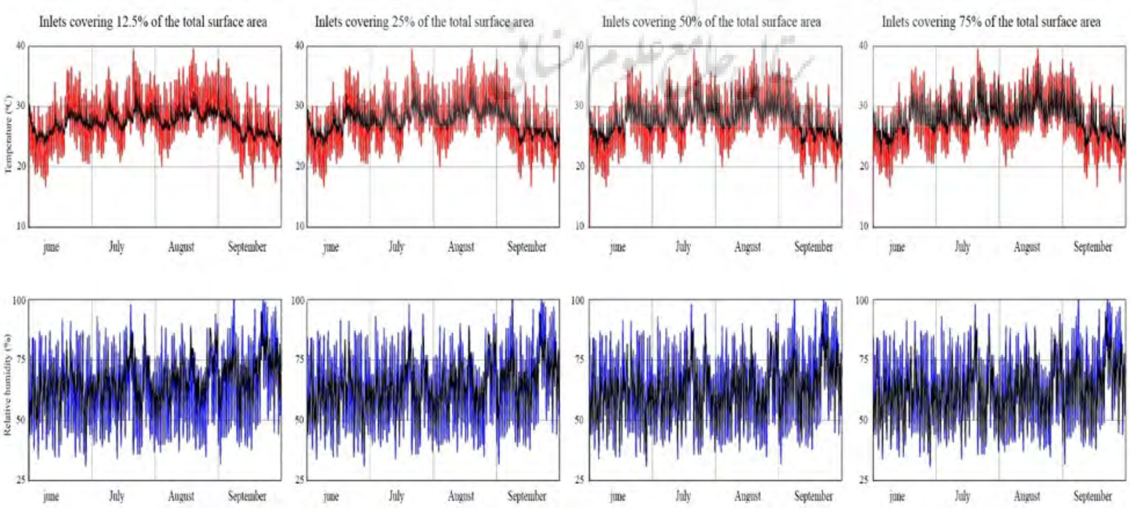


Fig. 15: T and RH in models with vertical inlets

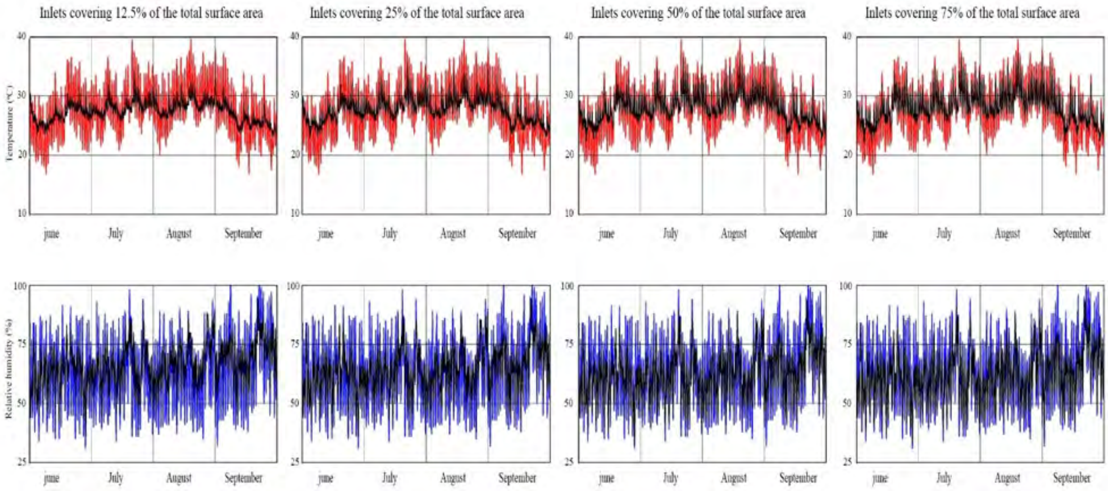


Fig. 16: T and RH in models with horizontak inlets

Table 2: Hygrothermal simulations

01	The model with natural ventilation and without wind-driven rain
02	The model with natural ventilation and wind-driven rain
03	Model without natural ventilation rain and wind-driven
04	Model without natural ventilation and with wind-driven rain
05	Grid inlets covering 75% of the total surface area
06	Grid inlets covering 50% of the total surface area
07	Grid inlets covering 25% of the total surface area
08	Grid inlets covering 12.5% of the total surface area
09	Vertical inlets covering 75% of the total surface area
10	Vertical inlets covering 50% of the total surface area
11	Vertical inlets covering 25% of the total surface area
12	Vertical inlets covering 12.5% of the total surface area
13	Horizontal inlets covering 75% of the total surface area
14	Horizontal inlets covering 50% of the total surface area
15	Horizontal inlets covering 25% of the total surface area
16	Horizontal inlets covering 12.5% of the total surface area

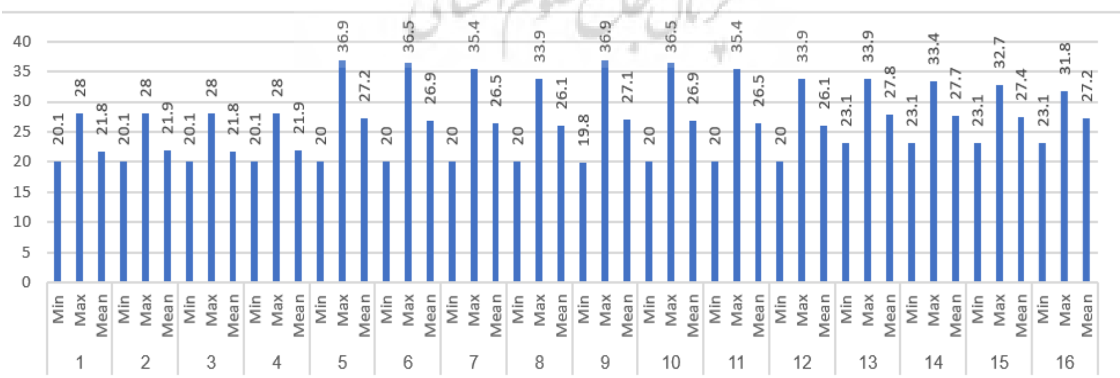


Fig. 17: Graph comparing indoor air temperature between simulated samples

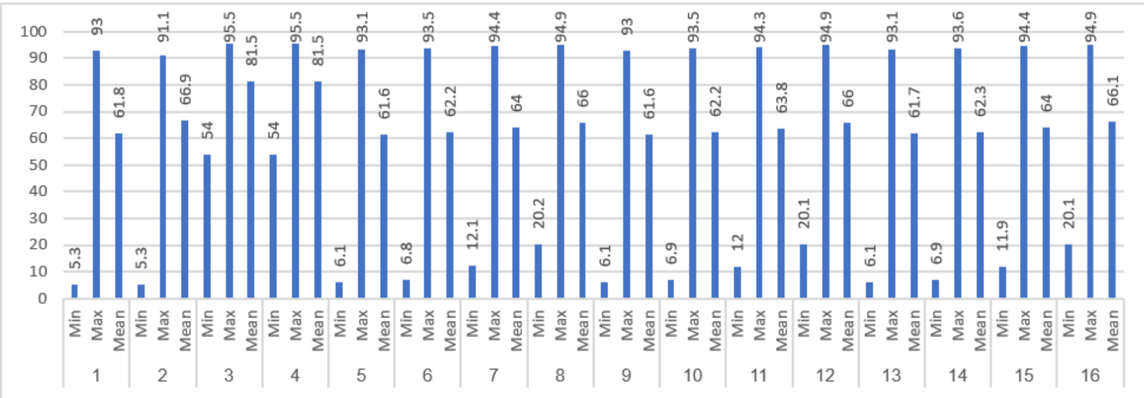


Fig. 18: Indoor relative humidity comparison diagram of simulated samples

not significantly different, but it can be argued that window shutters with vertical inlets performed slightly better. Fig 19 illustrates the average ceiling temperature in diverse circumstances. The maximum and average values can be noticeably decreased by lowering the area of the inlets of the window shutters. The envelope with horizontal inlets among the window shutters performs better in lowering the average ceiling temperature.

The average floor temperature among the simulated samples is represented in Fig 20. Conditions for models with flexible envelopes are far better than sample buildings. Only the maximum amount in the case of wind-driven rain and natural ventilation is better than some models with window shutters. The maximum values of the average floor temperature increase, and the average decreases as the area of the window shutter inlets decreases. Flexible envelope cases all responded in the same way.

Fig 21 also portrays the average surface temperature under various simulation conditions. The maximum and average values drop as the area of the inlets in window shutters increases. The same behavior was seen in all instances of models with flexible envelopes. The operative temperature in the environment is represented in Fig 22 under various simulation conditions. It is evident that as the area of flexible envelope inlets reduces, this variable does as well, with the optimal conditions being produced by inlets having an area of

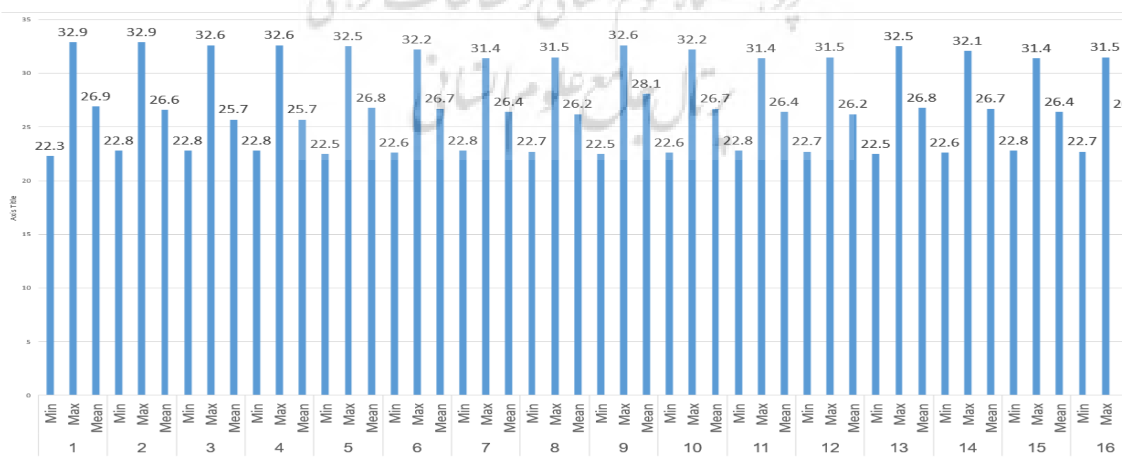


Fig. 19: Graph representing the average ceiling temperature of simulated samples

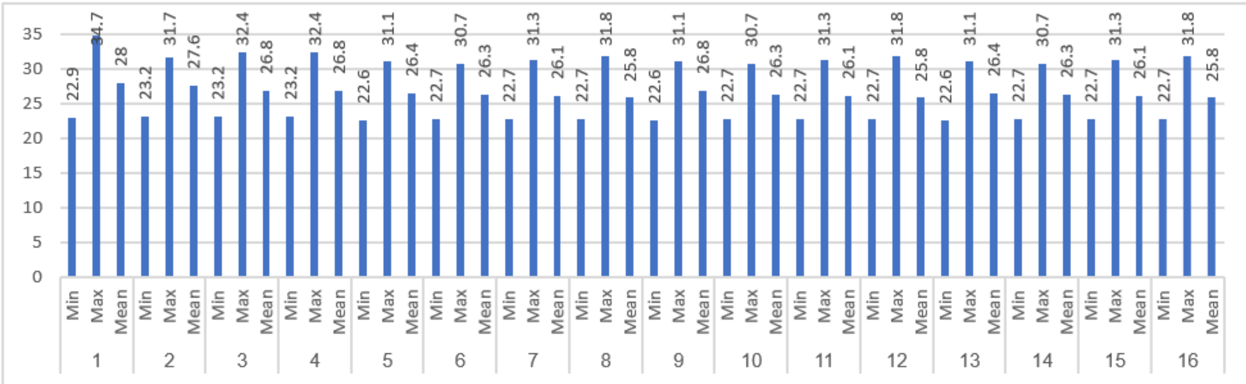


Fig. 20: Graph representing the mean floor temperature of simulated samples.

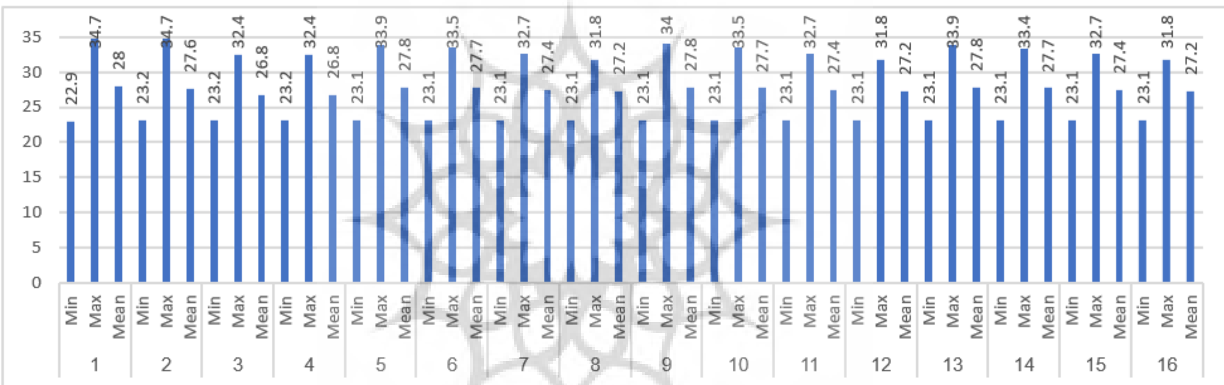


Fig. 21: Mean surface temperature distributions in simulated samples

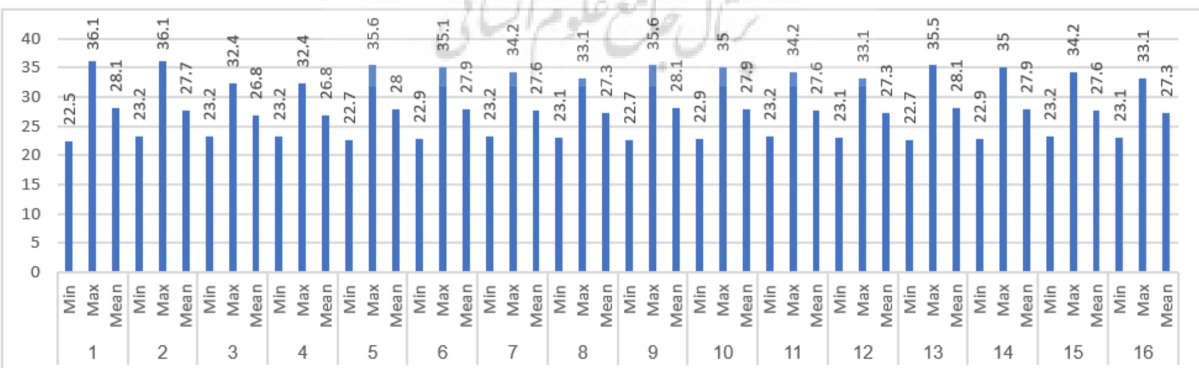


Fig. 22: Graph of operative temperature among simulated samples

12.5% of the total envelope area.

RESULTS AND DISCUSSION

By analyzing the various vernacular flexible envelope conditions and modifying their inlets, it is possible to conclude that the existence of flexible envelopes (window shutters) in comparison to the time when they are absent can effectively improve the indoor climate conditions when inhabitants open them to use natural ventilation in overheating condition. When comparing Figures 17-22, it can be observed that while the minimum values are equal and occasionally lower when flexible envelopes are not present, the average and maximum indoor air temperature is lower. The study of indoor relative humidity values reveals that while average values in window shutters with inlets as large as 75% of the total envelope area perform better, the minimum and maximum relative humidity values in indoor spaces are lower than in other situations without window shutters. Although the minimum values in the research on surface temperature conditions are nearly identical in all models, the average and maximum values are noticeably lower in models with window shutters. This is also true for ceiling and floor temperatures, but the minimum value for both is less in the case of flexible envelopes. Finally, in the study of operative temperature in different cases, it can be seen that the maximum and average value is lower in the presence of

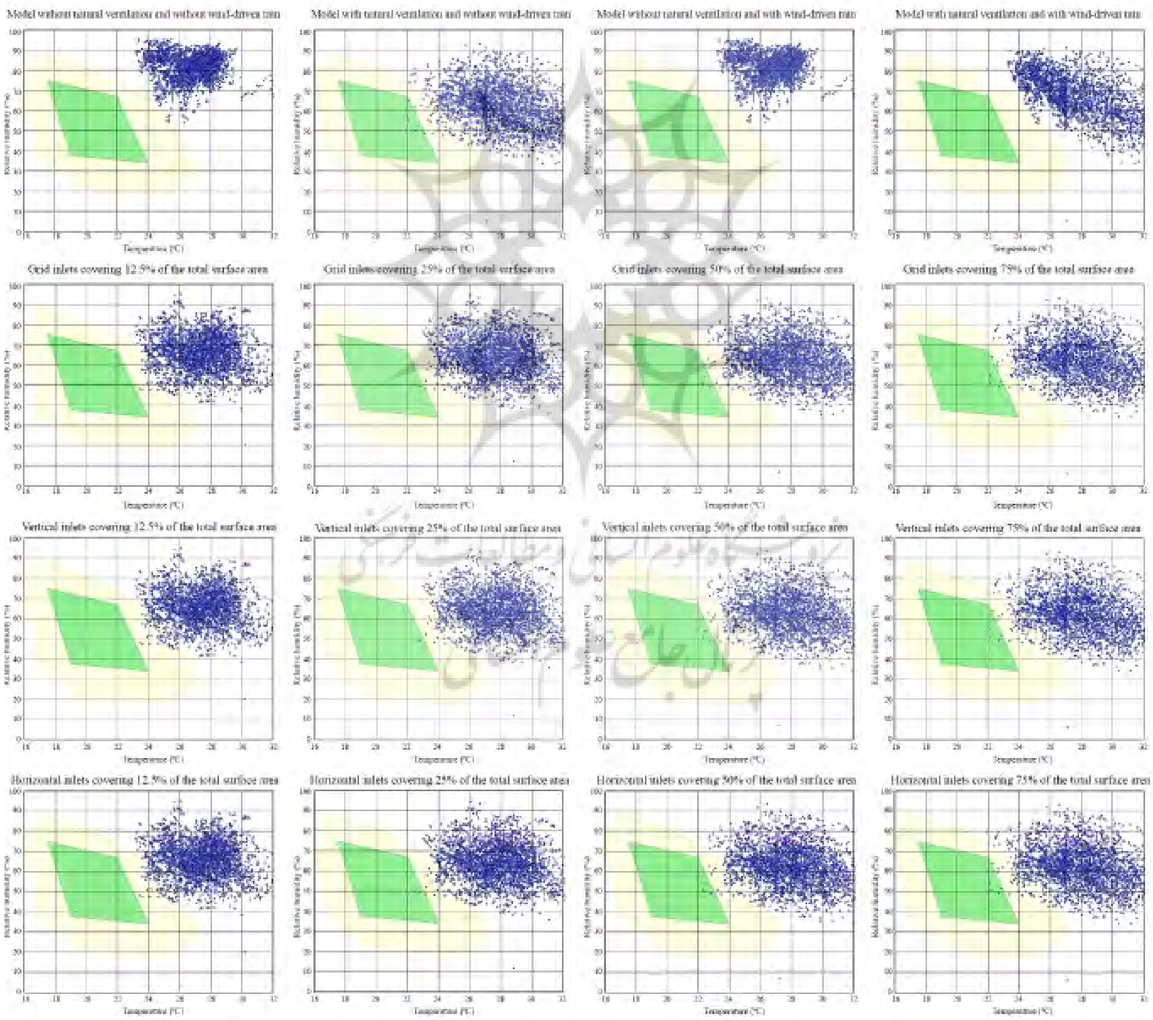


Fig. 23: Comfort air temperature & relative humidity

flexible envelopes, and minimum values are approximately equal to their values in models without window shutters. When occupant opens the windows to let in natural ventilation, the flexible envelopes improve the inner climate condition.

It should be noted that this criterion only applies when window shutters are used to cover a window entirely. Fig 23 compares adaptive thermal comfort diagrams in all 16 different simulation modes. In this figure, the horizontal axes represent temperature, and the vertical axes represent relative humidity. As shown in the figure, comfort conditions are better in situations with flexible envelopes. Examining all cases and considering the adaptive thermal comfort of people in the environment, it can be acknowledged that when the area of inlets in the flexible envelopes is equal to 12.5% of the total wall area, the thermal comfort conditions of residents are better. Considering the relative humidity, as shown in fig 18, and the average surface temperature in fig 21, it may be noted that when the window shutter has vertical inlets along the envelope, it works better than other models.

According to Figures 17-18, it can be seen that the air temperature has better conditions in samples with an area of 12.5%. In contrast, in the case of relative humidity, it can be seen that the average humidity in the simulated samples where the inlets have an area of 75% is acting better. Finally,

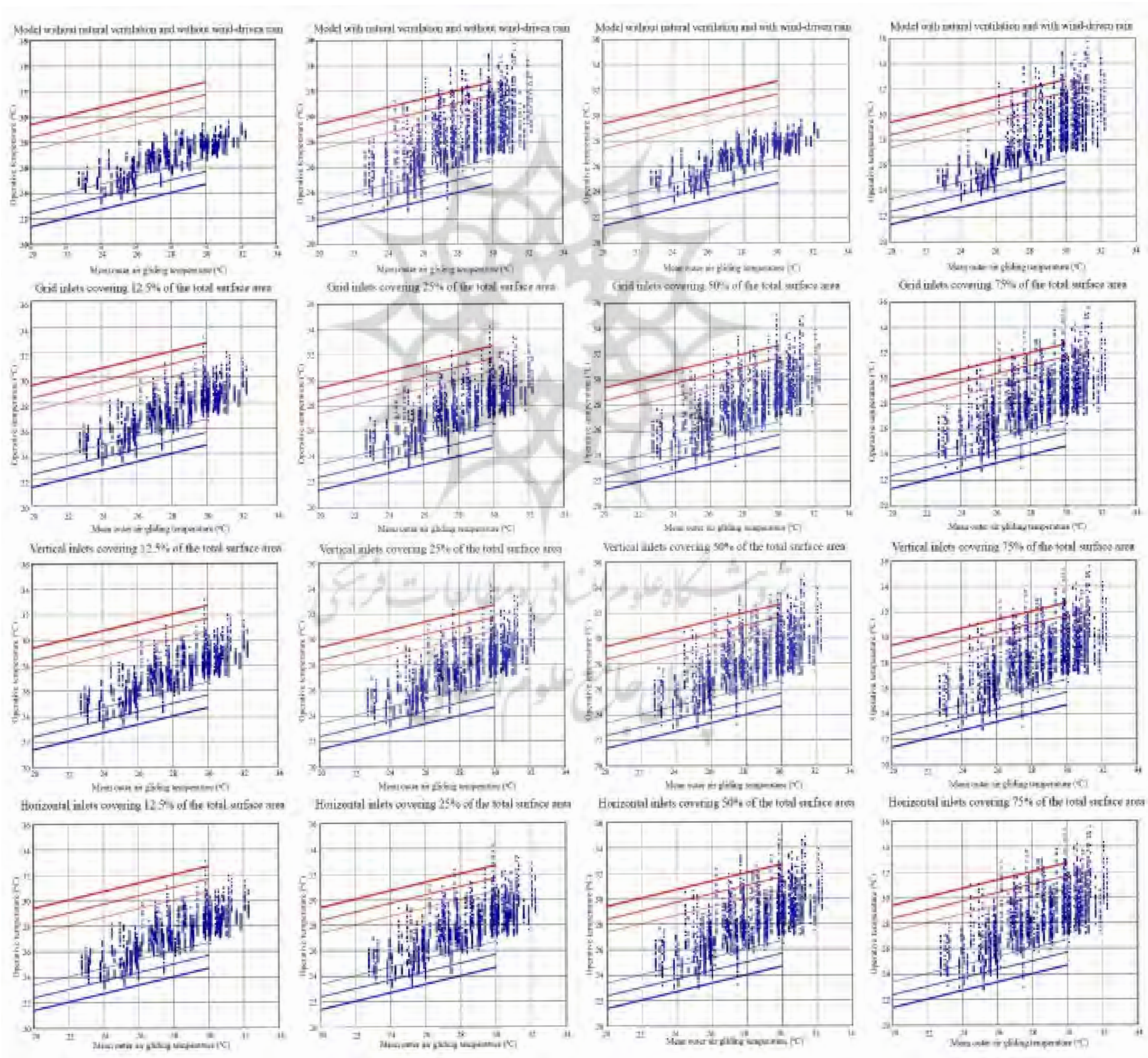


Fig. 24: Comfort mean gliding temp & operative temp (EN 15251, 2007)

in fig 24, we can see the comfort temperature concerning the operative temperature and the average outside air temperature. According to the figure, it can be seen that the conditions are much better in samples with an inlet area of less than 25% of the total envelope area. In this figure, the horizontal axes represent the mean outer air gliding temperature, and the vertical axes represent the operative temperature.

CONCLUSION

We investigated the effect of flexible envelopes or window shutters on the indoor climate condition of the space by investigating the hygrothermal performance of a building in Golestan's temperate and humid climate in Iran. First, in this climate, a building without window shutters was chosen, and its hygrothermal performance was simulated, followed by the simulation of models with different window shutters (flexible envelopes). When we compared the results of the simulations of the samples with flexible envelopes to those without them, we discovered that by opening the windows during overheating inside the space, the conditions in the samples with flexible envelopes were far better than the samples without them. It was discovered that flexible envelopes with an inlet area to total flexible envelope ratio of 12.5% to 25% and inlets constructed as vertical shapes instead of grids or horizontal shapes are clearly better. Although conditions improve with flexible envelopes, they are still far from ideal. It is suggested that buildings with different construction specifications and wall thicknesses be examined in the future.

Our studies are conducted in conditions based on the adaptive comfort of residents, and it is suggested that other zones in temperate and humid climates be studied to compare the results with each other.

AUTHOR CONTRIBUTIONS

M. Karimi designed the study, performed the literature review and experimental design, analyzed and interpreted the data, prepared the manuscript text and edition, and applied simulations. S. Heidari and S.M. Mofidi. Contributed to the project's conceptual framework, controlled experiments, and provided good advice throughout the paper; they supervised the whole work and led the research in general. All authors have read and approved the final manuscript.

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CONFLICT OF INTERESt

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy, have been completely witnessed by the authors.

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