

# Performance Evaluation of Digitally Fabricated Perforated Screens Inspired by Mashrabiya in Hot and Humid Climate

Refaa Alkhatib<sup>1</sup>, Bastian Wibranek<sup>2</sup>[0000-0001-6341-2633], Antonio Martinez-Molina<sup>3</sup>[0000-0002-3937-7329]

<sup>1</sup>University of Texas at San Antonio, Texas, United States of America

<sup>2</sup>Darmstadt University of Applied Sciences, Darmstadt, Germany

<sup>3</sup>Drexel University, Philadelphia, United States of America

**ABSTRACT:** In response to the escalating energy costs associated with air conditioning, architects and researchers increasingly turn to passive cooling strategies, emphasizing effective heat reduction, shading, and natural ventilation. One possibility is to introduce elements from vernacular architecture around the world into different climates. This study is aiming to evaluate the performance of a traditional element from hot arid climates to hot-humid climates. The traditional Mashrabiya screens from the Arabic architecture used to mitigate high indoor temperatures while regulating sunlight and preventing glare. Four screens were prototyped with controlled perforation parameters, utilizing Rhinoceros 3D and Computer Numerical Control (CNC) technology. The screens were produced with varying perforation percentages and thicknesses. A testbed reflecting common U.S. construction techniques was constructed for assessment, incorporating indoor and outdoor sensors measuring temperature, air velocity, humidity, and light intensity. The methodology included controlled airflow laboratory testing and outdoor testing that lasted a minimum of 48 hours for each screen, alongside a control scenario without any screen. Air movement was generated for laboratory testing using Surfer software for multiple scenarios to understand the effect on the indoor air speed when using the different screens. The collected data revealed diverse performances among the screens. The screen with 30% perforation and a 10 cm thickness demonstrated the best performance, effectively moderating indoor temperature and distributing light. Screens with the very high perforation percentages allowed for elevated air temperatures, while those with minimal perforation did not generate sufficient airflow. However, the screens struggled to maintain comfortable indoor humidity levels during high humid outdoor conditions, prompting further investigation into enhancing performance in high humidity. The study establishes a basis for further research on developing screens that can help mitigate hot and humid climates to create comfortable indoor environments.

**KEYWORDS:** Mashrabiya, Passive Cooling, Natural Ventilation, Vernacular Architecture, Digital Fabrication.

## INTRODUCTION

The name Mashrabiya is derived from the Arabic word “drink” and originally meant “a drinking place” (Fathy 1986, 46). In the past, people would put water jars next to the Mashrabiya screen so that the incoming breeze cooled down the water, while the evaporated water from the jars helped with evaporative cooling in the space. The Mashrabiya has five main purposes: shading, natural ventilation, evaporative cooling, reducing the temperature of the interior, and providing privacy and cultural decorative elements (Fathy 1986). In this study we will be focusing on Texas (USA), where according to the U.S Energy Information Administration, the average electricity consumption is 26% higher per home than the national average, with a large part going to air conditioning throughout the year (EIA 2020).

Mashrabiya screens have continued to be used and developed in modern architecture. They serve as an adaptive skin controlling direct sunlight entering the space, as seen in the Albahar Tower in Abu Dhabi (Holloway 2015), and as a structural pattern, as in the Brick Pattern House (Gaete 2019). Mashrabiya screens have also been incorporated into concrete buildings, such as the Mashrabiya house built in 2011, to showcase cultural values (Jett 2011). Additionally, Mashrabiya took different shapes and materials, and it can be cantilevered, louvered timber wall, louvered window or screen panels. It has also been made from wood, stone and gypsum clay. Currently, there is a growing interest in reviving traditional elements in contemporary architecture, leading to ongoing research on new ways to incorporate Mashrabiya screens in modern buildings (Abdelkader and Park 2017).

Interestingly, a study investigated the Ottoman and Andalusian traditional screens through field work and simulation, including air temperature and movement testing, and light distribution of both screens. The research revealed that Mashrabiya not only controlled natural ventilation but also distributed sunlight better inside the room compared to a window without any type of screen (Salem 2019).

In addition to its cultural significance and versatility in architectural design, the functional benefits of Mashrabiya screens have also been explored in various studies. Some scholars analyzed the use of traditional environmental treatments in achieving thermal comfort, including implementing of Mashrabiya screens (Shahda and Noiser 2021). Other researchers studied sustainable design strategies for mosques, where Mashrabiya screens were used alongside other passive techniques such as thermal mass and stack ventilation (Azmi and Kandar 2019). Some

academics worked on developing a second skin façade based on Mashrabiya functions and cooling techniques. The study showed the possibility of creating a second skin façade on an office building in Arizona (USA) and calculated the potential energy savings that could be achieved (Khadra & Chalfoun 2014). Also, analyzing the aerodynamics when wind hits Mashrabiya screens would help create a self-cool wall depending on venturi effect (Ferwati 2013). An investigation in Egypt influenced the annual energy load by modifying the perforation and depth of the screens. 30% of energy savings were achieved when an external deep perforated solar screen was oriented to the south and west (Sherif et al. 2012). These studies suggest that Mashrabiya screens remain relevant in contemporary architecture and sustainable design practices.

The multiple features and functions of Mashrabiya were emphasized in Alothman's comprehensive literature review showing different ways to test the screens depending on what factors needed to achieve (Alothman 2017). It also should be noted that the effectiveness of Mashrabiya screens can be enhanced when integrated with other passive strategies as revealed by Bagasi, proving that the thermal mass had impacted the results of data monitoring for a Mashrabiya performance in Saudi Arabia (Bagasi 2020). Just like Mashrabiya screens were originally introduced and tested in hot and dry climates, Jali screens are the Indian equivalent which were also developed for that harsh environment. Jali screens are architectural feature comparable to Mashrabiya in terms of function, although they differ in nomenclature and design. Unlike Mashrabiya, evaporative cooling was not feasible when utilizing Jali screens in hot and humid regions. Hawa Mahal is an exemplary structure that showcases various Jali screen designs, with differing opening sizes and depths ranging from 2.5 cm to 11.5 cm (Kumar 2014). Kumar investigated the performance of the screens in the hot, humid, and dry climates of India through field monitoring and laboratory testing of screens with varying perforation percentages and opening sizes to find out how these screens help to mitigate indoor temperature and humidity levels.

The industry of fabricating Mashrabiya screens evolved through history, starting with wooden screens were traditionally made by carving wooden balusters. However, today computer numerical control (CNC) and laser cutting technologies are used with different materials to create various shapes. One researcher created "Cool Brick" as one of the first 3D-printed models inspired by Mashrabiya that creates a passive cooling device that has hollows inside for water to pass through (Fratello and Rael 2015). Currently no physical examples of an architectural-scale 3D-printed Mashrabiya exist.

Despite the extensive research on Mashrabiya latticework, there is a lack of studies exploring its potential to mitigate heat and humidity in hot and humid climates. Advances in modern fabrication techniques now enable the precise alteration of geometrical parameters such as perforation, depth, and opening geometry, thereby offering an opportunity to modulate the airflow of the shading device. Accordingly, this study aims to reintroduce perforated screens with varying perforation percentages and thicknesses to evaluate their performance in the hot and humid climate (ASHRAE 2A) of San Antonio, Texas, USA.

## 1.0 METHODOLOGY

The primary objective of this investigation is to assess the airflow dynamics facilitated by the devised screens. This evaluation is conducted through two main experiments, indoor laboratory testing with controlled air velocities and outdoor testing in the natural weather. The methodology commences with the design and fabrication of the screens, followed by laboratory testing involving two distinct scenarios and subsequent outdoor testing for the same screens.





### 1.1 The testing room

A 1.8 x 1.8 x 1.8-meter testing room was designed and constructed with traditional US techniques using wood studs and plywood with no insulation and two hung windows. Each window is a double pane and measures 91.4 cm by 91.4 cm.

### 1.2. Design and digital fabrication technique

Four distinct perforated screens were modeled and fabricated based on two main factors: thickness and perforation percentages. Perforation percentages were based on previous studies on old Mashrabiya's performance (Salem, 2019). Each screen measures approximately 91.44 cm x 91.44 cm with varying opening sizes and thicknesses ranging from 5 cm to 10 cm. CNC technology was used to cut the screens from building insulation Styrofoam, a lightweight material that allowed for easy cutting and forming of different sizes and shapes. Then the screens were painted white to reflect as much solar radiation as possible. Table 1 describes the properties of each screen, including its thickness, perforation percentage, and open area ratio. The accompanying image shows the CNC cutting process used to create the screens.

**Table 1:** Perforated screens properties. Source: (Author 2024)

Properties	Screens			
				
Exterior opening size (cm <sup>2</sup> )	103	103	161	161
Interior opening size (cm <sup>2</sup> )	25	25	58	79
Thickness/ Depth (cm)	5	10	10	5
Exterior perforation percentage	60%	60%	70%	70%
Interior perforation percentage	13%	13%	30%	45%
Sectional angle between ext. and int. openings	26°	14°	14°	14°

### 1.3. Laboratory testing experiments

Laboratory experiments were systematically conducted within a controlled environment featuring consistent temperatures and regulated air circulation. Wind speeds were induced through a fan calibrated at three distinct velocities. Two specific experimental scenarios were investigated:

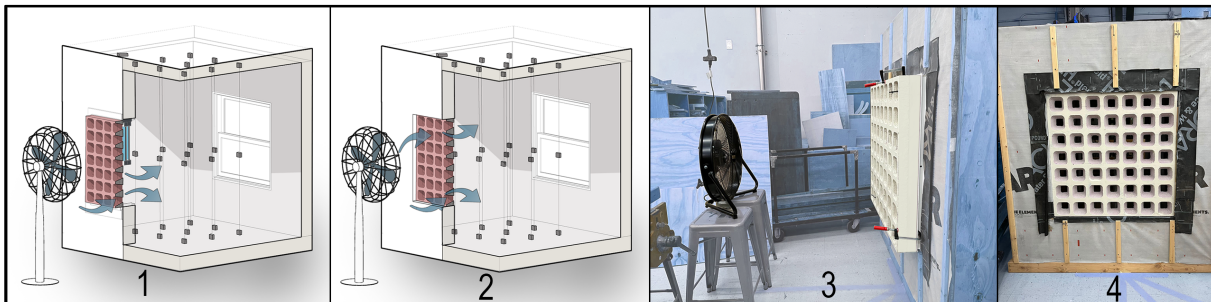
#### 1. Screen Placement over the hung window:

In this scenario, each screen was positioned over the open hung window of the testing room, directing airflow exclusively to the lower section of the screen. The primary objective of this scenario was to assess the performance of each screen when employed with hung windows, thereby evaluating their effectiveness in situations where air flows solely through the lower portions of the screen.

#### 2. Screen Placement within window Opening:

In the second scenario, the hung window was removed, and each screen was placed within the window's opening, allowing airflow across the entire perforated surface of the screen. The aim of this scenario was to evaluate the performance of each screen in ventilating a room using either a casement or sliding window, providing insights into their effectiveness in scenarios where airflow spans the complete perforated area.

To ensure standardized conditions, a fan was strategically positioned in front of the screen, operating at three distinct air speeds (2.9, 4.5, and 6.1 Km/h) in accordance with ASHRAE standards (ASHRAE 55 2020). Another time, the fan was positioned with 45° angle from the screens surface and on speed 4.5 km/h. An outdoor sensor was deployed on the roof to measure air temperature and relative humidity in the testing surroundings. Additionally, twenty-seven interior sensors of the Hobo Onset type were strategically placed as a 3D grid within the test room to visualize air movement during each experiment by measuring air temperature and relative humidity. Indoor air velocity was manually measured at each sensor location using a Hot Wire Thermo-Anemometer with a data logger. The experimental setup is depicted in Figure 1.

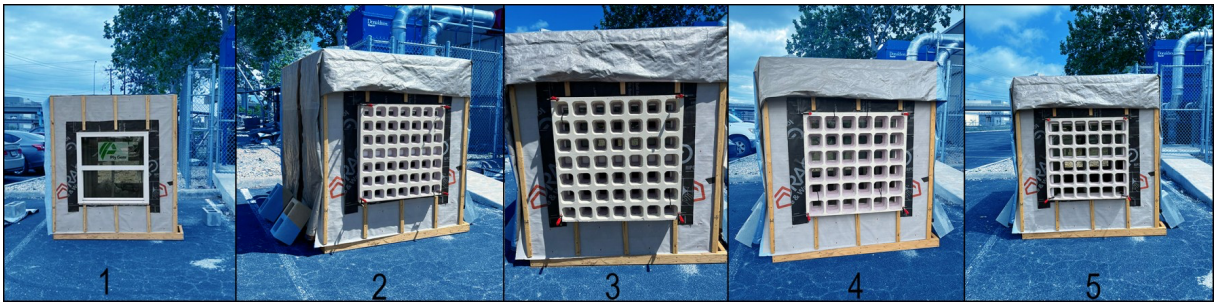


**Figure 1:** 1- Experiment setup when placing the screens over the hung window. 2- Experiment setup when placing the screen in the window opening. 3+4- examples of experiments setups in the laboratory. Source: (Author 2024)

### 1.4. Outdoor testing

The testing room was positioned outside in the parking lot of the laboratory building facing south and each screen was placed over the window. The experiment setup included data collection using Hobo Onset sensors (in and out of the testbed) over a continuous two-day period for each screen, with data collection taking place from April 9<sup>th</sup> to April 23<sup>rd</sup>, 2023.

It is important to note that the testing room was situated over asphalt, which may have affected the micro-temperature around the room. This limitation has been considered when interpreting the results. Figure 2 provides a visual representation of the experiment setup and some images of the experiment.



**Figure 2:** 1: Outdoor setup for the testing room. 2-5: images of the screens following screens order as Table 1. Source: (Author 2024)

## 2.0 RESULTS AND DISCUSSION

This section presents the outcomes of the digital fabrication and CNC cutting processes, as well as the analysis of field data, which is divided into two primary parts. The first part pertains to laboratory testing, where airspeed was regulated, and encompasses:

- Testing each screen with and without the window at three different air speeds (2.9, 4.5, 6.1) Km/h.
- Placing a fan at a 45° angle from the window opening with an air speed of 4.5 Km/h for all four screens.

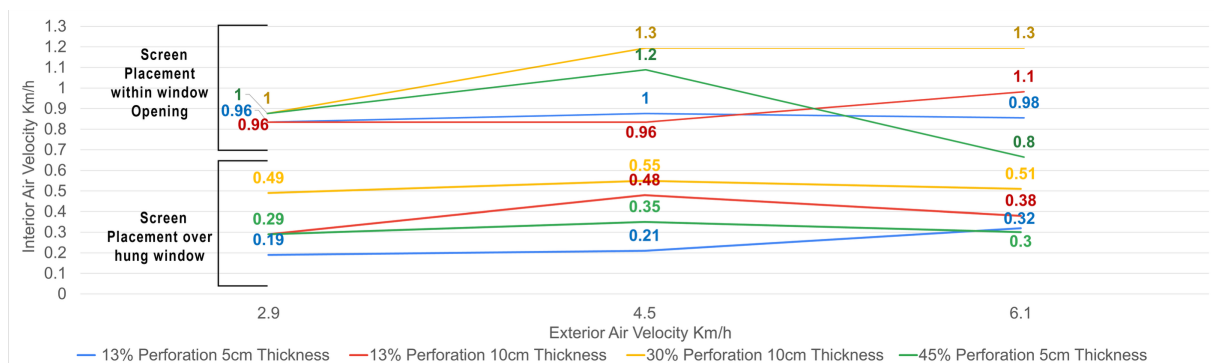
The second part was outdoor testing, which include collecting data continuously for at least 48 hours for each screen placed on top of an open hung window in the laboratory's parking lot. The results consist of field measurements of indoor and outdoor air velocity, air temperature, relative humidity, and light intensity.

### 2.1. Design and digital fabrication technique for the four screens

The Rhino software facilitated the generation of diverse geometries and opening depths using Grasshopper, enabling the manipulation of certain parameters to achieve numerous shapes and precise angles. In this study, a fundamental geometry was selected to regulate solely the thickness and opening sizes. The external and internal opening dimensions differed from one another. For ease of testing, the author employed Styrofoam, though more eco-friendly materials are recommended for future investigations. The CNC milling machine took about 6 hours to cut the 5cm thick screens, while the 10cm thick screens were fashioned by joining two 5cm pieces with a specialized foam adhesive. In sum, the CNC cutting process required over 15 hours to accomplish.

### 2.2. Laboratory testing with controlled air velocities

Based on Table 2 and Figure 3, the screens showed better performance in allowing air to pass through without the window than when half of the screen was used for ventilation. The screen with 30% perforation and 10cm thickness showed the best ability to let the air pass through and distribute the air inside the interior space in all scenarios. Table 2 shows that the percentage of outside received air velocity decreases as the exterior velocity increases. This could be due to the air curtains created when air turbulence hits the screen. The most significant drop in air velocity can be seen when the exterior air velocity was 6.1 km/h.



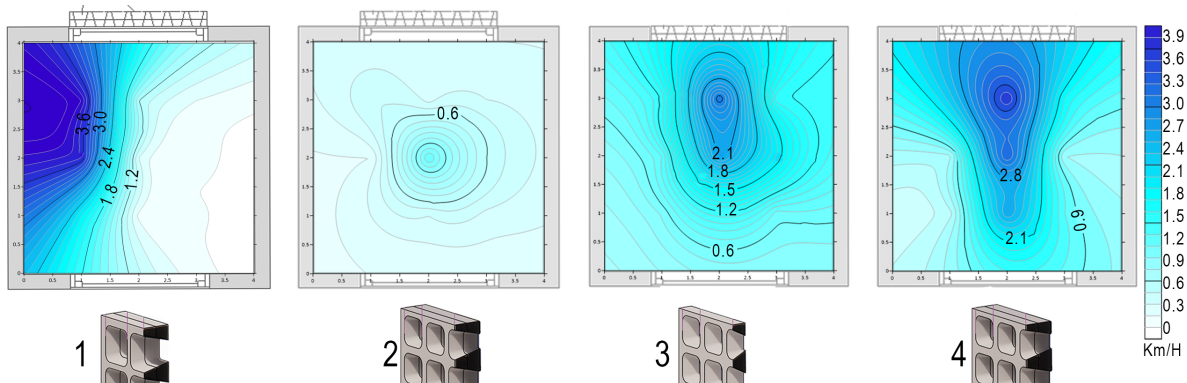
**Figure 3:** Comparison between the screens in the two different scenarios. Source: (Author 2024)

**Table 2:** Test results of the four screens when tested over the hung window and without it. Source: (Author 2024)

		Screens											
		5			10			10			5		
		Screens											
Over hung window	Thickness/ Depth (cm)	5			10			10			5		
	Interior perforation percentage	13%			13%			30%			45%		
	Outside wind velocity Km/h	2.9	4.5	6.1	2.9	4.5	6.1	2.9	4.5	6.1	2.9	4.5	6.1
	Inside wind velocity Km/h	0.19	0.21	0.32	0.29	0.48	0.38	0.5	0.55	0.51	0.29	0.35	0.3
	% velocity of outside received	7%	5%	5%	10%	11%	6%	17%	12%	8%	10%	8%	5%
Average air perforation %		6%			9%			13%			8%		
Without the window	Outside wind velocity Km/h	2.9	4.5	6.1	2.9	4.5	6.1	2.9	4.5	6.1	2.9	4.5	6.1
	Inside wind velocity km/h	0.96	1.04	0.98	0.96	0.96	1.08	1.02	1.3	1.3	1.03	1.21	0.8
	% velocity of outside received	33%	23%	16%	33%	21%	18%	36%	29%	21%	36%	27%	13%
	Average air perforation %		24%			24%			28%			25%	

Upon analyzing and generating air mappings for air movement at 1m height inside the testbed for different scenarios. Figure 4 shows some examples of them, and the following observations were made:

- The internal angle of the screen functions as an impediment to the airflow within a certain angle, redirecting the air to the opposite side of the room. Figure 4-1 shows one example when the screens faced 45° airflow from the fan at a speed of 4.5Km/h.
- Augmenting the direct wind speed results in heightened turbulence within the room, causing the air to circulate in circular patterns. See Figure 4-2, when the fan speed was 6.1 km/h on screen with 13% perforation.
- Increasing the thickness of the screen creates a lengthier pathway for the air creating venturi effect, consequently accelerating its passage. In 3 and 4 of Figure 4 below is a comparison between the two screens with same perforation percentages but different thickness in air mapping when fan speed was 6.1 km/h. The screen with higher thickness (Figure 4-4) generated higher indoor air velocities.
- Expanding the opening sizes of the screen allows more air to pass through, albeit at lower velocities.
- The screen featuring 30% perforation and a thickness of 10cm demonstrates superior air distribution within the space, leading to more similar conditions throughout the room.



**Figure 4:** Air mapping examples for four different scenarios. Generated in Surfer software. Source: (Author 2024)

### 2.3. Outdoor testing-temperature and humidity analysis

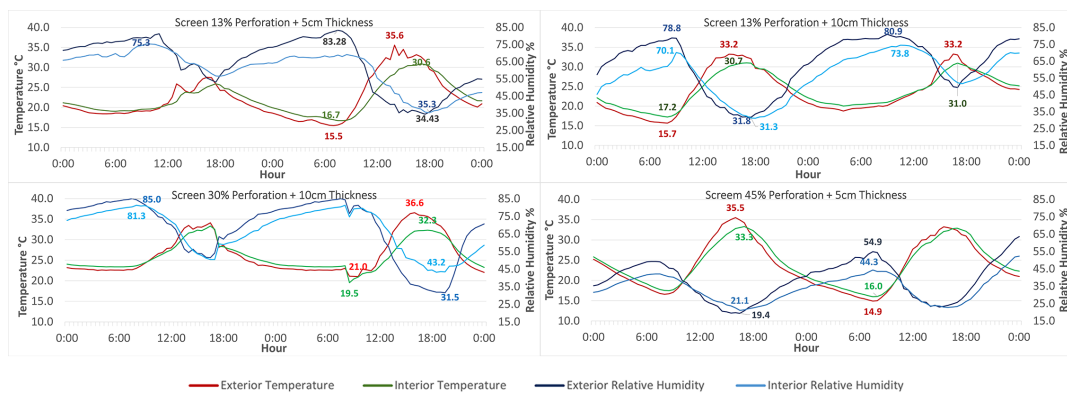
Starting with the screen of 13% perforation and 5cm thickness, the prevailing wind direction on the first day was primarily from the east and north, exhibiting modest velocities ranging from 4.8 to 8.0 km/h. External humidity levels averaged 80%, while internal humidity stood at 75.3%. The indoor temperature closely mirrored the outside conditions, fluctuating within the 21 to 26.7°C range and peaking at approximately 24.4°C, corresponding to the highest observed external temperature as illustrated in Figure 5 (top left). The subsequent day, experienced hotter and sunnier weather, with external temperatures reaching 35.6°C and internal temperatures rising to 30.6°C ( $\Delta T = 5^\circ\text{C}$ ). The prevailing wind originated from the north and east, with average velocities of 12.9 to 16.1 km/h. Although humidity remained elevated during the morning, internal levels consistently ranged between 55% and 66%. The increased wind velocities on the second day contributed to moderating the room temperature compared to the initial day. Despite the lack of insulation in the room, the small openings in the screen facilitated natural ventilation, assisting in maintaining lower peak temperatures within the space.

Next, the screen with 13% perforation and 10cm thickness was tested, Figure 5 (top right). The weather conditions were marked very similar for both days of testing by scattered clouds and sunshine, with the highest temperature

reaching 33.2°C. Inside the room, the maximum temperature was 30.6°C ( $\Delta T = 4.8^\circ\text{C}$ ). The peak wind speeds during testing occurred in the afternoon when the heat was at its maximum, predominantly originating from the southeast at velocities ranging from 8.0 to 11.3 km/h. The exterior relative humidity was higher in the morning, reaching its peak at 79% on the first day, while the interior relative humidity reached 70%. On the next day, the maximum exterior relative humidity was 81%, while the interior relative humidity was 74%.

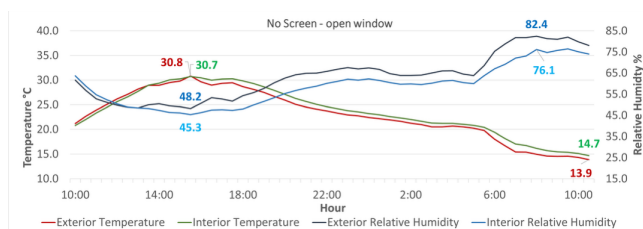
When the screen of 30% perforation and 10cm thickness (seen in Figure 5 bottom left), the weather conditions on both days of testing were quite similar, with mostly cloudy skies and high wind velocities ranging between 16.1-20.9 km/h. The wind direction was primarily from the east, with some coming from the south. On the day when the highest exterior temperature was recorded at 36.6°C, the interior temperature reached 32.3°C ( $\Delta T = 4.2^\circ\text{C}$ ). The high wind velocities may have contributed to the elevated interior temperatures. The maximum exterior relative humidity reached 85%, while the interior relative humidity was 81.3%, which is still considered high.

During the first day of testing of the last screen with 45% perforation and a thickness of 5 cm (figure 5 bottom right), the wind primarily came from the north and east with velocities ranging from 11.3-14.5 km/h, while the highest outside temperature reached 35.5°C and the inside reached 33.3°C ( $\Delta T = 2.2^\circ\text{C}$ ). The following day, the wind shifted to the south and east, and the higher temperature peaked in the afternoon. Notably, the inside temperature was very close to the exterior temperature. By comparing the wind direction of both days, the temperature was higher indoors when the wind was directed to the screen on the south side, which probably caused higher temperature levels on the second day of testing. The relative humidity was similar to the exterior in the afternoon on the first day, while in the morning of the second day it reached a maximum of 54.9%, and inside the room, it was 44.3%.



**Figure 5:** Interior and exterior temperature and relative humidity of the testing room for each screen. Source: (Author 2024)

For 24 hours, the room's window was left open without a screen and data is shown in figure 6 below. According to the data, the indoor temperature closely mirrored the exterior, slightly exceeding it at times. When the outside temperature reached 30.6°C, the indoor temperature registered at 30.7°C ( $\Delta T = 0.1^\circ\text{C}$ ). Indoor relative humidity peaked at 76.1%, while exterior humidity was 82.4%, both considered high. The wind, mainly from the east and some from the south, averaged between 14.5-20.9 km/h. The open window allowed warm air and direct sunlight, creating suboptimal thermal comfort. In contrast, perforated screens effectively moderated indoor conditions by allowing airflow, proving more efficient than simply opening a window.



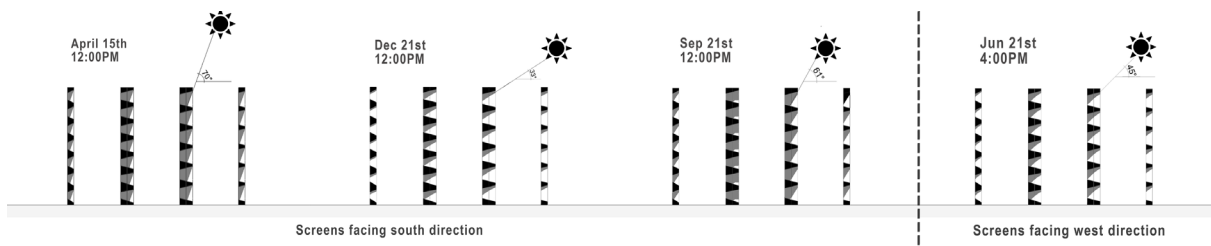
**Figure 6:** Interior and exterior temperature and relative humidity of the testing room with open window and no screen. Source: (Author 2024).

Based on the gathered data, it is evident that the screen with 5 cm of thickness and 13% perforation was the most effective in maintaining a cooler room temperature when the external temperature reached its peak ( $\Delta T = 5^\circ\text{C}$ ). Similarly, the screen with 10 cm of thickness and 30% perforation also demonstrated effectiveness in moderating indoor temperatures ( $\Delta T = 4.2^\circ\text{C}$ ). Conversely, the screen with 45% perforation and 5 cm thickness proved less effective in moderating room temperature compared to the other screens. While relative humidity closely matched exterior levels in most instances, the screen with 13% perforation and 5 cm of thickness unexpectedly created a significant gap between the maximum exterior humidity and the interior humidity.

#### 2.4. Outdoor testing-light intensity analysis

The direct sunlight inside the space can cause higher uncomfortable light intensity and glare. The below shadow study for the screens helps to understand the times of year the sun penetrates indoors the most. The four designed screens have equal opening depths from all four sides. In the case of the screens facing west, during hot summer

days, the sun will penetrate the screens with 5cm thickness and high perforation percentages (Figure 8 left). Only the screen with 10 cm thickness and the least perforation will prevent direct sunlight during the hottest hour of the day in summer. Sun angles on different dates are shown in Figure 7.

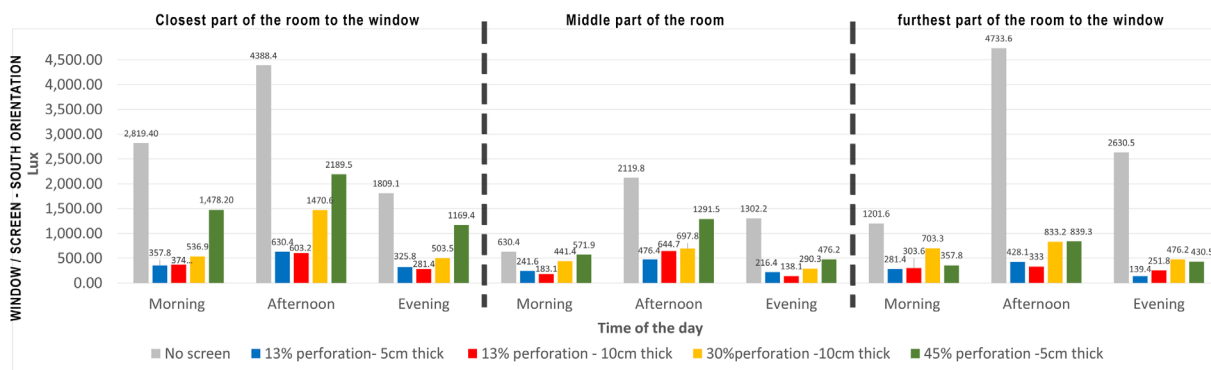


**Figure 7:** Sun angle on the four screens when facing south on the day of testing, winter solstice, and autumnal equinox. Sun angle on summer solstice when facing west. Source: produced via Revit simulation. Source: (Author 2024)

In the case of the screens facing south as this research investigates, the direct sunlight is facing the screens at noon, and the direct sunlight does not enter the room when using a screen with 13% perforation and 10 cm thickness the whole year, because the sun did not penetrate when it was on its lowest angles in December. When the sun angle increases during spring and summer days, there is a complete absence of sunlight penetration through all screens from the spring equinox to the autumn equinox. That also means the sun does not penetrate on June 21<sup>st</sup> at the summer solstice because the sun is higher. Starting from autumnal equinox, direct sunlight begins to penetrate the screen with the highest perforation percentage and lowest thickness, namely the 45% perforation and 5 cm thickness screen in this case. This pattern continues until the sun angle starts to decrease again, reaching its lowest point during the winter solstice.

Light intensity was monitored at 30-minute intervals during screen testing, with room sections divided for analysis (see Figure 8). Afternoons saw acceptable average intensities (323-646 lux) for 13% and 30% perforation screens, meeting ASHRAE standards for spaces like cafeterias and classrooms. However, morning and evening intensities were insufficient, requiring additional artificial lighting.

The 45% perforated screen, with higher openness and 5 cm thickness, allowed intense sunlight, resulting in brightness exceeding 1,076 lux in the first two sections—too high for comfortable indoor lighting, causing glare and discomfort. Conversely, the 30% perforation screen showed high intensity near the window but, with 10 cm thickness, evenly distributed light, reducing glare and preserving outdoor views. With an opening size of 0.84 square meters, the 30% perforated screen achieved a balance in controlling indoor light intensity. Data collected without shading devices revealed unsuitably high light intensity, emphasizing the need for such devices to regulate sunlight.



**Figure 8:** Light intensity for each screen in each room section based on the location from the window/screen placement. The window is located on the left of the graph. Source: (Author 2024).

## CONCLUSION

This research aimed was to identify the most advantageous combination of perforation percentages and thicknesses that yield optimal results for Mashrabiya screens in hot and humid climates. In determining the optimal perforation percentages, the traditional Mashrabiya screen percentages served as a baseline to initiate the venturi effect. Subsequently, these screens underwent testing with varying air velocities, both in front of an open hung window and without the window. The study involved measuring interior and exterior air velocities and visualizing air movement inside the room under different scenarios using Surfer software. Outdoor testing in San Antonio, Texas, USA, provided data on air temperature, relative humidity, and light intensity for each screen.

Results revealed that the performance of each Mashrabiya screen is unique, dependent on perforation, opening size, and thickness. The screen with a 5 cm thickness and 30% perforation was most effective in ventilating the room, reducing temperature, and distributing light while blocking direct sunlight. However, real-world testing uncovered a limitation in maintaining comfortable interior humidity levels during outdoor tests, necessitating further improvements for high-humidity conditions. The study underscores the need for further research to implement Mashrabiya screens as a passive cooling technique in buildings facing extreme heat in hot- humid climates.

This investigation forms the groundwork for exploring additional variables and introducing new cooling devices to enhance the cooling efficiency of screens. Future research avenues include exploring factors such as screen shape, orientation, and design, conducting real-world tests in diverse settings, and evaluating energy efficiency compared to traditional cooling systems. These endeavors aim to contribute to developing of passive cooling solutions for our built environment.

## ACKNOWLEDGEMENTS

Authors would like to thank Panos Karaiskos and Dr.Hoffman for their contribution to this research.

## REFERENCES

- Abdelkader, R., and J. Park. 2017. "The Evolving Transformation of Mashrabiya as a Traditional Middle Eastern Architecture Element." *International Journal of Civil & Environmental Engineering* 17 (1).
- Almerbati, N. 2016. *Hybrid Heritage: An Investigation into the Viability of 3D-printed Mashrabiya Window Screens for Bahraini Dwellings*. Leicester, UK: De Montfort University.
- Alothman, H. 2017. *An Evaluative and Critical Study of Mashrabiya in Contemporary Architecture*. Nicosia: School of Applied Sciences of Near East University.
- Archtoolbox. 2021. "Recommended Lighting Levels in Buildings." Archtoolbox. <https://www.archtoolbox.com/recommended-lighting-levels/>.
- ANSI/ASHRAE Standard 55-2023. *Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2023. (First issued 1966; updated periodically, most recently in 2023.)
- Azmi, N. A., and M. Z. Kandar. 2019. "Factors Contributing to the Design of Environmentally Sustainable Mosques." *Journal of Building Engineering* 23: 27-37. <https://doi.org/10.1016/j.jobbe.2019.01.024>
- Bagasi, A. A., and J. K. Calautit. 2020. "Experimental Field Study of the Integration of Passive and Evaporative Cooling Techniques with Mashrabiya in Hot Climates." *Energy and Buildings* 225.
- Belzer, D., G. Mosey, P. Plympton, and L. Dagher. 2007. *Home Performance with ENERGY STAR: Utility Bill Analysis on Homes Participating in Austin Energy's Program*. Golden, CO: National Renewable Energy Laboratory. <https://doi.org/10.2172/910503>
- De Dear, R., and G. Brager. 2002. "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55". *Energy and Buildings*, 34 (6): 549–561. [https://doi.org/10.1016/s0378-7788\(02\)00005-1](https://doi.org/10.1016/s0378-7788(02)00005-1)
- Fathy, H. 1986. *Natural Energy and Vernacular Architecture*. Chicago: University of Chicago Press.
- Ferwati, M. S. 2014. *Self-cooling wall*. *Online International Interdisciplinary Research Journal* 3 (6, Nov–Dec). [https://www.academia.edu/7488347/Self\\_cooling\\_wall?email\\_work\\_card=view-paper](https://www.academia.edu/7488347/Self_cooling_wall?email_work_card=view-paper)  
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- Gaete, J. 2012. "Brick Pattern House / Alireza Mashhadmirza." *ArchDaily*, November 26, 2012. <https://www.archdaily.com/298353/brick-pattern-house-alireza-mashhadmirza>
- Headley, D., N. Almerbati, P. C. Ford, and A. Taki. 2015. "From Research to Practice: Exploring 3D Printing in Production of Architectural Mashrabiya." In *Living and Learning: Research for a Better Built Environment: 49<sup>th</sup> International Conference of the Architectural Science Association 2015*, edited by R. H. Crawford and A. Stephan, 1009–1017. Melbourne: The Architectural Science Association and The University of Melbourne.
- Heidari, A., S. Sahebzadeh, and Z. Dalvand. 2017. "Natural Ventilation in Vernacular Architecture of Sistan, Iran; Classification and CFD Study of Compound Rooms." *Sustainability* 9 (6): 1048. <https://doi.org/10.3390/su9061048>.
- Holloway, J. 2013. "Modernizing the Mashrabiya: Smart-Skinned Al Bahar Towers near Completion." *New Atlas*, February 7, 2013. <https://newatlas.com/al-bahar-towers/26139/>.
- Jett, M. 2011. "The Mashrabiya House / Senan Abdelqader." *ArchDaily*., October 14, 2011. <https://www.archdaily.com/175582/the-mashrabiya-house-senan-abdelqader>
- Khadra, A. A., & N. Chalfoun. 2014. "Development of an Integrated Passive Cooling Façade Technology for Office Buildings in Hot Arid Regions." *WIT Transactions on Ecology and The Environment* 190. <https://doi.org/10.2495/eq140501>
- Kumar, S., J. Mathur, S. Mathur, M. K. Singh, and V. Loftness. 2016. "An Adaptive Approach to Define Thermal Comfort Zones on Psychrometric Chart for Naturally Ventilated Buildings in Composite Climate of India." *Building and Environment* 109, 135–153. <https://doi.org/10.1016/j.buildenv.2016.09.023>
- Kumar, P. 2014. *Traditional Perforated Screens of India*. Final thesis project of MSc Sustainable Environmental Design. London: Architectural Association School of Architecture.
- Rael, R. 2015. "Cool Brick." *Emerging Objects*. March 7, 2015. <http://emergingobjects.com/2015/03/07/cool-brick/>.
- Salem, R. 2019. *Evaluating Environmental Performance of Mashrabiya*. London: University of Westminster.
- LocalConditions.com. n.d. "San Antonio, TX Past Weather." *LocalConditions*. Accessed February 10, 2025. <https://www.localconditions.com/weather-san-antonio-texas/78201/past.php>.
- Shahda, M. M. M., and Noseir, S. 2021. *Traditional Environmental Treatments in Arab Architecture: As a Guide to Contemporary Architecture*. Port-Said Engineering Research Journal 25 (2). <https://doi.org/10.21608/psrj.2021.72763.1106>
- Time and Date AS. n.d. "Past Weather in San Antonio, Texas, USA — Yesterday or Further Back." *Time and Date*. Accessed February 10, 2025. <https://www.timeanddate.com/weather/usa/san-antonio/historic>.
- U.S. Energy Information Administration (EIA). N.d. - "Residential Energy Consumption Surveys (RECS) Reports." *U.S. Energy Information Administration*. Accessed February 10, 2025. <https://www.eia.gov/consumption/residential/reports.php>