International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 09 Issue: 03 | Mar 2022 www.irjet.net p-ISSN: 2395-0072

Significance of Jaali on Thermal Performance of Buildings: The Effects of Daylighting and Air Penetration in Hot Dry and Warm Humid Climates

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Abstract - *Traditional architecture has proven popular for simplistic solutions to difficult climate and environmental concerns. The pursuit of thermal and visual comfort has become more difficult as we embrace new materials and processes. Jaalis have traditionally been utilized in buildings to provide thermal comfort, privacy, shading, and manage daylighting and air penetration. Despite the growing interest in incorporating these vernacular tactics into modern structures, there are few studies that look at the connection between varied screen geometries, perforation percentages, shape, and materials, as well as their effects on the indoor environmental quality from both aesthetic and thermal perspectives. A comparative investigation of the performance of the Jaali is performed using case studies from India's hot dry climate and warm humid environment. The combined effect of daylighting and air penetration on the thermal performance of a structure is discussed in this study in terms of perforation percentage and size. This research gives a thorough understanding of the parameters of Jaali, which have an essential factor in a building's thermal comfort, and serves as a starting point for additional research into pattern designs in terms of daylighting and air penetration. The findings inspire architects and engineers to devise a framework for optimizing the usage of Jaali perforations in accordance with the building plan.*

Key Words: Jaali, Perforated screens, Daylighting, Air penetration, Thermal performance, Passive cooling, Natural ventilation, Perforation percentage, Perforation size, Sustainable architecture

1. INTRODUCTION

A perforated stone or latticed screen with an ornate pattern made up of geometry or calligraphy is known as a Jaali. In Indo-Islamic and Islamic architecture in general, this sort of architectural decoration is common. It provides protection from the glare of the sun while facilitating natural lighting and air circulation thus acting as a passive cooling feature. When a more practicable alternative is identified, architectural techniques, styles, and traditions become outdated. In today's world, the simplest option is to use HVAC appliances, which results in increased energy consumption and carbon emissions. This necessitates a return to traditional architecture and the borrowing of some of its aspects after fully comprehending its potential. This paper examines one such passive design method, Jaali, which has been used in traditional Indian buildings, as well as its possibilities in modern design.

Various aspects of thermal comfort can be achieved by adjusting the various parameters of a Jaali. Although there have been individual investigations on the influence of Jaali on thermal and visual comfort, the influence of Jaali patterns, perforation size, and percentage on thermal comfort has yet to be completely investigated. The impact of external traditional perforated screens - Jaalis, which are often used in the Middle East and Southeast Asia, on building thermal comfort in two climate contexts – hot dry and warm humid is investigated in this study. Screen geometries, perforation size, perforation percentages, thicknesses, orientations, and climate zone variances are among the variables investigated.


Fig -1: Nachna Parvati-Temple Jaali, Gupta period
Fig -2: Jaali showing geometrical and floral patterns

1.1 History of Jaali

Since time immemorial, the Jaali, or perforated screens, have been widely used in Indian architecture. 'Jaali' is derived from the Sanskrit word for 'net'. Jaali was a method of design popular in India throughout the Mughal and Rajput periods, and it was usually composed of sandstone, marble, and clay.

These latticed and perforated slabs were intended to be used as window coverings, room dividers, and balcony railings. Although they are not unique to South Asian construction, they are a popular architectural feature among Mughal architects. The Jaali not only gave artistic flair to the spectacular Indo-Islamic architectural wonders of this golden era, but they also served functional objectives including air circulation, shade from harsh sunshine, and privacy. The Jaali exemplifies the Mughal fascination of arabesque and geometric motifs. The Jaali was typically of a simpler hexagonal and octagonal shape in early Mughal architecture under Akbar. During his grandson Shah Jahan's reign, additional plant and floral motifs were employed.

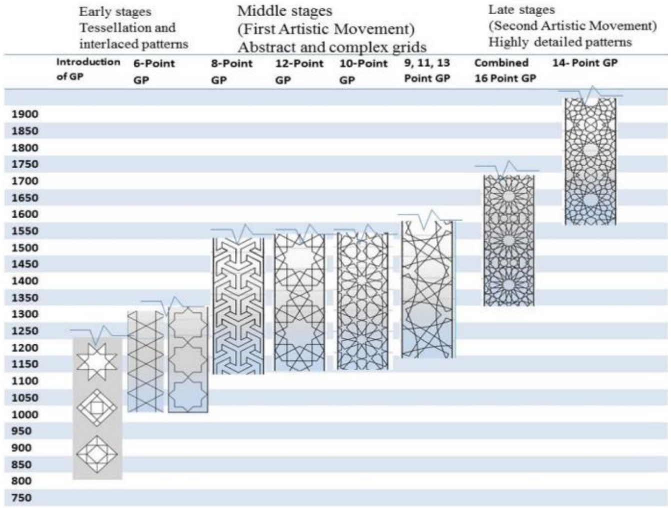


Fig -3: Graph showing the evolution of complexity in the Jaali patterns

1.2 Functions of Jaali

Jaali is not just a culturally decorative element, but has also many important functions as a significant environmental element.

Fig -4: Functions of Jaali

2. CASE STUDIES

There are five hot climates in India, ranging from hot-desert to hot-humid. Thus, Jaali has been researched in a range of two climates in order to accomplish the major goal of this study, which is to investigate its primary feature of climatic responsiveness. The fieldwork takes place in two climates: a hot semi-arid climate (Jaipur, India) and a humid sub-tropical climate (Agra, India). It was chosen for its progressive changes in humidity, precipitation, and wind speed.

The Jaali at the palace of Hawa Mahal was selected for the hot semi-arid climate of Jaipur. The palace is known to be structured in such a way that it permits the proper volume of air with creative techniques for summer cooling and winter heating, as well as constant cross ventilation. In Agra's humid subtropical climate, the Tomb of Salim Chisti, a prominent destination of prayer, was chosen for its unique Jaali. This Jaali, built of marble, is a vivid specimen of traditional Indian architecture expertise. The comfort achieved in a naturally ventilated area using Jaali as the major source of ventilation (opening) was researched in terms of the particular characteristics. The temperature difference provided by the Jaali, the quantity of wind let in by the Jaali, and the quantity of daylight gained in the area were all measured.

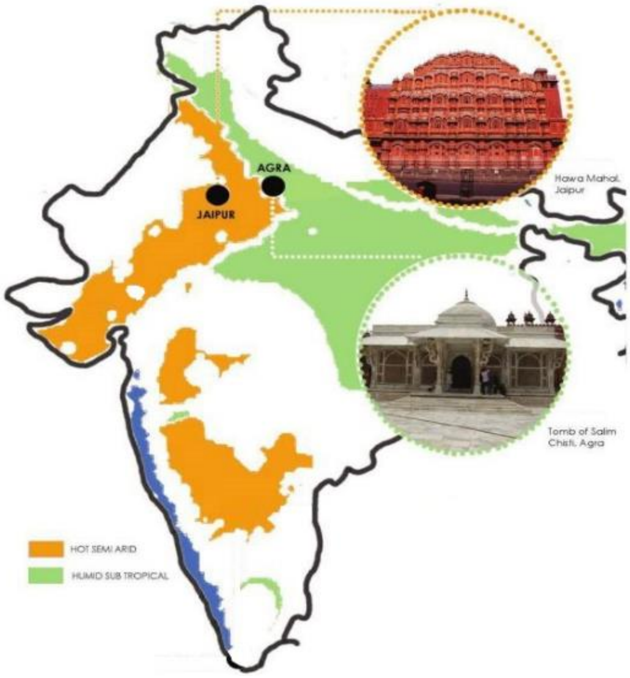


Fig -5: Climatic classification showing the case studies chosen

A spot measurement tool was utilised to measure temperature, humidity, wind velocity, surface temperature, and luminance. To assess the performance of the Jaali in particular, a comparison of measures from the outside to the inside must always be made, ideally at the same time.

2.1 Hawa Mahal, Jaipur

The 16th-century Hawa Mahal is one of the finest examples of passive cooling systems in a hot dry region. Flow of air is accomplished by 953 different types of fenestrations, with varying lattice work on each floor, allowing air to flow at a steady velocity throughout the building.

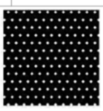
Fig -6: Sketches showing the windows to wall ratio and the wind flow

Due to the venturi effect, cool air enters the structure through lattice work and small windows, generating a difference in temperature. According to the Bernoulli-Venturi principle, Jaalis are positioned at an angle to maximise wind flow. In this Palace, there are three different varieties of Jaali. Glazed Jaali, Floral shaped perforated Jaali, and Rectangular shaped perforated Jaali are those types. Both of the perforated Jaalis on the West facade have been chosen to be researched.

Fig -7: Figure showing the different patterns in the Hawa Mahal

Fig -8: The queen's chamber viewed from the inside

Table -1: Summary of Measurements taken from the Hawa Mahal, Jaipur

	DESIGN OF THE SCREEN		TEMPERATURE DIFFERENCE	WIND PENETRATION	DAYLIGHT LEVEL
	SECTION	ELEVATION	AVG OUTDOOR: **34.0C**	AVG OUTDOOR: **2.02 m/s**	AVG OUTDOOR: **10,750 LUX**
JAALI-01 PERFORATION **12%**			AVG INDOOR: **31.2 C** OUTDOOR-INDOOR TEMPERATURE DIFFERENCE: **2.8 K**	**AVG 58% OF THE OUTDOOR WIND** WAS LET INSIDE	AVG INDOOR: **105 LUX** DAYLIGHT FACTOR ACHIEVED INDOOR: **0.98**
JAALI-02 PERFORATION **35%**			AVG INDOOR: **30.8 C** OUTDOOR-INDOOR TEMPERATURE DIFFERENCE: **3.2 K**	**AVG 65% OF THE OUTDOOR WIND** WAS LET INSIDE	AVG INDOOR: **160 LUX** DAYLIGHT FACTOR ACHIEVED INDOOR: **1.48**

2.2 Tombs in Fatehpur Sikri, Agra

The tomb of Salim Chishti is probably one of the greatest examples of Mughal art and architecture. It's made of white marble and has magnificent lattice windows on all sides. The carvings on the Jaalis are extremely detailed. The majority of these Jaalis are crafted from a single stone. Aside from this tomb, there is another red sandstone structure named the tomb of Islam Khan, with similar Jaali which serves the same purpose.

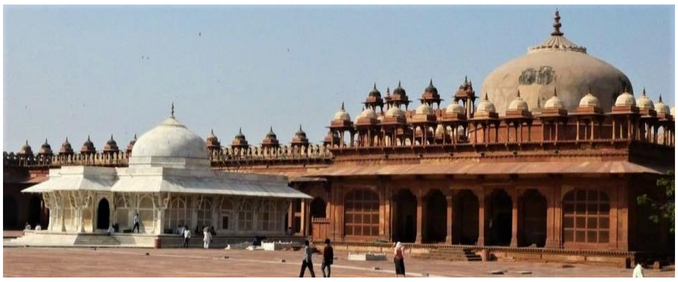


Fig -9: The tomb of Islam Khan located near the tomb of Salim Chishti

A large sloping stone projection (Hindi chajja) supported by beautiful serpentine brackets shades the building. Each bracket is monolithic, with lacelike floral and geometric designs cut into the curves' gaps. Jaali 03 refers to marble Jaali, while Jaali 04 refers to sandstone Jaali. Because it appears in all orientations, this pattern was chosen for investigation. Salim Chisti's tomb is built on a 1m-high platform with five steps leading to the entry portico.

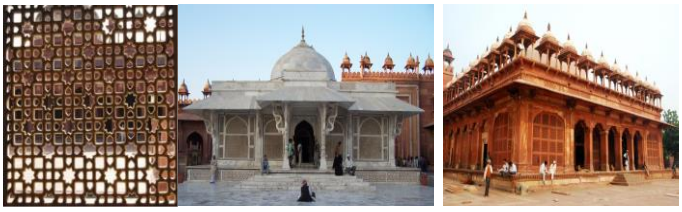
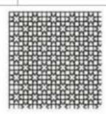
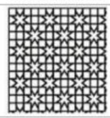


Fig -10: Figure showing the pattern used in the tombs

The ivory-colored marble structure is exquisitely sculpted. Black and yellow marble mosaics in geometric designs adorn the plinth. Islam Khan's tomb is a red sandstone structure with 36 little domed kiosks or chattris atop it.

Table -2: Summary of Measurements taken from the tombs in Fatehpur Sikri, Agra

	DESIGN OF THE SCREEN		TEMPERATURE DIFFERENCE	WIND PENETRATION	DAYLIGHT LEVEL
	SECTION	ELEVATION	AVG OUTDOOR: **32.8 C**	AVG OUTDOOR: **1.94 m/s**	AVG OUTDOOR: **27,500 LUX**
JAALI-03 PERFORATION **65%**			AVG INDOOR: **30.0 C** OUTDOOR-INDOOR TEMPERATURE DIFFERENCE: **2.8 K**	**AVG 50% OF THE OUTDOOR WIND** WAS LET INSIDE	AVG INDOOR: **478 LUX** DAYLIGHT FACTOR ACHIEVED INDOOR: **1.74**
JAALI-04 PERFORATION **75%**			AVG INDOOR: **31.8 C** OUTDOOR-INDOOR TEMPERATURE DIFFERENCE: **1.0 K**	**AVG 73% OF THE OUTDOOR WIND** WAS LET INSIDE	AVG INDOOR: **789 LUX** DAYLIGHT FACTOR ACHIEVED INDOOR: **2.90**

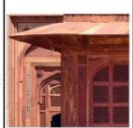
2.3 Comparative Analysis

In the observation table, the temperature differential obtained indoors, daylight levels, and air penetration are shown. This is owing to the space's design, which orients the Jaali toward the wind's direction. Continuous across ventilation achieved in the space from all the sides. There is no shade feature in the Hawa Mahal and is compensated by the smaller perforations and windows. The presence of a shade element in the tombs keeps direct sunlight out for the majority of the day.

The Jaali 01's perforations were floral in shape, 30mm in diameter, and the screen was only 10mm thick; and because of its shape, it did not allow direct sunlight inside. The perforations are extremely small, averaging about 11% per square metre. As a result, only a little amount of air could enter the area. The semi-arid environment receives very little rain and hence the lack of shade element, thus it would be beneficial to let the rain fall on the building surfaces to offer convection cooling. Unless the windows are open, this space doesn't receive direct sunlight. The daylight factor was 0.5, which is adequate for everyday purposes. The Jaali 02 has rectangular holes that are angled downwards and are 100mm thick. It did not allow direct sunlight into the palace because it was angled downwards. Because the panel has a perforation percentage of 30% per sq.m., it allows a huge amount of air to get through.

Table -3: Comparative analysis of the selected case studies

JAALI SPECIFICATIONS								THERMAL PERFORMANCE		
CLIMATE	JAALI	DETAILS	JAALI PATTERN	PERFORATION PERCENTAGE	AREA OF EACH PERFORATION (SQ.M)	THICKNESS	SECTION	AVG. EXTERNAL TEMPERARURE	AVG. INTERNAL TEMPERARURE	EXTERNAL-INTERNAL TEMPERATURE DIFFERENCE
HOT SEMI ARID CLIMATE	JAALI-01	HAWA MAHAL, JAIPUR QUEENS'S CHAMBERS 16TH CENTURY 26.9N 75.8E		12%	0.03 radius 0.003 sq.m	60mm		34.0 C	31.2 C	2.8 K
	JAALI-02	HAWA MAHAL, JAIPUR SEMI OPEN SPACE 16TH CENTURY 26.9N 75.8E		35%	0.10X0.05 0.005 sq.m	100mm		34.0 C	30.8 C	3.2 K
HUMID SUBTROPICAL CLIMATE	JAALI-03	TOMB OF SALIM CHISTI, FATEHPUR SIKRI TRANSITIONAL SPACE 14TH CENTURY 27.1N 78.0E		65%	0.04X0.04 0.0016 sq.m	100mm		32.8 C	30.0 C	2.8 K
	JAALI-04	TOMB OF ISLAM KHAN, FATEHPUR SIKRI PRAYER SPACE 15TH CENTURY 27.1N 78.0E		75%	0.06X0.06 0.0036 sq.m	100mm		32.8 C	31.8 C	1.0 K

JAALI SPECIFICATIONS			DAYLIGHT PERFORMANCE			AIR PENETRATION			CONCLUSION
CLIMATE	JAALI	DETAILS	SHADING ELEMENT	OUTDOOR ILLUMINANCE (AVG)	INDOOR DAYLIGHT FACTOR	ORIENTATION OF THE SCREEN - WIND DIRECTION	AVG. EXTERNAL WIND VELOCITY	AVG. AIR PENETRATION %	ANALYSIS
HOT SEMI ARID CLIMATE	JAALI-01	HAWA MAHAL, JAIPUR QUEENS'S CHAMBERS 16TH CENTURY 26.9N 75.8E		10750 LUX	0.98	West winds - Screen facing West	2.02 m/s	58%	This Jaali allows 60% of the outside air velocity but has a low perforation. So only a small amount of air enters the space and provides sun protection. As a result, it provides the main ventilation of the room, providing comfort.
	JAALI-02	HAWA MAHAL, JAIPUR SEMI OPEN SPACE 16TH CENTURY 26.9N 75.8E		10750 LUX	1.48	West winds - Screen facing West	2.02 m/s	65%	This Jaali is used in semi-open spaces as it has relatively large openings to allow a greater amount of air. Angled perforations block direct sunlight and blocks vision.
HUMID SUBTROPICAL CLIMATE	JAALI-03	TOMB OF SALIM CHISTI, FATEHPUR SIKRI TRANSITIONAL SPACE 14TH CENTURY 27.1N 78.0E		27500 LUX	1.74	North winds - Screen facing West	1.94 m/s	50%	The high perforation rate ensures good night ventilation and the sunshade elements keep sunlight out throughout the day.
	JAALI-04	TOMB OF ISLAM KHAN, FATEHPUR SIKRI PRAYER SPACE 15TH CENTURY 27.1N 78.0E		27500 LUX	2.90	North winds - Screen facing North	1.94 m/s	73%	The high perforation and small shade allow direct sunlight to pass through all day.

3. FINDINGS

The amount of direct sunlight that enters and exits the space, as well as the volume of air that enters and escapes the room for basic ventilation, are determined by the perforation percentage. Solar protection and air penetration, as well as day lighting, are important considerations in the construction of the Jaali. A specific perforation percentage can have holes of any size, and a specific perforation size can be a component of any perforation percentage. Perforation percentage effects the volume of air entering the room as well as the direct sunlight when the size or area of a perforation delivers a specific air velocity into the space.

Fig -11: Figures showing the daylight entering through the Jaali screens

The design criteria of Jaali concentrate on two primary requirements: preventing direct solar radiation and ensuring adequate air velocity. Perforation % refers to the ratio of open to closed perforations in a Jaali. The first step in creating a Jaali is determining the perforation %, which is determined using the following parameters. The dry climate seeks to prevent significant volumes of air from entering the space, according to climate research. To achieve evaporative cooling, humid circumstances necessitate a considerable volume of air. In wet climates, a shading element is usually included, however in dry climates, the Jaali with small perforations will operate as a shading element. The percentage of perforation is directly proportional to the amount of daylight.

Table -4: The table showing the factors that decide the perforation percentage of the Jaali

PERFORATION %	12%	35%	65%	75%
SIZE	0.003 sq.m	0.005 sq.m	0.0016 sq.m	0.0036 sq.m
THICKNESS	60mm	100mm	100mm	100mm
HUMIDITY LEVEL	DRY	DRY	HUMID	HUMID
PROVIDE SHADING	YES	NO	NO	NO
PREVENT GLARE	YES	YES	NO	NO
DAYLIGHTING	NO	NO	YES	YES

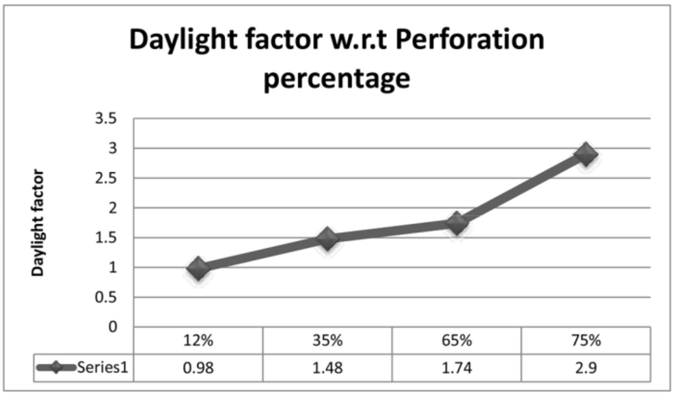


Chart -1: Graph showing the daylight factor with respect to perforation percentage

The size of each perforation is not determined when defining the perforation percentage. Perforation percentages can be built in a variety of ways, and so operate differently. Because of the hot, dry climate, the perforation percentage in Jaali 1 is 12 percent, with perforations measuring 0.003 m2. However, the same 12 percent perforation Jaali can be built with a larger perforation area (larger perforations), which may not function as good as the Jaali with smaller perforations.

The Jaali 3 and 4 have a 65 and 75 percent perforations, respectively. The Jaali 4 enables 73 percent of the outside air velocity, but the Jaali 3 only allows 50 percent of the outside air velocity. As a matter of fact, the size of the perforation has an impact on the air velocity inside the gap.

Table -5: The table showing the air penetration percentage of the Jaali from the case studies

PERFORATION DIMENSION	0.03 radius	0.10*0.05	0.04*0.04	0.06*0.06
PERFORATION SIZE	0.003 sq.m	0.005 sq.m	0.002 sq.m	0.004 sq.m
OUTSIDE WIND VELOCITY (m/s)	2.2	2.2	1.7	1.7
AVERAGE AIR PENETRATION %	60%	67%	44%	70%

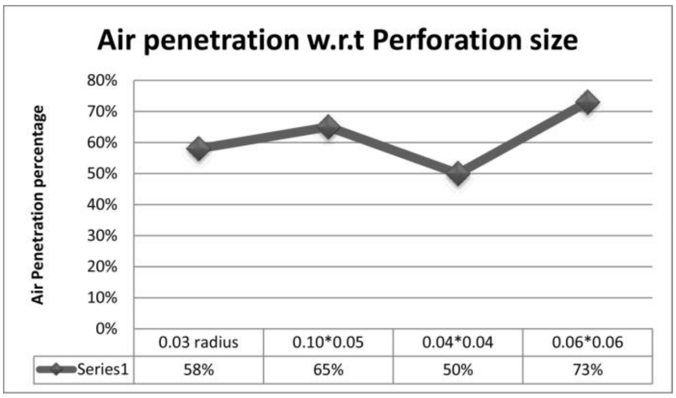


Chart -2: Graph showing the air penetration with respect to perforation size

4. CONCLUSIONS

The research of the Jaali's origins revealed the Jaali's diversity as well as its importance in traditional hot-climate architecture. Every case of the Jaali identified demonstrates its sensitivity to changes in hot conditions and the functions it performs. In some circumstances, the Jaali are also employed in the inner walls to allow for air flow within the space caused by pressure differential between the spaces.

According to some published study, employing the Jaali as sun screens will save 30% of the energy consumed to cool the area. The goal of this study is to learn more about the Jaali by looking at its important properties, such as giving ventilation and light and understanding how it affects the thermal performance of the buildings.

As a result of quantifying the Jaali through case studies, correlations between the Jaali and the space and function were discovered. The following are the three research findings:

- The relationship between the Jaali's size (perforation percentage) and the amount of air, shade, and day lighting it will supply.
- The air velocity required in the room or the amount of daylight required in the space can determine the space's comfort. The size of the perforation is chosen in light of this requirement.
- The perforation percentage is directly proportional to the amount of daylight that enters the space. The larger the percentage of perforation, the better the day light will be within the space.

To properly integrate Jaalis in design to provide improved comfort, one must first comprehend them. The Jaali is a prominent component of Mughal architecture that keeps the interior rooms cool. It regulates airflow and decrease the temperature of internal areas. The study aids in the creation of an optimum Jaali pattern that architects and building performance engineers can utilise to create building screens that improve interior air quality and reduce energy usage. The paper's findings show that the perforation percentage and size of Jaali screens can be adjusted to create well-lit, thermally comfortable indoor spaces.

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