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Optimization of the direction and number of atrium openings in a centralized model for improving thermal comfort in office buildings in hot and dry climates (case study of Yazd city)

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Abstract

Passive design strategies such as central atriums have emerged as effective solutions to reduce heat load and improve thermal comfort in hot and dry climates such as Yazd due to increasing concerns about climate change. This study examines the impact of various atrium opening configurations on thermal comfort and energy consumption in Yazd. It aims to determine the optimal combinations of openings to enhance year-round comfort, particularly during the challenging summer months. The study utilizes the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices to assess climatic performance, which is modeled using the Grasshopper plugin and the Honeybee and Ladybug algorithms. Results indicate that the optimal atrium design involves positioning openings in an eastern orientation, with a PMV of 2.218. This significantly reduces summer heat load and improves comfort during milder seasons. Additionally, combinations of eastern with southern or northern openings were also identified as effective, as they reduced internal heat gain during summer while maintaining comfortable conditions during spring and autumn months. The findings highlight that in summer, the East orientation provides the highest thermal comfort, followed by the East-North-South orientation with a PMV of 2.207. The East-North-West orientation provides satisfactory performance in both spring and summer, but not as effectively as the East-North-South orientation. This research highlights the importance of optimizing atrium opening configurations to reduce reliance on mechanical systems and enhance energy efficiency. This is particularly in climates with extreme summer temperatures, such as Yazd.

Keywords: Opening orientation, number of openings, central atrium, thermal comfort, hot and dry climate, Yazd city.

1. Introduction

Various technologies and design options can enhance the performance of buildings, steering them towards achieving a future with zero energy consumption (Moosavi et al., 2014). A central atrium is a large, spacious glass area typically situated at the center of a building .It is commonly used in non-residential buildings to provide natural light and absorb solar heat into the interior spaces (Ayala et al., 2013). Modern atriums were initially designed in temperate climates to ensure adequate sunlight supply (Shaeri et al., 2023). Studies have been conducted on atriums and their impact on energy consumption in buildings across different climates. As climate change continues, this building design aspect can become crucial. The use of atriums in buildings in hot and dry climates is an appropriate design choice, as it helps reduce the heating load of the building by increasing solar heat absorption (Zhai et al., 2023). A well-designed atrium with natural ventilation can reduce the cooling load of a building during hot seasons. The design of atriums in hot climates must be carried out carefully due to the risk of overheating during the warmer months (Shahmortezaei & Sabernejad, 2016). In summer, energy consumption in buildings with atriums may increase due to excessive solar heat absorption. However, by strategically utilizing the available openings in the atrium, the solar chimney effect can be created above the atrium, which induces air suction. This airflow helps cool the internal environment of the atrium and its adjacent spaces (Shakouri et al., 2022). Therefore, using a central atrium in hot climates requires careful consideration of the number of openings, dimensions, and orientation (Rice, 2023). The end openings of the atrium play a key role in natural ventilation and solar radiation, particularly during the hot season in hot and dry climates. From an energy efficiency perspective (Sorayaei et al., 2023), heat, natural light, acoustics, and natural ventilation are the most effective design parameters for ensuring comfort in a central atrium (Saxena & Sharma, 2021). The thermal performance and ventilation of atriums depend on the characteristics of the openings, the atrium's geometry, the properties of the roof and windows, and the building materials. Among these, the size of the exit openings is the most important factor (Acred & Hunt, 2014). Several studies have examined the impact of opening aspects on the thermal performance of atriums (Mouriki et al., 2008).Hunt and colleagues investigated the impact of atrium geometry on natural ventilation. They concluded that the lower section of the atrium should be larger than the upper section and emphasized the importance of the size of the exit openings at the end of the atrium (Holford & Hunt, 2003) Using louvers on atrium windows can also help prevent excessive heat and natural light during hot seasons. This study primarily aims to

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evaluate the positioning and orientation of central atrium openings to optimize thermal comfort. It seeks to simulate various conditions of central atriums in the hot and dry climate of Yazd. In this context, thermal comfort modeling will be performed using parameters like PMV (Predicted Mean Vote) to assess the impact of design changes on the thermal comfort of occupants. The research aims to provide solutions for improving the conditions of central atrium comfort that maximize thermal comfort in the surrounding spaces while minimizing the need for heating and cooling systems.This study will focus on the effects of orientation and the number of openings in the central atrium of Yazd. Advanced modeling software such as Rhino and the Grasshopper plugin will be used for these analyses. These software tools, especially with the help of complex algorithms, can simulate different environmental conditions and assess their impact on thermal comfort. In this study, various models will be used to analyze airflow, solar radiation, and thermal behavior across different seasons. Since the research adopts a comparative approach, it aims to solve climatic challenges by identifying each climate and working towards better conditions. Therefore, the spring season will be considered a moderately hot climate (March-April-May), and the fall will be considered a moderately cold climate (September-October-November). The Honeybee plugin will be used to simulate various environmental conditions and analyze the results. One of the primary objectives of this research is to optimize the direction and number of atrium openings to enhance thermal comfort. This optimization should maximize natural ventilation and daylight during the hot seasons in a hot and dry climate, minimizing energy consumption for cooling.

Research Questions: This research aims to answer the following questions:

- Which direction of atrium openings has the most significant impact on thermal comfort during the hot seasons in Yazd's hot and dry climate?
- How many openings in a central atrium can optimize natural airflow and reduce thermal load during the hot seasons in a hot and dry climate?
- To what extent can the optimal orientation and number of openings impact thermal comfort?

2. Research Background

Some studies have evaluated the thermal performance of atriums using various ventilation strategies, with some of them employing other techniques such as solar protection (Pfafferott et al., 2004). These strategies have been combined. The results showed the use of various ventilation strategies, including nighttime ventilation and stack ventilation, can significantly improve thermal performance (Ayala et al., 2013), They have significant cooling potential. Hybrid nighttime ventilation strategies are more effective in buildings with high thermal mass. Hossein and Osthauseen studied various atrium configurations combined with a thermal control system (SC) (Hussain & Oosthuizen, 2012).The results showed that thermal comfort in spaces where solar energy aided natural ventilation was more comfortable when a thermal control system (SC) was used in the atrium (Shafiei Fini & Moosavi, 2016). Aylaw and colleagues examined the combination of atriums and solar chimneys for space cooling. The results showed an increase in natural ventilation. Numerical simulations of fire experiments in an atrium with natural ventilation demonstrated improved airflow and cooling effectiveness (Ayala et al., 2013). It showed no significant differences between the roof geometries, and the atrium shapes were evaluated. Although the best configuration was a combination of vertical and sloping walls, thermal comfort in the lower floors below the neutral pressure level increased with converging sloping walls (Zou et al., 2025) . A study on venturi-shaped roofs for buildings with natural ventilation driven by wind showed that the optimal configuration is without guide vanes (van Hooff et al., 2011). In another study, Barsim and colleagues evaluated the impact of combined natural and mechanical ventilation in fire tests within an atrium. The dynamic behavior of smoke was determined with both natural ventilation and hybrid ventilation systems (Barsim et al., 2020). Gong and Hong analyzed an atrium building.They examined the effects of natural ventilation influenced by two gravitational forces within the atrium (Gong, 2019). Atrium simulation methods using CFD (Computational Fluid Dynamics) and energy models have been analyzed (Pan et al., 2010). The effect of pre-cooling nighttime ventilation on reducing the thermal load in a non-residential building exposed to a hot climate was evaluated. The results showed that the cooling load decreased by 27% when a combination of wind and natural stack ventilation was used (Ratajczak et al., 2023). This study also showed that dynamic thermal simulations have limited errors in predicting results and are acceptable for evaluating natural ventilation (Ye et al., 2024). In hot and humid climates, fresh air can enhance natural ventilation in atriums (Shayanian & Qhadikolaei, 2024). In such climates, gravity-driven ventilation is only adequate during the intermediate seasons. Additional ventilation from wind or mechanical ventilation is necessary in the summer to ensure indoor thermal comfort (Liu et al., 2009). Therefore, there is a need for further studies in BWh climates to define appropriate design and techniques utilizing the potential of natural ventilation. Lin and colleagues have suggested evaluating the impact of external wind on building geometry using CFD models. Abdullah and colleagues demonstrated that with shutters and water spraying, the indoor air temperature could vary by up to 8.7°C from the average (Lin & Linden, 2002). In Table 1 presents the relevant literature related to the research topic.

Table 1
Literature Review

References	Case Study	Limitations	Requirements/Efficiency	Related Parameters	Method	Design Parameter	Impact
Ye ،Zhang ، Li ،& Braham (2024) ،	An office building in Wuxi, Jiangsu Province, China	Solar heat gain discharged is approximately 100W per m² at the internal glass surface in double-glazed shells.	Reduces heat load up to 25% of the glass height.	Atrium Dimensions	Analytical Model, Field Measurements	Height, Window Size, Shading Devices, Double Glazed Shell	Airflow Rate, Solar Heat Gain, Energy Efficiency
)Jin et al., 2024(	Buildings A and B, Science Center in Suzhou, China	Requires changes in courtyard design and structure to optimize ventilation	Airflow and thermal environment evaluation under internal-external pressure differences	Internal & External Pressure, Speed and Temperature	Natural Simulation Model, Field Experiments	Natural Ventilation System	Ventilation and Temperature
)Heydari et al., 2024(	High-rise office buildings in Tehran	Four-sided atriums have lower energy reduction performance.	One-sided atriums provide the most significant energy load reduction, while four-sided atriums perform better in natural light use.	Atrium Position and Geometry	CFD Simulation, Energy Consumption Simulation	Atrium Geometry	Energy Load Reduction, Natural Ventilation
Gong & Hang (2019), van Hooff ، Blocken ، Aanen ،& Bronsema (2011)،	A guesthouse in China	Side lighting roof form is more prominent than the roof above the atrium in hot and humid climates with less daylight.	(Height) 2.5m wall-to-ceiling gap. (Connection) For side lighting models, a 1.5m overhang above the clerestory regions. (Solar Chimney) Taller solar chimneys provide greater heat absorption and transfer.	Site Measurements, Dynamic Thermal Model (DTM), CFD	Energy Consumption Simulation	Roof Shape, Height, Connection, Solar Chimney	Airflow Rate, Temperature Distribution
Shafiei ، Fini & Moosavi (2016) Ayala Cantizano ، Gutiérrez-Montes ،& Rein (2013) ،	Three-story office building in a temperate climate	Larger floor heights require more effective opening areas. More floors increase the temperature within the building.	Controllable openings can reduce the hours when the temperature exceeds 25°C by half.	Floor Height, (Size) Moderate upper opening size,	DTM, CFD, Small-Scale, Theoretical, Mathematical ,	Opening Size, Position, Number, Status	Airflow Rate, Temperature
،Pfafferott & ،Herkel Wambsganß، (2004) Hussain & Oosthuizen ،(2012) Moosavi et al. (2014)	Green building educational center, Taiwan	Rectangular atriums with a high length-to-width ratio are more energy-efficient.	Larger atriums improve ventilation in high-rise buildings. For heating, the larger the glass height, the smaller the atrium diameter.	Opening Size, Glass Height	CFD, Analytical Model, Energy, DOE-2.1E	Atrium Size, Height, Shape	Airflow Rate, Energy Load
Taleghani et al. ،(2014) Moosavi et al. (2014)	Concordia University Engineering Building, Canada	High thermal mass and low external temperature are required for high efficiency.	Heat removal via concrete slabs is 2 to 5 times higher when the average inlet air temperature is 12°C compared to 15 or 18°C.	Mass, Average Inlet Air Temperature	Full-Scale Testing, CFD, Reduced-Scale	Materials (Thermal Mass)	Heat Removal, Airflow Rate, Temperature Distribution
Ayala et al. ،(2013) Moosavi et al. (2014)	Green building educational center, Taiwan	Connected opening geometry significantly impacts transient behavior.	(Size) Minimal temperature difference between large openings or atrium spaces to the outside. (Position) To effectively evacuate stagnant upper heat, upper opening position should be high. (Operation) Smart control of openings needed to avoid wind impact on airflow patterns.	Atrium Size, Connected Opening Geometry	CFD, Reduced-Scale, Mathematical Model, Theoretical Analysis	Ventilation Performance (Opening Size, Position, Operation)	Flow Regimes, Airflow Patterns
& ،Lin ،Liu Chou ،(2009) Wang et al. (	Green building educational center, Taiwan	Theoretical models may not fully simulate real-world layering complexities.	Larger atriums and connected openings improve ventilation. (Enclosure Level) In multi-story buildings connected to central atriums, nighttime pre-cooling at higher atrium floors may experience delays.	Connected Opening Geometry, Enclosure Level	Theoretical, Experimental, Mathematical Model	Atrium Geometry (Size, Enclosure Level, Layering)	Transient Layering Behavior, Nighttime Pre-Cooling

In addition, evaporative cooling, pre-cooling, and humidity control are issues that have been suggested for further studies in semi-hot climates (Abdullah et al., 2009).
Mousavi and colleagues investigated effective designs for natural ventilation in atriums and their thermal performance. Atrium geometry, openings, roof features, and window materials are among the parameters that affect natural ventilation in the atrium and thermal comfort. They also concluded that the exit openings' size has the most significant impact on thermal comfort and ventilation (Yetiş & Kayılı, 2024).
Mousavi and colleagues examined effective designs for natural ventilation in atriums and their thermal performance. The geometry of the atrium, the design of its openings, roof features, and the materials used for windows are key factors that affect natural ventilation and thermal comfort. Additionally, they concluded that the size of the exit openings plays the most significant role in thermal comfort and ventilation (Moosavi et al., 2014).
Heidari and colleagues also focused on searching for forms that offer high energy efficiency and indoor air quality during the hot seasons. In this study, the geometry and the position of the atrium were examined simultaneously. The tools used to assess the atriums included Computational Fluid Dynamics (CFD) and integrated building energy consumption simulation. The results show that in square and rectangular designs (in the east-west direction), the most significant reduction in energy load is associated with one-sided atriums (Heydari et al., 2024). Jin and colleagues, in their study, explored natural ventilation systems in public buildings with consideration for both thermal and ventilation needs. In this paper, the building design for a science museum and library, focusing on natural ventilation centered around a central atrium, was conducted. Jin and colleagues aimed to fully utilize natural ventilation to cool the spaces under local climatic conditions by optimizing floor layouts, building orientation, and interior structure. the different roof design models, and internal ventilation system control strategies were more precisely proposed to address these issues. Architectural design optimization can maximize energy savings by up to 46.54% (Jin et al., 2024). Pilihchiha and Zarrinmehr concluded that passive methods, such as solar chimneys, can significantly contribute to building ventilation, heating, and cooling. After conducting several simulations with EnergyPlus software, they identified latitude as a key factor in improving solar chimney performance. They suggested that more optimized results could be achieved by altering the room dimensions, using climate-appropriate materials, adjusting the width and height of the solar chimney openings, and creating a shaded atrium (Pilechiha et al., 2022).This research specifically focuses on optimizing the design of atriums in hot and dry climates, such as Yazd. The study aims to identify the best orientation and number of atrium openings for cooling performance during the summer, particularly using the greenhouse effect and wind suction as a passive cooling system. Figure 1 illustrates the research methodology.
The novelty of this research lies in its precise and scientific investigation of the impact of atrium orientation and the number of openings, demonstrating how proper atrium design can serve as a sustainable solution for reducing indoor temperatures during the summer. In this study, the atrium is not only considered as a decorative space but also as a passive cooling system. Harnessing solar radiation on the atrium roof and generating significant heat, it can naturally direct cool air flow through wind suction into the building and adjacent spaces. Utilizing the greenhouse effect on the atrium roof and optimizing the opening design, particularly in hot and dry climates like Yazd, is recognized as an innovative and effective solution for natural ventilation and improving thermal comfort during hot seasons. This approach helps reduce dependence on HVAC cooling systems and can significantly decrease cooling energy consumption. Therefore, by making a precise comparison of the effects of orientation and the number of openings in central atriums, this research, investigates the optimal conditions for thermal comfort in the hot and dry climate of Yazd. The findings can complement and expand upon previous research.

2.1. Fanger's Thermal Comfort Model

Based on empirical observations, Fanger defined a metric called the "degree of feeling known as the PMV (Predicted Mean Vote) index. This index represents the average feeling of individuals under similar environmental conditions. In other words, the PMV index predicts how a group of people will feel in terms of comfort or discomfort when exposed to specific environmental conditions. It is recognized as one of the most important and reliable physiological temperature indices and has various applications in various fields (Kaihoul et al., 2024). In addition to urban and regional planning studies, this index is also used in fields such as meteorology and tourism to analyze thermal comfort and determine suitable conditions for individuals (Sorayaei et al., 2023). The index is calculated through relations 1 to 6, which are described in Table 2.

$$PMV = (0.303^{E-0.036M} + 0.028)[(M - W) - H - E_C - C_{rec} - E_{rec}] \quad (1)$$

$$E_C = 3.05 \times 10^{-3}[5733 - 6.99 \times (M - W) - P_a] + 0.42(M - W - 58.15) \quad (2)$$

$$C_{rec} = 0.0041m(34 - Ta) \quad (3)$$

$$e = (3.05 \times 10^{-3}(256_{tsk} - 3373 - p_a) + E_{sw}) \quad (4)$$

$$E_{rec} = 1.72 \times 10^{-5}m(5867 - P_a) \quad (5)$$

$$H = K_{cl} = t_{sk} - \frac{t_{cl}}{I_{cl}} \quad (6)$$

The PMV scale is a 7-point system for assessing thermal sensation, ranging from -5.3 (cold) to +5.3 (hot). The value Zero on this scale represents a neutral thermal sensation, meaning the individual feels neither too hot nor too cold (Shahmortezaei & Sabernejad, 2016). The closer the value is to zero, the more comfortable the thermal conditions are for the individual (Hatefnia & Ghobad, 2015).

Table 2

Variable Descriptions (Rahaei & Poorsayahi, 2022)

Convective Dry Heat Loss $\left({}^{w}/_{m^2}\right)$	H	Effective Mechanical Force $\left({}^{w}/_{m^2}\right)$	W
Average Skin Temperature) □(	T_{sk}	Partial Vapor Pressure (Pascal)	P_a
Evaporation Heat Transfer on Skin Surface in Neutral Condition	E_c	Average Radiation for Entire Body $\left({}^{w}/_{m^2}\right)$	I_a
Evaporation Heat Transfer from Evaporation $\left({}^{w}/_{m^2}\right)$	E_{rec}	Metabolic Rate $\left({}^{w}/_{m^2}\right)$	M
Convective Evaporation Heat Transfer $\left({}^{w}/_{m^2}\right)$	C_{rec}	Evaporation Heat Transfer from Skin Surface $\left({}^{w}/_{m^2}\right)$	e
Air Temperature)□(	T_a	Clothing Surface Temperature)□ (	T_{cl}

The PPD index is introduced to indicate the percentage of individuals dissatisfied with the thermal conditions of the environment and is calculated based on the PMV index (Ye et al., 2024). This index is expressed as a percentage and is calculated using relation 7.

$$PPD = 100 - 95e^{-(0.03353PMV4+0.217PMV2)} \qquad (7)$$

According to ASHRAE Standard 55 (De Vecchi et al., 2015). the PMV range is between -3 and +3. These values represent the thermal sensation, with the concepts based on the ASHRAE standard and the PMV variable specified in Table 3.

Table 3

Concepts of the PMV Range from -3 to +3 in ASHRAE Standard (ASHRAE, 2017).

Thermal Sensation	Very Warm	Warm	Slightly Warm	Neutral	Slightly Cold	Cold	Very Cold
PMV Range	+3	+2	+1	0	-1	-2	-3(7)

To calculate the thermal chimney formulation, relations 8 to 11 are used (Wang & Lei, 2019).

$$L = \frac{L_1 \times r_1 \times E_1 + L_2 \times r_2 \times E_2 + L_3 \times r_3 \times E_3 + \cdots + L_n \times r_n \times E_n}{r_1 \times E_1 + r_2 \times E_2 + r_3 \times E_3 + \cdots r_n \times E_n} \qquad (8)$$

$$T_r = T_{r_1} \times r_1 + T_{r_2} \times r_2 + T_{r_3} \times r_3 + \cdots + T_{r_n} \times r_n \qquad (9)$$

$$A_i = A_{i_1} + A_{i_2} + A_{i_3} + \cdots + A_{i_n} \qquad (10)$$

$$h_{wf}(T_w - T_f) = h_{gf}(T_f - T_g) + \frac{mC_p}{w} \times \frac{dT_f}{d_x} \qquad (11)$$

To calculate the airflow resulting from natural ventilation through the solar chimney phenomenon(Shahmortezaei & Sabernejad, 2016) in the central atrium, relations 12 to 14 are used (Fereidoni et al., 2025).

$$Q = C_d A_0 \sqrt{\frac{2\left(\frac{T_{fo} - T_r}{T_r}\right) gL}{(1 + A_r)2}} \qquad (12)$$

$$A_r = {}^{A_0}/_{A_i} \qquad (13)$$

$$Q_1 = Q_{r1}, Q_2 = Q_{r2}, Q_3 = Q_{r3}, \ldots, Q_n = Q_{rn} \qquad (14)$$

3. Theoretical Framework

The modeling for this case study was conducted in the Grasshopper plugin environment, which is installed on Rhino software. Simulations for lighting, thermal comfort, energy, and climatic analysis were carried out in the Honeybee and Ladybug environments, with their plugins added to the Grasshopper platform. These plugins enable energy and daylighting analysis (Sadeghipour Roudsari & Pak, 2013). In the Grasshopper plugin environment, the Honeybee and Ladybug plugins can parametrically write building physics simulation algorithms. In other words, all the variables within a simulation can be instantly modified, allowing for highly flexible simulations. Honeybee and Ladybug a wrapper for energy and thermal comfort simulation software, connecting energy-related simulations to Open Studio and Energy Plus, and analyzing thermal comfort issues through these platforms (Pilechiha et al., 2022). A study conducted by (Ashdown et al., 2006).based on a comparative study between simulation models and experimental analysis, demonstrates that Radians analysis performs with high accuracy. Furthermore, Reinhart (Reinhart et al., 2013). Shows that the accuracy of PMV simulations is comparable to that of the experimental model, indicating the reliability of the data (Zhou et al., 2023). In Figure 2, the research tools used in this study are depicted.

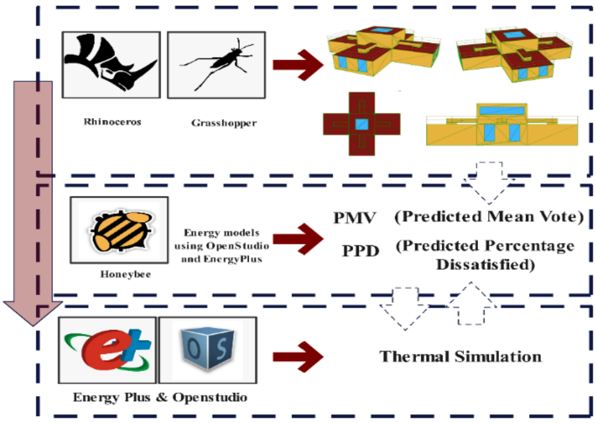


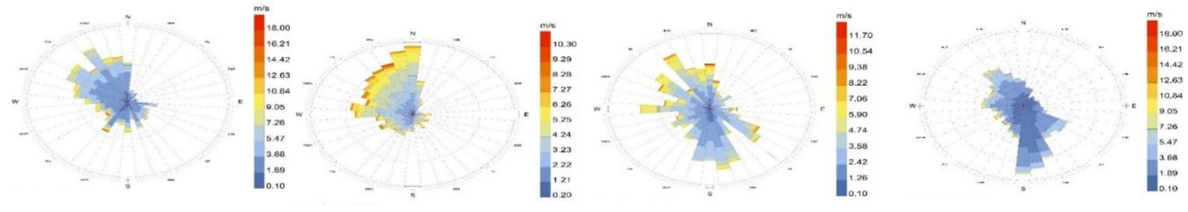
Fig. 2. Research tools

3.1. Climate analysis of yazd

Yazd is located in the central geographical region of Iran and is influenced by various climatic systems throughout the year (kheyrossadat, 2020). Due to its location on the global dry belt, Yazd experiences cold and dry winters, and hot, dry, and extended summers; like most desert areas, the seasonal and even daily temperature fluctuations in Yazd, are significant, with the absolute minimum temperature at Yazd station recorded at -3.2°C and the absolute maximum temperature reaching 41.28°C. Table 5 presents the climatic parameters of Yazd based on the maximum, minimum, and average values. Climatic analyses are shown in Figures 3, 4, and 5.

Table 4
Terms of solar chimney formulas (Wang & Lei, 2019).

Climatic Parameter	Unit	Monthly		
		Maximum	Minimum	Average
Dry Temperature	□	41.28	-3.2	20.89
Relative Humidity	%	78.76	10	44.38
Wind Speed	$m/_s$	8.14	0	4.07
Direct Normal Radiation	$Wh/_{m^2}$	26543	0	13271.5
Diffuse Horizontal Radiation	$Wh/_{m^2}$	390	209.8	299.9
Horizontal Radiation	$Wh/_{m^2}$	36974.8	0	18487.4
Sky Cover		9	0	4.5



Wind Direction & Speed in Spring Wind Direction & Speed in Wind Direction & Speed in Wind Direction & Speed in

Fig. 3. Wind direction and speed in yazd city

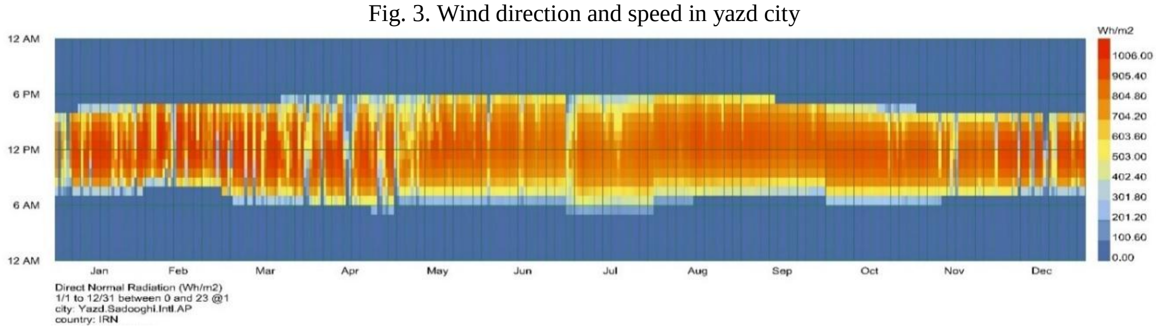


Fig. 4. Solar radiation in yazd city

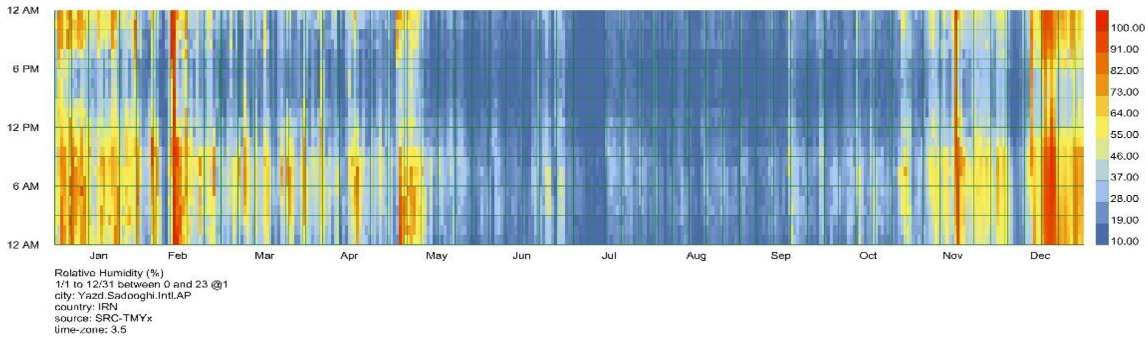


Fig. 5. Humidity levels in yazd city

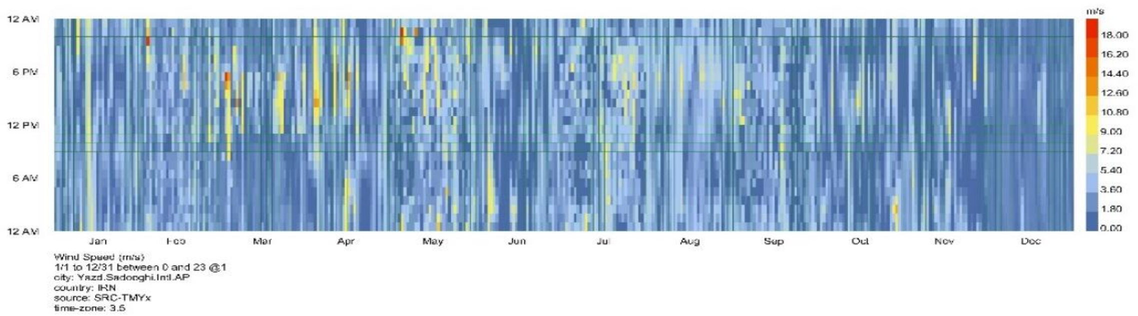


Fig. 6.- Wind speed in yazd city

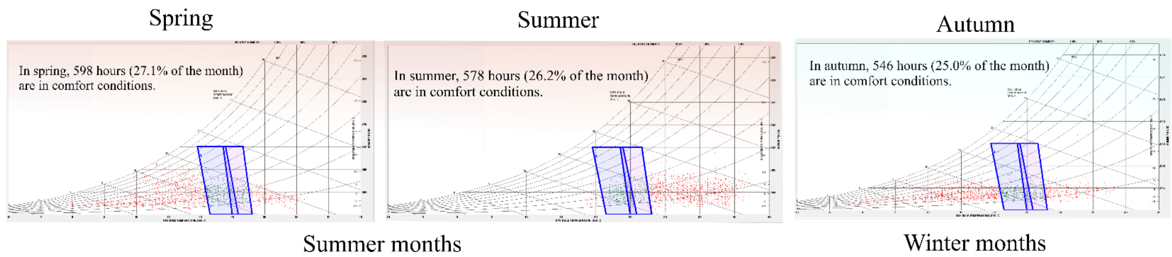


Fig. 7. Psychrometric chart of yazd city in spring, summer, and autumn

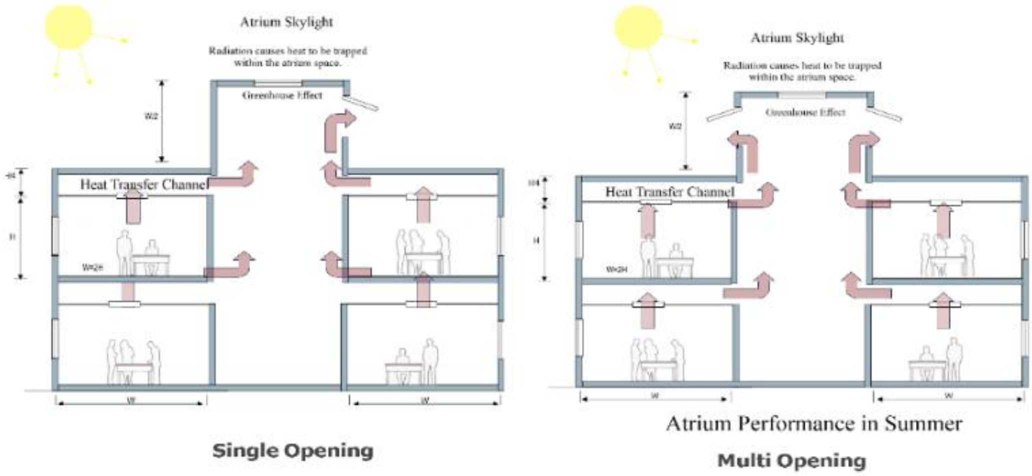


Fig. 8. Conceptual model of atrium performance in summer in two opening states

in Figure 7, the psychometric chart shows that the summer season requires cooling measures and proper ventilation in Yazd, which generally has a hot and dry climate. Meanwhile, optimal thermal comfort conditions can be achieved in spring and autumn without using mechanical systems by utilizing natural ventilation and the optimized design of passive systems.

4. Research Model Description

This research aims to optimize the placement and number of openings in atriums across various geographical orientations. To achieve these goals, the simulation models are divided into two categories: single-window and multiple-window models. The simulation models are categorized as either single-window or multi-window models to address the research objectives. The analysis focuses on a five-story office building located in Yazd. Each room is assumed to have average dimensions of 5 meters in length, 5 meters in width, and 3 meters in height, with a skylight window measuring 3.5 meters, which is considered closed for the simulation. The thickness of each 's ceiling is assumed to be 25 cm, and the window frames for all rooms are also 25 cm. Additionally, the window-to-wall ratio for the building's main façade is assumed to be 40%, based on the ASHRAE standard (De Vecchi et al., 2015). This model was developed from Khanal and colleagues' designs for natural ventilation in a solar chimney (Khanal & Lei, 2011) .During the spring, summer, and autumn, the atrium openings and the channel vent are open to allow natural ventilation to exit through the atrium windows. Since the goal is to select the best orientation for the atrium openings and the simultaneous number of openings, all simulation scenarios keep the dimensions of the openings, the skylight window (which is closed by default), the floor plan dimensions, and the atrium proportions fixed. Therefore, the vertical skylight window remains fixed, and the natural ventilation system exits through the side walls of the atrium.The model considered in this research is shown in Figure 8. The materials used are defined based on the National Building Regulations, Chapter 19, which are appropriate for Yazd's climate (Topic 19 of National Building Regulations / Saving Energy Consumption, 2020) .Since the climate issue in the hot and dry city is mainly related to the warmer seasons, the research findings focus on the spring, summer, and autumn seasons, while the atrium's performance in winter is not considered.

In Table 5, the characteristics of the wall materials in the model are specified. These materials are derived from the study comparing the impact of external wall materials on occupant comfort and the selection of optimal materials for hot and semi-arid climates. The highest temperature for the wall was 31.51°C in the summer, which, due to the high heat of the space, is suitable for the hot and dry climate of Yazd. Based on the results obtained, this temperature creates thermal comfort in the space (Momeni & Tanoorsaz, 2023) .Table 6 shows the material properties, and Table 6 shows the model's dimensions. Additionally, the model images in plan, elevation, and 3D views are presented in Figure 9.

Table 5
Material properties of the model(momeni & tanoorsaz, 2023)

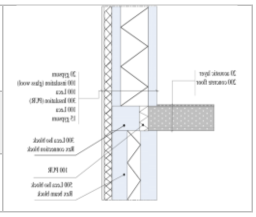
Default Materials in the Model	Thermal Transmittance (U) J/k	Thermal Resistance (R) $m^2.k/W$	Thermal Capacity (C) $W/m^2.k$	
Uninsulated Leca Block	0.520	1.923	229774	

Table 6
Research model details

Parameter	Value	Parameter	Value
Room Height	3.5	Atrium Width	5.00
Atrium Length	5.00	Channel Window Length	0.50
Channel Window Height	0.30	Room Window Width	0.90
Room Window Height	1.92	Room Width	5.00
Channel Width	0.50	Atrium Window Width	3.50
Atrium Window Height	0.75	Atrium Skylight Window	3.50
Room Length	5.00	Skylight Vent	0.50

Since this research aims to find a solution for optimizing the placement and number of atrium openings, the criterion of time is related to the minimum and maximum angles of solar altitude at different latitudes in various orientations of the central atrium form. The designed model, with features such as a central atrium, climate-appropriate windows for Yazd city(*Topic 19 of National Building Regulations / Saving Energy Consumption*, 2020), skylights, and ventilation channels, forms an efficient natural ventilation system that can particularly enhance thermal comfort in hot and dry climates. This design helps improve internal conditions, reduces the need for mechanical ventilation systems, and minimizes energy consumption. Figure 10 - Classification of Models for Simulation. Initially, window placement is examined as a single opening in four orientations: North, East, South, and West. Then, a simultaneous analysis of two openings is conducted. In the next phase, three openings are analyzed, and all four openings are simulated. The optimal response at each stage is extracted and reported, then compared with the optimal responses. Ultimately, the optimal response will be reported in order of priority.

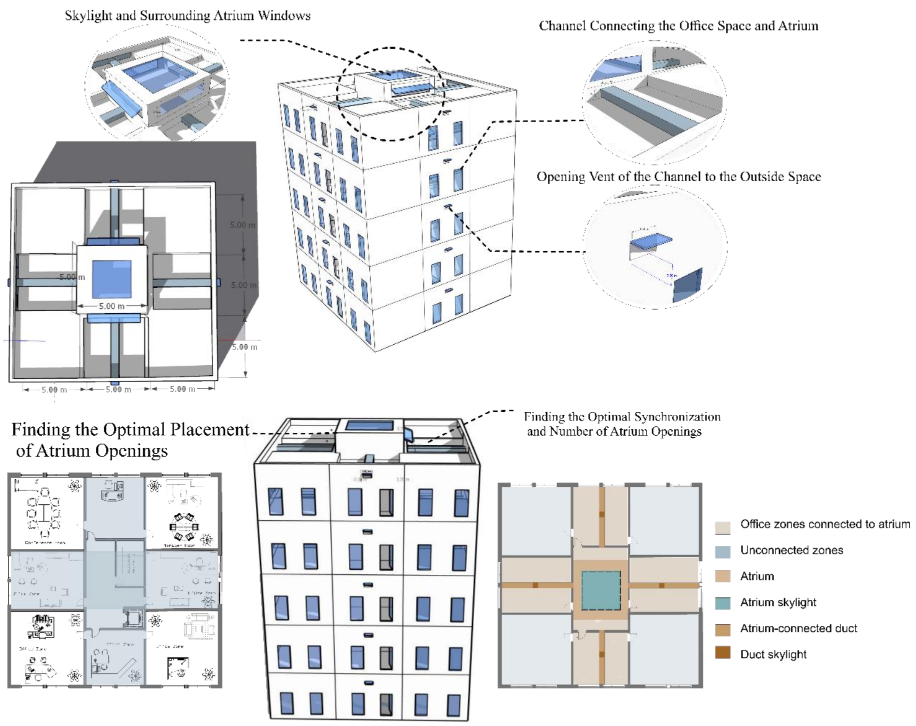


Fig. 9. Energy simulation model orientation

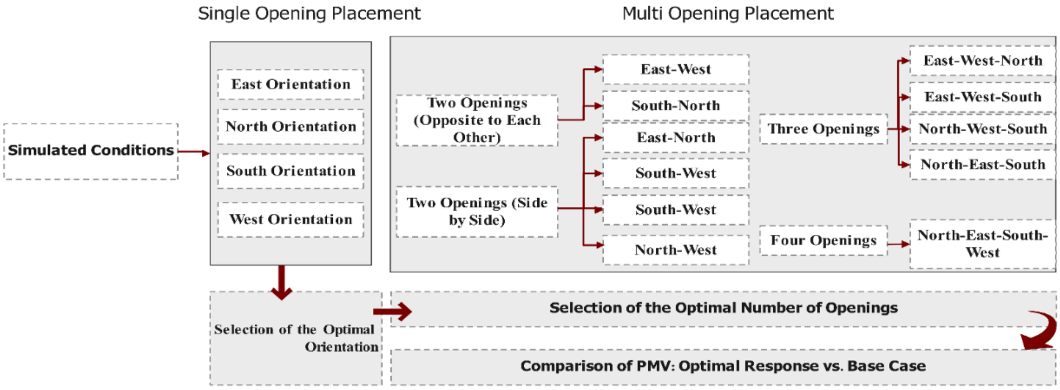


Fig. 10.. Different configurations for optimizing atrium openings

Table 7
Values during the simulation

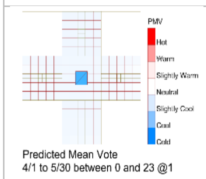
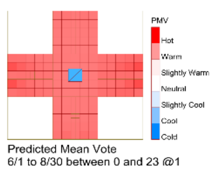
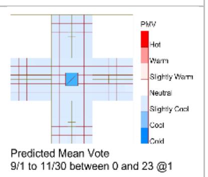
Parameter	Value
Location / Climate zone	Yazd, Iran/BWh
Floor area	225.00 m^2 (15.00 m× 15.00 m)
Channel	0.5×5 m^2
Zones height	3.50 m
Room Window	0.9×1.92 m^2
Atrium height from last floor	5.00 m
Schedule	Sat to Wed (9:00 to 17:00)
HVAC settings	Always off
Infiltration rate per area	0.0003 m^3/S.m^2
Number of people per unit of area	0.10 People/m^2
Output intervals	Annual
Number of Floor	Five floors

The table 7. summarizes the main parameters used for the building simulation in Yazd, Iran, which is in the BWh climate zone. The building has a floor area of 225 m², a channel measuring 0.5 m by 5 m, and a zone height of 3.5 m. Each room has a window size of 0.9 by 1.92 meters, and the atrium rises 5 meters above the top floor. The building operates from Saturday to Wednesday, 9:00 AM to 5:00 PM. The HVAC system is turned off, and the infiltration rate is 0.0003 cubic meters per second per square meter. There are 0.10 occupants per square meter, and data is collected annually. The building has five floors. The analyses cover the five-story building across three seasons: hot (summer), mild warm (spring), and mild cold (autumn). Results are presented as spatial averages for the building. Key points for thermal comfort analysis include the office spaces and atrium on the ground floor, which were chosen to assess temperature and natural ventilation during these seasons.

4.1. Thermal comfort evaluation based on PMV

The performance of the initial model featuring a single opening was evaluated. During summer (June to August), the eastward orientation, with a Predicted Mean Vote (PMV) of 2.20, exhibited the lowest internal heat gain and consequently the greatest reduction in thermal load. Conversely, the north and south orientations, with PMV values of 2.23 and 2.238, were associated with the highest levels of perceived heat. During the mild seasons (spring and autumn), openings performed closer to thermal comfort. In spring (Mar-Apr-May), the westward and eastward orientations, with PMV values of -0.327 and -0.348, were closest to comfort. In autumn (Sep-Oct-Nov), the north and south orientations, with PMV values of -0.936 and -0.934, performed best.

Table 8
Thermal comfort in single atrium opening

Orientation	Spring (Mar-Apr-May)	Summer (Jun-Jul-Aug)	Autumn (Sep-Oct-Nov)
			
East	-0.348	2.20	-0.974
North	-0.359	2.23	-1.00
South	-0.352	2.238	-0.936
West	-0.327	2.266	-0.969

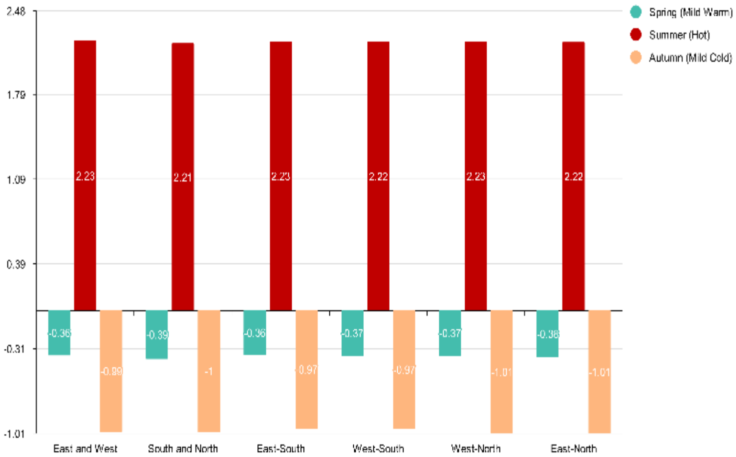
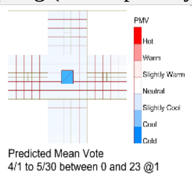
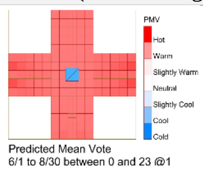
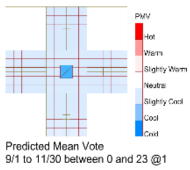


Fig. 11. Thermal comfort of interior space for single opening

The eastward orientation of openings demonstrated the highest performance during summer, achieving a Predicted Mean Vote (PMV) value of 2.20. This configuration minimized internal heat gain and significantly reduced thermal load. In spring, the eastward orientation also performed well, with a PMV value of -0.348. In contrast, the north and south orientations yielded the best results in autumn, with PMV values of -0.936 and -0.934, respectively. Overall, the eastward orientation is optimal for both hot and mild seasons. Figure 11 and Table 8 show the thermal comfort values for the interior of the atrium and the office zones in all four seasons for the four atrium opening placements as a single window.

Table 9
Thermal Comfort of Interior Space for Simultaneous Two Openings

Orientation	Spring (Mar-Apr-May)	Summer (Jun-Jul-Aug)	Autumn (Sep-Oct-Nov)
			
Two Opposing Windows			
East and West	-0.363	2.232	-0.995
South and North	-0.392	2.21	-0.996
Two Adjacent Windows			
East-South	-0.360	2.226	-0.967
West-South	-0.367	2.22	-0.970
West-North	-0.366	2.226	-1.01
East-North	-0.380	2.219	-1.01

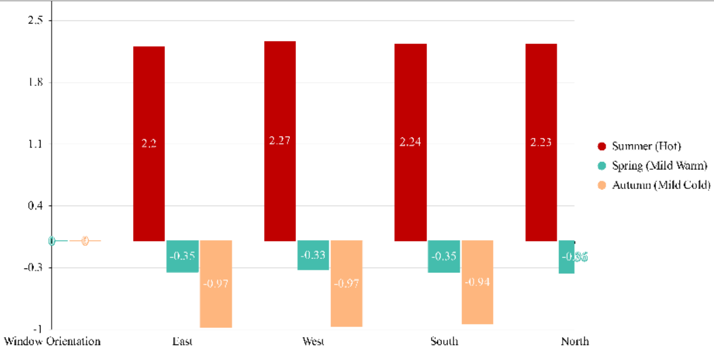
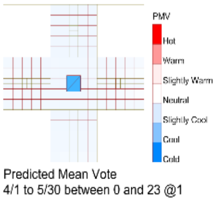
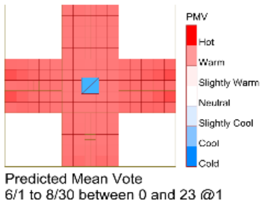
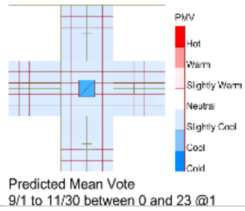


Fig. 12.- Thermal comfort of interior space for simultaneous two openings

Continuing the research on the impact of atrium opening orientations on thermal comfort in Yazd's hot and dry climate, six different combinations of two openings, placed in either opposite or adjacent directions, were examined. The results from these scenarios revealed that during the summer, the combinations of openings in the east-south and east-north directions, both with a PMV value of 2.24, experienced the least internal heat gain compared to other combinations. This indicates that these configurations in atrium design can significantly reduce the summer thermal load. On the other hand, the north-south combination, with a PMV value of 2.48 during the summer, generated the highest level of heat perception in the space. During the mild seasons, specifically spring and autumn, the PMV

Table 10
Thermal comfort of interior space for three atrium openings

Orientation	Spring (Apr-May-March)	Summer (Jun-July-Aug)	Autumn (Sep-Oct-Nov)
			
East-North-South	-0.386	2.207	-0.996
East-North-West	-0.375	2.223	-1.013
West-North-South	-0.392	2.299	-0.996
East-South-West	-0367	2.227	-0.975

values for all combinations were within the thermal comfort range. In the spring, the west-south combination, with a PMV of -0.06, and the west-north combination, with a PMV of -0.068, provided the best thermal performance, closely approaching comfort conditions. In autumn, the north-south combination, with a PMV value of -0.55, exhibited the closest thermal comfort conditions. Considering the dominant climate of Yazd, characterized by very hot and dry summers, managing indoor temperatures during this season is critical. Therefore, the east-south or east-north combinations are recommended as the most suitable options for atrium design in this climate. These combinations perform optimally during the summer and provide acceptable thermal conditions in the milder seasons. Figure 12 and Table 9 present the results for two openings.

Continuing the research on optimizing the placement of atrium openings in the hot and dry climate of Yazd, three-way combinations of windows in different directions were also analyzed. Figure 13 and Table 10 illustrate the thermal comfort of the interior space for three simultaneous atrium openings.The combination of windows facing east, north, and south (East-North-South) demonstrated the best thermal performance for summer conditions, as indicated by a PMV value of 2.346. Among all tested combinations, this PMV value was the lowest compared to other combinations, which ranged from 2.38 to 2.40, resulting in the least internal heat gain and better conditions for reducing the thermal load during the summer. The West-North-South combination, with a PMV of -0.068 in spring and -0.743 in autumn, created the most favorable conditions for thermal comfort. Other combinations also performed acceptably during these seasons, but the differences were significantly smaller compared to the summer and winter seasons.Based on the results, it can be concluded that the East-North-South combination is the most suitable option for atrium design in Yazd's hot and dry climate. Figure 14 and Table 11 present the thermal comfort for four simultaneous atrium openings. The results show that the East-North-South and East-South-West configurations yield identical outcomes, with a PMV value of 2.38 in the summer and a thermal comfort condition of -0.076 in the spring.

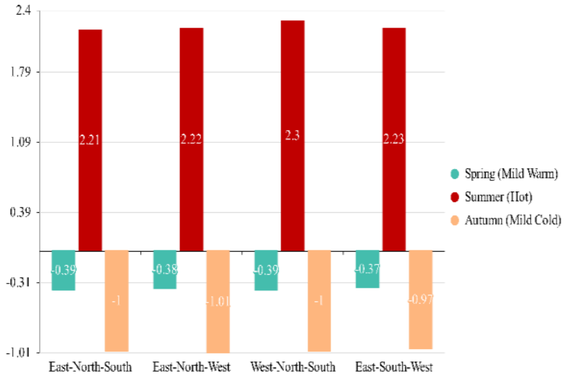
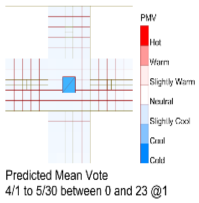
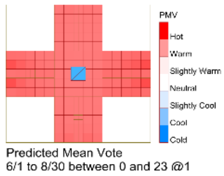
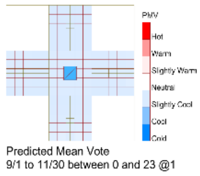


Fig. 13. Thermal comfort of the interior space for simultaneous three openings

In autumn, a PMV value of -0.76 is considered acceptable. In contrast, the East-North-South-West combination yields PMV values of -0.378 in spring, 2.218 in summer, and -0.993 in autumn, demonstrating good overall performance. This combination, particularly during the summer with the lowest internal heating (PMV = 2.34), outperforms other configurations. Additionally, it provides acceptable thermal comfort during the mild seasons. Therefore, the study confirms that the East-North-South-West combination is a solid option for managing thermal comfort in the hot and dry climate of Yazd.

Table 11
Thermal comfort of the interior space for four atrium openings

	Spring(Mar-Apr-May)	Summer (Jun-Jul-Aug)	Autumn (Sep-Oct-Nov)
Orientation			
East-NorthSouth-West	-0.378	2.218	-0.993

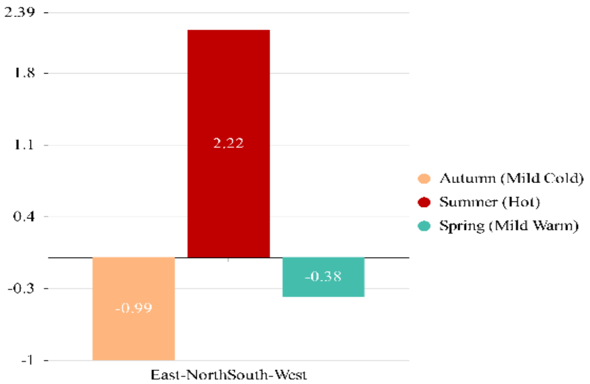


Fig. 14.- Thermal comfort of interior space for simultaneous four openings

4.2. Thermal comfort index PPD

Thermal comfort is one of the most important factors influencing the enhancement of indoor environmental quality. Occupants of indoor spaces constantly seek an environment that provides optimal thermal comfort. According to the optimal thermal comfort index, as per ASHRAE Standard 55, the PMV range between 0.5 < PMV < -0.5 is considered the ideal range, where the dissatisfaction among individuals with the environmental conditions also decreases. In other words, the closer the PMV value is to zero, the lower the percentage of dissatisfied individuals (PPD) will be (Cheung et al., 2019). In Equation 15, the index of dissatisfaction of individuals in the space based on PMV will be obtained. Table 12 presents the thermal comfort index for all orientations and the simultaneous number of openings based on the PPD index as determined in the research.

$$PPD = 100 - 95 \times e^{-(0.3353 \times PMV^4 - 0.2179\, PMV^2)} \quad (15)$$

The Percentage of People Dissatisfied (PPD) reaches its lowest value, approximately 5 percent, when the Predicted Mean Vote (PMV) is near zero, which represents thermal neutrality. According to Fanger's diagram, open windows and channels alone, without mechanical ventilation, do not provide sufficient comfort during the summer months. As a result, additional cooling systems are necessary to maintain thermal comfort during the hotter periods of the year.

In contrast, spring and autumn offer the opportunity to achieve thermal comfort without the need for mechanical cooling or heating systems, as optimal placement and synchronization of atrium openings can naturally regulate indoor temperatures. During spring, thermal comfort can be achieved with less than 1% dissatisfaction, while in autumn, the design of the central atrium can maintain comfortable conditions without heating systems, with a maximum dissatisfaction of 3.66%, as indicated by the PPD value. For optimal thermal comfort in office spaces with a central atrium, it is essential to maintain a PMV near zero, which minimizes PPD. Effective control of atrium openings during spring and autumn ensures thermal comfort with minimal occupant dissatisfaction. However, the conditions in summer require the introduction of cooling systems due to inadequate natural ventilation, while in autumn, a well-designed atrium can eliminate the need for heating systems.In the summer, orientations such as West-North-South and South exhibit the highest PMV values (PMV = 2.299 and PMV = 2.266, respectively). These high PMV values indicate significant thermal load and discomfort in these orientations during the hot months, making them less suitable for hot climates. In comparison, the East orientation performs the best, exhibiting the lowest PMV value (PMV = 2.218), which minimizes internal heat gain and offers relatively better thermal comfort in the summer. Similarly, the East-North-South configuration (PMV = 2.207) and the East-North-West orientation (PMV = 2.223) also perform well in summer, with relatively lower internal heat gain compared to other orientations. However, they still exhibit higher PMV values than East, making East the optimal choice for summer in terms of reducing thermal discomfort.

In spring, all orientations perform reasonably well, with East-North-South-West (PMV = -0.378) and East-North-South (PMV = -0.386) showing PMV values very close to thermal comfort conditions (approximately PMV = 0).

Table 12
Thermal Comfort Index PPD

Orientation	Spring (Mar-Apr-May)	Summer (Jun-Jul-Aug)	Autumn (Sep-Oct-Nov)	PPD Spring	PPD Summer	PPD Autumn
East-North-South-West	-0.378	2.218	-0.993	2.66	99.92	14.99
East-North-South	-0.386	2.207	-0.996	2.59	99.90	15.22
East-North-West	-0.375	2.223	-1.013	2.69	99.92	16.54
West-North-South	-0.392	2.299	-0.996	2.54	99.97	15.22
East-South-West	-0.367	2.227	-0.975	2.76	99.93	13.68
East and West	-0.363	2.232	-0.995	2.80	99.93	15.14
South and North	-0.392	2.210	-0.996	2.54	99.91	15.22
East-South	-0.360	2.226	-0.967	2.83	99.93	13.13
West-South	-0.367	2.220	-0.970	2.76	99.92	13.33
West-North	-0.366	2.226	-1.010	2.77	99.93	16.30
East-North	-0.380	2.219	-1.010	2.65	99.92	16.30
East	-0.348	2.200	-0.974	2.94	99.89	13.61
North	-0.359	2.230	-1.000	2.84	99.93	15.52
South	-0.352	2.238	-0.936	2.90	99.94	11.11
West	-0.327	2.266	-0.969	3.13	99.96	13.26

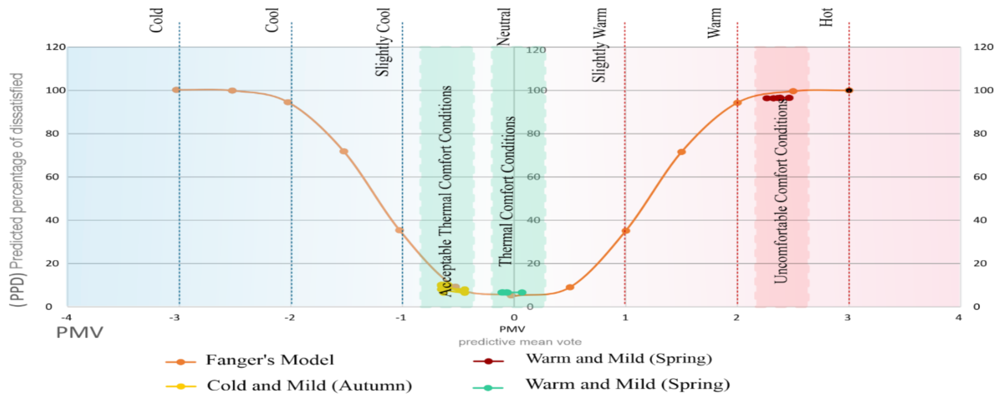


Fig. 15. PPD and PMV analysis based on fanger's model

Other orientations, such as East-North-West (PMV = -0.375), also provide adequate comfort. The West-North-South orientation, although performing slightly worse with a PMV of -0.392, still remains within an acceptable range for thermal comfort.Similarly, in autumn, the East-North-South-West combination performs best with a PMV of -0.993, which is very close to the thermal comfort range, indicating minimal dissatisfaction. The East-North-South (PMV = -0.996) and East-North-West (PMV = -1.013) orientations also provide favorable thermal conditions during the cooler months. Other configurations, such as West-North-South (PMV = -0.996) and East-South-West (PMV = -0.975) offer relatively good comfort but with slightly higher PMV values compared to the best-performing orientations.

Optimal Orientations:

East: This orientation performs the best in summer, with the lowest PMV value (PMV = 2.218), minimizing internal heat gain and ensuring better thermal comfort in the hot months.

East-North-South: This configuration also performs well, especially in spring (PMV = -0.386) and summer (PMV = 2.207), providing effective thermal comfort and reducing thermal load during hot periods.

East-North-West: This orientation offers satisfactory thermal comfort in spring (PMV = -0.375) and summer (PMV = 2.223), but it is slightly less effective than East-North-South in autumn.

Less Optimal Orientations:

West-North-South: This orientation has acceptable PMV values in spring (PMV = -0.392) and autumn (PMV = -0.996), but performs poorly in summer (PMV = 2.299), making it less suitable for hot climates. The high PMV value in summer indicates significant thermal load.

South: This orientation shows elevated PMV values in summer (PMV = 2.266) and a higher PPD in autumn (95.49), leading to increased occupant discomfort and making it less effective for maintaining thermal comfort during hot months.

West: This orientation performs poorly in both summer (PMV = 2.266) and autumn (PMV = -0.969), resulting in higher occupant dissatisfaction during these seasons.

The East orientation represents the most optimal choice for a central atrium in the hot and dry climate of Yazd. It provides the best thermal comfort in summer by minimizing internal heat gain (PMV = 2.218), while also sustaining acceptable comfort in spring and autumn. The East-North-South configuration also performs well, particularly in summer and spring, offering effective thermal comfort with reduced thermal load during hot periods.In contrast, West-North-South and South are less suitable due to elevated PMV values in both summer and autumn, leading to increased thermal discomfort. Therefore, the East orientation is the recommended option for office environments featuring a central atrium in hot and dry climates like Yazd. This configuration consistently reduces thermal load and maintains occupant comfort throughout the year.

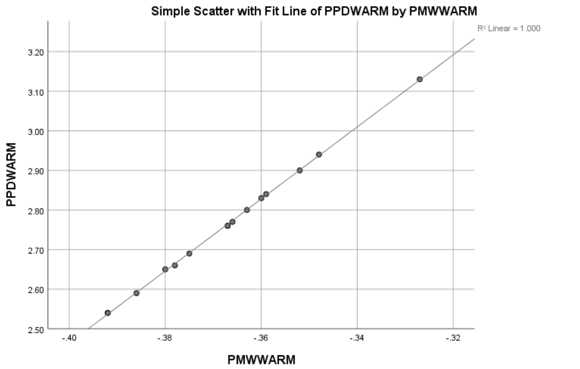


Fig. 16. PPD and PMV Scatter plot in Spring

The regression line in the graph illustrates the relationship between the Percentage of People Dissatisfied (PPD) and the Predicted Mean Vote (PMV). The positive slope of 0.45 indicates that increases in PMV, which correspond to higher perceived temperatures or reduced comfort, are associated with a slight increase in PPD. Therefore, as environmental temperature rises or thermal comfort decreases, the proportion of individuals dissatisfied with thermal conditions increases. Figure 16 presents the scatter plot of data for the spring season, with a coefficient of determination (R^2) of 1.00 for the linear regression model, indicating a perfect linear fit and a strong relationship between PPD and PMV.Given the positive correlation between PPD and PMV, it can be inferred that the orientation of buildings and the number of openings significantly influence thermal comfort in hot and dry climates, such as Yazd. The data in the graph, which includes multiple atrium orientation configurations, reveal only minor variations in PPD and PMV values. For most orientations, including East, West, South, and North, PPD values approach 100%, indicating that nearly all individuals experience acceptable thermal comfort in these scenarios.icient of determination (R^2) for the linear regression model is 1.00, suggesting a perfect linear fit and a strong relationship between PPD and PMV

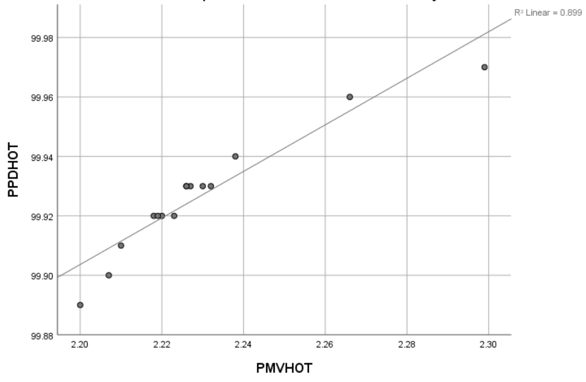


Fig. 17 - PPD and PMV Scatter plot in Summer

The positive correlation between Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV) indicates that both the orientation and the number of atrium openings substantially influence thermal comfort in the hot and dry climate of Yazd. The data in the graph demonstrate only a modest increase in PPD and PMV values across different orientations. For most orientations, including East, West, South, and North, PPD values approach 100%, reflecting nearly optimal thermal comfort for most occupants. Figure 17 displays the scatter plot for the summer season. The coefficient of determination (r^2) for the linear regression model is 0.899, which indicates a strong linear relationship between PPD and PMV. These results demonstrate that the orientation and number of openings in a building are primary factors influencing thermal comfort during the hot months. However, additional variables may also contribute to thermal comfort outcomes.

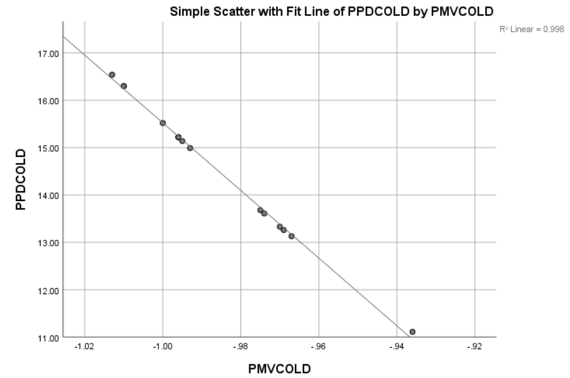


Fig. 18 - PPD and PMV scatter plot in autumn

.Figure 18 presents the scatter plot for the autumn season, with a coefficient of determination (r^2) of -0.998 for the linear regression model, highlighting a very strong inverse relationship between PPD and PMV. This suggests that with optimal placement and synchronization of atrium openings, thermal comfort can be achieved in the autumn months without the need for additional heating systems.The regression line in the graph illustrates the relationship between PPD (Percentage of People Dissatisfied) and PMV (Predicted Mean Vote) during the autumn season. The regression line exhibits a strong negative slope, with an r^2 value of -0.998, indicating a highly significant inverse relationship between PPD and PMV. As PMV decreases (which typically signifies an improvement in comfort or a reduction in perceived temperature), PPD also decreases significantly, suggesting that as the environmental temperature becomes more comfortable or cooler, the percentage of dissatisfied individuals decreases substantially. The strong negative correlation between PPD and PMV suggests that in autumn, optimizing atrium openings can effectively enhance thermal comfort during the cooler months. The data in this graph, which includes various atrium orientation configurations, demonstrates that the PPD values are close to minimal dissatisfaction. For most orientations, the PMV values are within a comfortable range, indicating that thermal comfort is well-maintained during autumn.

Table 13
Comparison of thermal comfort results for orientations

Best Orientation	Spring(Apr-May-March)	Summer (Jun-July-Aug)	Autumn (Sep-Oct-Nov)
East	-0.348	2.2	-0.974
East and West	-0.363	2.232	-0.995
East-North-South/ East-North-West	-0.386	2.207	-0.996
East-North-South-West	-0.378	2.218	-0.993

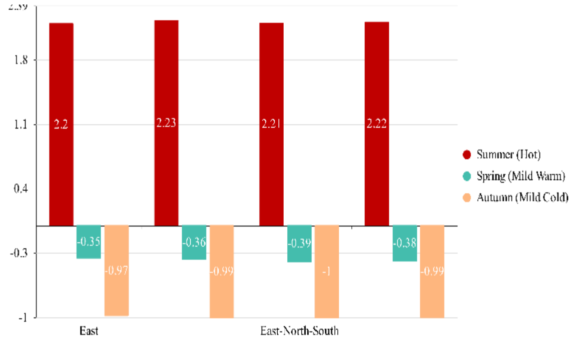


Fig. 19. Provides a visual comparison for the orientations

Figure 19 provides a visual comparison of the thermal comfort results for the orientations, complementing the data in Table 13. It highlights the relationship between PPD and PMV, emphasizing the impact of different orientations and window configurations on thermal comfort throughout the seasons.

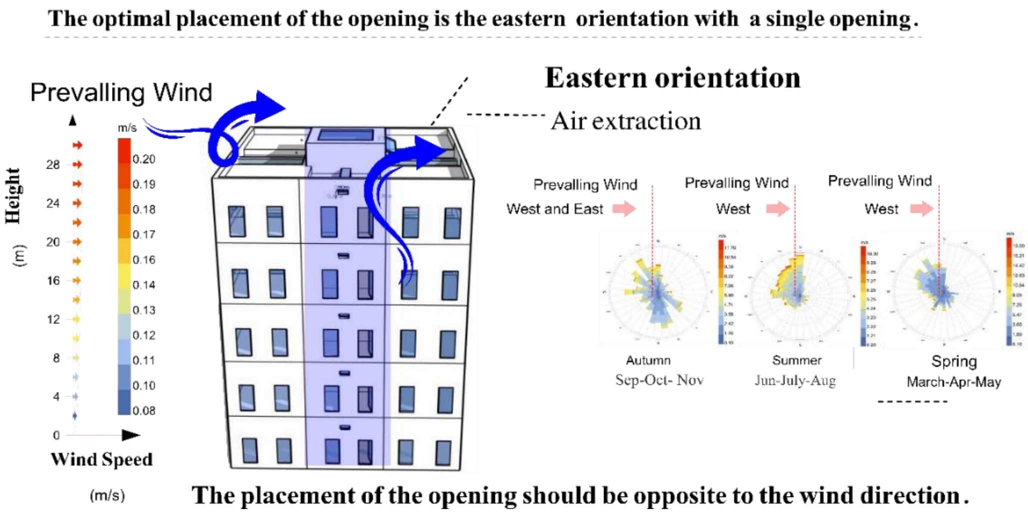


Fig. 20. The optimal placment of atrium openings

The East orientation exhibits the best performance in spring, with a PMV value of -0.348, indicating thermal comfort very close to neutral conditions (around PMV = 0), making it the most optimal choice for this season.
The East-West orientation achieves a PMV of -0.363, providing thermal comfort comparable to the East-North-South and East-North-South-West orientations, which yield PMV values of -0.386 and -0.378, respectively. These results indicate slightly reduced thermal comfort compared to East and West, but still fall within the comfort range. In summer, the East orientation achieves a PMV value of 2.218. This value indicates a substantial increase in thermal load and associated discomfort, yet it remains the most effective among the evaluated orientations compared to the other orientations. The East-North-South orientation achieves a PMV value of 2.207, indicating marginally improved thermal comfort in summer due to reduced internal heat gain. East-North-South-West and East-West show PMV values of 2.218. The East-North-South-West and East-West orientations yield PMV values of 2.218 and 2.232, respectively. These values reflect higher levels of discomfort compared to East and East-North-South. Form the best with a PMV value of -0.996, indicating near-optimal thermal comfort conditions. East and West (PMV = -0.995) and East-North-South-West (PMV = -0.993) also perform well, providing slightly better comfort compared to East (PMV = -0.974). Although the East orientation remains suitable in autumn, East-North-South provides optimal thermal comfort and reduces reliance on supplementary heating systems. The East-North-South orientation consistently demonstrates superior performance across all seasons by balancing thermal comfort and minimizing heat gain, especially dThe East orientation is effective in spring and summer; however, its higher PMV value in summer results in greater discomfort compared to East-North-South.ort than East-North-South. The East-North-South-West and East-West orientations are

less optimal, especially in summer, as their higher PMV values correspond to increased thermal discomfort.

In summary, the East-North-South orientation provides the most effective year-round thermal comfort. The East orientation is optimal for spring and summer. East-North-South-West and East-West are appropriate for cooler months but result in higher discomfort during warmer periods. Given that the prevailing wind in Yazd blows from the west, the placement of openings opposite to the prevailing wind direction can significantly enhance the natural ventilation effect. By positioning the atrium openings in opposition to the wind direction, a suction effect is created, which helps to expel warm air from the building. This passive cooling mechanism effectively lowers the internal temperature, reducing the reliance on mechanical cooling systems during the hot months. In conclusion, this research supports the adoption of East-North-South configurations in hot and dry climates like Yazd, where wind direction plays a critical role in improving natural ventilation. The proper placement of openings can optimize thermal comfort conditions, reduce energy consumption, and improve overall indoor environmental quality, especially during the critical summer months. The optimal placement of atrium openings, shown in Figure 20, further illustrates the effectiveness of this strategy in enhancing natural ventilation and improving thermal comfort through passive design.

The results of this research provide an analysis of optimal atrium opening configurations, which are compared with findings from studies conducted in diverse climatic contexts. The following section examines the implications of these findings and contrasts them with previous research.Aram & Alibaba, optimized the design of a one-story office building with a corner atrium, focusing on the orientations of atrium openings and the ratios of window openings in a Mediterranean climate. Their results emphasize the importance of orientation in determining energy efficiency and thermal comfort, which aligns with the findings of this study. However, this study extends beyond one-story buildings by considering a five-story office building, which introduces complexities related to verticality and heat distribution across multiple floors (Aram & Alibaba, 2019). Aldawoud,investigated the impact of atrium plan geometries and components on building thermal performance, finding that energy consumption in narrow, elongated, and high aspect ratio rectangular atriums is significantly higher than in square atriums. While this finding is relevant due to the shared focus on atrium configurations, the present research emphasizes the significance of orientation and the number of openings, which have a substantial effect on natural ventilation and thermal comfort (Aldawoud, 2013). Nasrollahi et al. investigated the effect of building area ratio (BAR) on energy performance, lighting, and thermal comfort, concluding that an atrium building area ratio (ABAR) of 1:4 offers optimal performance. The current study did not address ABAR, instead concentrating on the orientation of atrium openings, which provides more direct control over thermal comfort and internal heat gain in Yazd's hot and dry climate.hould be minimized, particularly for buildings with a penetrable atrium, with a range of 0.183–0.196. Our study did not directly examine ABAR but rather focused on optimizing natural ventilation by adjusting the orientation and number of atrium openings to reduce internal heat gain, particularly during the summer months (Nasrollahi et al., 2015). Guan et al. investigated optimal design parameters, including the shape factor, height-to-span ratio (DSR), building volume ratio (VR), roof area ratio (SR), and facade depth ratio (FDR), and found that the most effective configurations are DSR = 2, VR = 0.13, SR = 0.1, and FDR = 2.5. While the importance of design parameters is acknowledged, the present study primarily emphasizes the orientation of atrium openings as the key factor influencing thermal comfort in Yazd (Guan et al., 2022). Xu et al.investigated the effects of SAR, roof transparency, and the area ratio of upper to lower atrium openings (TBAR) on thermal comfort in warm climates in China. Their research found that increasing SAR can gradually reduce air temperature and improve the thermal environment. This aligns with our findings, where certain orientations, such as East-North-South (PMV = 2.207) and East-North-South-West (PMV = 2.218) offer better thermal comfort by reducing internal heat gain in the summer (Guan et al., 2022; Ye et al., 2025)Wang et al. examined the impact of aspect ratio (SAR) on energy consumption in cold climates, suggesting that lower SAR values result in reduced energy use. Although their focus was on cold climates, the principle that SAR affects energy consumption is applicable to hot climates as well. The present research places greater emphasis on the specific orientation of openings, which plays a significant role in mitigating thermal discomfort in hot climates (Wang et al., 2017). In summary, this study investigated the impact of atrium orientation and synchronization on thermal comfort in Yazd's hot and dry climate. The findings support previous research emphasizing atrium design, but demonstrate that prioritizing the optimal placement of openings most effectively reduces internal heat gain during summer. The East-North-South configuration is identified as optimal for year-round thermal comfort, enabling improved ventilation and reduced reliance on mechanical systems.

5- Conclusion

In Yazd's hot and dry climate, this study examined the effect of different atrium opening orientations on thermal comfort. The model was based on a five-story office building with a central atrium. In summer, identifying the most efficient atrium opening configurations was essential for maximizing thermal comfort.In the spring, the East orientation proved to be the most effective, achieving a PMV of -0.348, which indicates thermal comfort close to neutral conditions. The East-West configuration (PMV = -0.363) followed closely, with the East-North-South (PMV = -0.386) and East-North-South-West (PMV = -0.378) configurations also offering good comfort. These results indicate that the East orientation performs best in spring, with minimal differences between the other orientations.

In the summer, the East orientation continued to deliver optimal performance, with the lowest PMV of 2.218, minimizing internal heat gain and offering better thermal comfort than other configurations. The East-North-South combination (PMV = 2.207) marginally reduced internal heat gain, followed by East-North-South-West (PMV = 2.218) and East-West (PMV = 2.232), which showed slightly higher discomfort levels. Despite the East performing the best, all orientations experienced increased thermal discomfort due to higher heat load during the summer. In autumn, East-North-South emerged as the best orientation, with a PMV of -0.996, closely followed by East-North-South-West (PMV = -0.993) and East-West (PMV = -0.995). These configurations maintained thermal comfort close to neutral conditions, while the East orientation (PMV = -0.974) provided good but slightly reduced comfort compared to others. The East-North-South configuration was identified as the most optimal for year-round thermal comfort, offering a consistent balance between minimizing internal heat gain in summer and maintaining comfort during the milder spring and autumn seasons. While the East orientation performs well in both spring and summer, it experiences higher discomfort in summer compared to East-North-South. The East-North-South-West and East-West orientations provided adequate comfort during spring and autumn but were less effective during summer due to increased thermal loads. This study highlights the importance of optimizing atrium opening orientation for each season to achieve optimal indoor thermal conditions. The East-North-South orientation emerged as the most effective option, balancing thermal comfort and minimizing heat gain, particularly during the hot summer months. Additionally, the research underscores the role of passive design strategies, such as optimal atrium design and natural ventilation, in reducing reliance on mechanical systems, thereby enhancing comfort and reducing energy consumption. Given the prevailing westerly winds in Yazd, positioning atrium openings opposite the wind direction enhances natural ventilation, expelling warm air and reducing the need for mechanical cooling systems during the hot months. This passive design strategy aligns with optimal atrium placement, further illustrated in Figure 20, demonstrating the effectiveness of natural ventilation in improving thermal comfort and energy efficiency.

Specifically, the purpose of this research is to analyze how atrium openings are oriented and synchronized in the atrium space. Using natural ventilation principles and the greenhouse effect, the atrium functions as a solar system. As air is expended through the openings in the atrium, dust and debris cannot enter because the openings are oriented counter-clockwise to the prevailing wind direction. According to the article's model, the atrium space is not directly connected to the office space. A channel connects the spaces indirectly, with air entering the atrium space through ceiling vents. Introducing fresh air into the atrium is made easier by this configuration. Furthermore, the greenhouse effect and atrium windows generate solar-driven suction, which causes warm air to rise and naturally exit the space. By enhancing air expulsion, this suction can improve ventilation within the atrium when it clashes with the prevailing wind.The solar-driven suction mechanism, if aligned against the prevailing wind, may function more efficiently, further aiding in the natural ventilation process and improving thermal comfort within the atrium. Thus, the design of the atrium's openings, particularly their orientation and timing, plays a crucial role in achieving optimal thermal conditions in the space.

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