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Optimizing Channel Configurations to Enhance Thermal Comfort in Connected Enclosed Atrium (Case Studies: Yazd and Tabriz)

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ABSTRACT: Global challenges, including climate change and rising energy consumption, necessitate sustainable architectural solutions. Optimizing architectural design for passive natural ventilation enhances energy efficiency and reduces reliance on mechanical systems. An investigation was conducted to examine how channel dimensions impact thermal comfort in connected, enclosed atria in Yazd and Tabriz. The objective is to determine channel configurations that maximize year-round thermal comfort while minimizing mechanical heating and cooling. With Rhino software and Honeybee and Ladybug plugins, simulation models were developed. A variety of channel dimensions were tested to determine the optimum PMV values throughout seasonal changes. A variety of channel widths were evaluated for thermal comfort. The atrium and adjoining spaces were improved by enhancing airflow and temperature regulation. In both cities, a 1-meter channel width consistently provided optimal thermal comfort. During winter, PMV should be -3.43, in autumn -0.66, in summer 2.41, and in spring 0.0041. As in Tabriz, the winter PMV is -4.94, the autumn PMV is -0.62, the summer PMV is 0.72, and the spring PMV is -1.13. One-meter channel widths maintain comfort through seasonal temperature variations and environmental conditions, eliminating the need for supplemental heating or cooling. The study highlights the importance of climate-responsive design and optimizing passive ventilation systems to enhance building energy efficiency. As a result, buildings can be designed for both hot and cold climates. Energy-efficient and comfortable architectural solutions are supported. A focus on channel dimensions for optimal natural ventilation is recommended for future building designs in similar climates.

Keywords: *Thermal comfort, channel configurations, connected atrium, passive systems, Yazd, Tabriz.*

INTRODUCTION

Natural ventilation systems bring outdoor air into buildings without the use of mechanical equipment, thereby reducing energy consumption and improving indoor air quality. In buoyancy-driven natural ventilation, a vertical exhaust opening, often located on the roof, must connect each floor (Holford & Hunt, 2003). Atria often serve this purpose. While natural ventilation can lower energy use, poorly designed atria may have the opposite effect. Atriums do not always reduce energy consumption. In some cases, buildings with atria consume more energy than similar buildings without them (Assadi et al., 2011; Baker & Steemers, 2003). The atrium is one of the most popular architectural designs in Iran today. Natural ventilation and heating were utilized in ancient and modern architectural designs, such as the Badgir, to generate the use of atria (Soflaee & Shokouhian, 2005; Su et al., 2025). Increasingly, atria are being used in Iranian architectural designs. Globally varying climatic conditions necessitate architects to design buildings based on specific climate zones. This need, particularly in critical thermal conditions, poses a challenge to architects. In addition to hot and dry climates, cold and dry climates also require special design considerations (Wang et al., 2017a). Efficient heating and cooling systems present significant challenges in demanding environments. This research aims to propose solutions tailored to these critical climate conditions. Buildings account for a significant portion of global energy use, particularly in cold regions, where

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heating, air conditioning, and ventilation collectively contribute substantially to consumption. As global warming raises Earth's temperatures, the demand for cooling systems grows. Iran's rapid urbanization has led to the construction of many atriums in its cities. These spaces are essential to office environments as public areas and significantly influence employee experiences; however, they can also drive up building energy costs if not utilized effectively. The building sector is estimated to account for a third of global carbon dioxide emissions (Khoroshiltseva et al., 2016; Wang et al., 2017b). As a gathering space and a source of natural light and solar radiation, atriums are frequently used in public buildings (Wang et al., 2017b). However, if misused, they can cause excessive energy consumption. Atriums have a large surface area, which makes them susceptible to external weather conditions, resulting in reduced thermal comfort and increased temperatures in hot and dry climates or cooling in cold and dry climates. Recent office construction has resulted in a massive waste of energy due to the illogical design of atrium spaces. Vertical thermal stratification is common in large spaces with heights exceeding 10 m, resulting in a greater temperature gradient vertically than in typical building spaces (Liu et al., 2020; Zhao et al., 2020). Most studies have confirmed such temperature distributions by coupling the air temperature with the wall surface temperature (Lu et al., 2020; Takemasa et al., 1996). An atrium directly connected to adjacent occupied zones (the non-enclosed atrium) could experience vertical thermal stratification in the surrounding areas. For example, the populated areas surrounding and connected to the atrium had a significant temperature difference, with the indoor temperature being higher on the upper layers (Romero-Odero et al., 2020; Tang et al., 2020). Depending on where the airflow moves within the atrium and adjacent zones, the effect on the surroundings varies vertically. An extreme fluctuation in vertical temperatures between neighboring zones is relatively common in buildings with non-enclosed atriums, such as shopping malls, where the upper layers tend to be hotter. In contrast, the lower layers are cold, resulting in uncomfortable thermal sensations (Ge et al., 2021). Due to the lack of accurate temperature estimation methods for such thermal environments, it is challenging to fundamentally improve the thermal conditions of these spaces without relying on air conditioning (Chow, 1996). Therefore, it is worthwhile to clarify the airflow patterns between the atrium and adjacent zones. Based on accurate predictions of the indoor temperature distribution, a more targeted optimization can be made. Airflow patterns in atriums are complex due to their large size and multiple openings, as well as various sources of heat (Shi et al., 2024). In summer, overheating and thermal stratification are exacerbated by glass roofs, which cause excessive solar heat gain (Ge et al., 2021; Lu et al., 2020). Thermal dissatisfaction is also associated with significant air infiltration during winter (Huang et al., 2007; Moosavi et al., 2014). Maintaining atrium buildings requires excessive energy consumption for heating and cooling (Xu et al., 2023). As a result, it is essential to analyze the atrium's thermal environment and provide effective thermal control measures. Several studies have examined the thermal environment of the atrium using different thermal control strategies (Ge et al., 2021). Abdullah et al. compared the cooling effects of two thermal mitigation measures (blinds and water spray) in an atrium of a three-story hotel in tropical climates (Abdullah et al., 2009). By adjusting the opening ratio according to outdoor weather conditions, Sokkar and Alibaba found that double-skin Skylights could achieve 77 % thermal comfort all year long with little influence from different glass materials (Sokkar & Alibaba, 2020). According to Moosavi et al., a four-story low-energy office building in Malaysia was studied to determine the cooling effects of passive and hybrid cooling strategies (thermal stack flue, cross ventilation, and water wall) (Walker et al., 2011). Several studies have examined the thermal environment of atriums using scaled models (Liu et al., 2009; Lu et al., 2021). Airflow patterns and thermal distribution within large atrium spaces cannot be captured entirely by field measurements alone. Hussain and Oosthuizen examined the airflow and temperature distribution inside a simple atrium building using various geometric configurations (Dai et al., 2022; Lu et al., 2020). According to Dai et al., CFD simulations were used to study thermal stratification in unair-conditioned atriums. Different scenarios yielded varying convective heat transfer coefficients on the atrium's inner surfaces, facilitating the development of strategies for zoning and operating public buildings to reduce heating, ventilation, and air conditioning (HVAC) loads (Dai et al., 2022). In a study by Chu et al., different air-supply angles, velocities, temperatures, and outlet heights were simulated during winter to determine their effects on the atrium's thermal and wind environments. Khayami et al. examined the form and proportion of atriums and explored earth sheltering to optimize the lighting and energy efficiency of buildings (Khayami et al., 2023). As a result of the analysis performed by Xue et al., optimal variables for optimizing atrium lighting were calculated (Xue & Liu, 2022). An open atrium shape optimization framework was developed by Ji et al. to maximize light, energy, and thermal comfort (Ji et al., 2023). As well, Ibrahim et al. proposed a height optimization strategy for surrounding buildings in hot and dry climates (Ibrahim et al., 2022). Based on the performance of three typical types of rural tourism buildings in northern China, Zhu et al. developed the optimal solution set for rooms of different sizes and types (Zhu et al., 2020). In a study published by Chi et al., nine kinds of study rooms with enhanced architectural performance were obtained by optimizing a digital gene map of university dormitories (Chi & Xu, 2022). As a result of analyzing the cooling load, heat load, and natural lighting conditions of office buildings, Jaalali et al. optimized building shape and façade (Jalali et al., 2020). The literature review in Table 1 summarizes the key studies and findings related to the

Table 1: Literature review

Researchers	Climate Zone	Design Variables	Performance Metrics	Research Methods	Research Tools	Research Objectives
(Su et al., 2025)	cold-Dry Climate	Shading, Air conditioning	Vertical temperature gradients	Computational Fluid Dynamics (CFD)	OpenFOAM	To analyze the thermal environment of a high-rise office atrium, improve thermal comfort, and optimize operational strategies for energy efficiency and thermal comfort
(Shi et al., 2024)	Hot and Dry	Atrium design	Thermal comfort dissatisfaction rate	simulation	TRNSYS-CONTAM co-simulation	To optimize thermal comfort and reduce vertical temperature gradients in a library atrium by adjusting air supply volumes, improving energy efficiency, and increasing occupant satisfaction.
(Chen et al., 2024)	Cold region	Atrium shape (four-directional, tri-directional), Window-to-Wall Ratio (WWR), Skylight Reflection Ratio (SRR)	Light comfort, Thermal comfort, Energy consumption	Optimization (NSGA-II), Machine Learning, Data-driven workflow	NSGA-II, LGBM algorithm, Building Performance Simulation	To optimize the energy consumption, light, and thermal comfort in teaching building atriums using multi-objective optimization and machine learning, with a focus on energy efficiency and occupant comfort.
(Beyraghshamshir & Sarkardehei, 2023)	Hot-Dry Climate	Ceiling of Atrium, Atrium Walls, Canopy	Energy Consumption	Scenario Analysis	DesignBuilder, EnergyPlus	Explore the energy performance of central courtyards and enclosed atriums, and provide methods for designing atriums.
(Khayami et al., 2023)	Hot, Arid Climate	SAR, VR, Earth Sheltering	Spatial Daylight Autonomy (sDA), EUI	Performance Simulation Analysis	Rhinoceros, Grasshopper, Ladybug Tools, EnergyPlus, Radiance	Determine the impact of various variables and identify the optimal integration mode for energy and daylight optimization.
(Chi & Xu, 2022)	–	Dimensions, Balcony Type, Wall System, Window-to-Wall Ratio (WWR), Glazing System, Shading Board Depth, Building Orientation	Thermal Comfort Evaluation, UDI, Energy Consumption	Optimization Algorithms: MOO	Rhinoceros, Grasshopper, Ladybug Tools, Octopus, EnergyPlus, Radiance, Design Explorer	Propose a digital gene map for university dormitory buildings to optimize building energy performance and enhance thermal and visual comfort levels.
(Xue & Liu, 2022)	Cold Zone	Skylight Visible Light Transmittance (VT), AR, Atrium Inclination, Fabric Coverage, Fabric VT, Wall Reflectivity, Roof Reflectivity	sDA, Daylight Glare Probability (DGP)	Optimization Algorithms: MOO	Rhinoceros, Grasshopper, Ladybug Tools, Radiance	Explore the relationship between atrium design variables and the lighting environment in commercial buildings; identify variables that significantly impact daylight quality.
(Guan et al., 2022)	Cold Zone	AR, SAR, Atrium Volume Ratio (VR), FDR	Energy Consumption, Carbon Emissions, Cost	Optimization Algorithms: Multi-objective Optimization (MOO)	Rhinoceros, Grasshopper, Ladybug Tools, Octopus, EnergyPlus, Design Explorer	Obtain optimal design parameters and solutions for atrium design factors in cold zones.
(Freewan, 2022)	Hot, Arid Climate	South Façade Inclination, North Façade Inclination	Energy Consumption	Performance Simulation Analysis	IES-VE SunCast, EnergyPlus, DesignBuilder	Study the energy performance of different building shapes with inclined south and north facades, as well as combinations of outward and inward-inclined walls.

Continiue of Table 1: Literature review

Researchers	Climate Zone	Design Variables	Performance Metrics	Research Methods	Research Tools	Research Objectives
(Wu et al., 2021)	HSWW Zone	AR, SAR	Temperature Distribution, Illumination	Performance Simulation Analysis	Fluent	Quantitatively analyze the impacts of AR and SAR on the lighting and thermal environments of atriums via simulation.
(Jalali et al., 2020)	Hot and Dry Climate	Rotation, Width, Length, Height, Movement along the X Axis, Movement along the Y Axis, Retreat, WWR	Heating Load, Cooling Load, UDI	Optimization Algorithms: MOO	Rhinoceros, Grasshopper, Ladybug Tools, Octopus, EnergyPlus, Radiance	Optimize office building façades using genetic algorithms with a sustainability approach.
(Wang et al., 2017a)	Cold Climate	SAR, Atrium Top (Surface Area (TA	Temperature Distribution, EUI	Performance Simulation Analysis	DesignBuilder, Airpak	Present quantitative relationships between SAR and energy performance; optimize TA to minimize annual energy consumption.
(Jin & Jeong, 2014)	–	Top Polygon Area, Top Length, Bottom Polygon Area, Bottom Length, Height, Tilt Angle, Rotation, Azimuth Angle	Heating Degree-Days, Cooling Degree-Days	Optimization Algorithms: Single-objective Optimization	Rhinoceros-Grasshopper, Galapagos	Propose a free-form building shape optimization process based on the Genetic Algorithm (GA); explore free-form buildings for various climate zones by deriving optimized shapes from the model.
(Chan & Chow, 2014)	Cold, HSCW, HSWW Zones	Façade Inclination	Cooling Load, Heating Load	Performance Simulation Analysis	EnergyPlus	Simulate the energy consumption of air-conditioned office buildings with sloping walls at various tilt angles and analyze the tilt angles across different climate zones.
(Aldawoud, 2013)	Hot-Dry, Hot-Humid, Cold, Mild	Atrium width-to-depth ratio (FDR), Aspect Ratio (AR)	Energy Consumption	Performance Simulation Analysis	DOE-2.1E	To assess the impact of atrium shape on total building energy consumption and identify the most energy-efficient atrium design.

research topic.

Direct solar radiation through the window may improve thermal comfort inside the building during the winter months and reduce heating costs. However, in the summer, the opposite effect occurs, as the distribution of sunlight can lead to overheating and exacerbate the cooling situation (Proietti et al., 2013). This performance is similar in hot and dry climates, where, due to the significant increase in solar radiation during the summer, office buildings experience a very high cooling load (Al-Masrani et al., 2018). Therefore, selecting the appropriate dimensions for the atrium skylight opening in both hot and dry climates, as well as in cold and dry climates, is crucial. Additionally, a thorough study of the design of the atrium skylight (area, position, etc.) in buildings is essential to consider the lighting level and its impact on the building's thermal comfort. Moreover, controlling excess heat and light from the atrium skylight can help reduce energy consumption. Thermal comfort refers to the subjective state that reflects the pleasure of the thermal environment. (Cheung et al., 2019). Human thermal comfort is the result of the energy balance between the body surface and the environment, which affects the physiology, psychology, and behavior of individuals (Li et al., 2023). It is almost a set of thermal conditions that is acceptable to at least 80% of people. Unusually, other individuals may sometimes feel cold or hot, a condition in which the human body can maintain its thermal balance without experiencing energy overload or a deficit (Tabadkani et al., 2022).

However, previous studies have not given significant consideration to thermal comfort indices in environmental conditions that affect the acceptance or rejection of microclimate conditions. Nonetheless, essential factors for thermal comfort include seasonal variations, metabolic rates, changes in body posture, and adaptation to local environmental conditions. The main factors affecting thermal comfort include relative humidity, air velocity, mean radiant temperature, air temperature, clothing insulation, and metabolic rate. It's essential to note that psychological parameters also influence thermal comfort, including individual expectations (Baghoolizadeh et al., 2023). This holistic approach to building design considers not only physical factors but also the psychological aspects of comfort and well-being. The configuration of human comfort is strongly influenced by four factors, including wind, radiation, humidity, and temperature (Guo et al., 2025). For cities such as Yazd and Tabriz, what are the optimal channel dimensions for enhancing thermal comfort in enclosed atriums connected to each other? Among these factors, temperature and humidity have the most significant impact on human health and comfort. One method used to achieve thermal comfort in buildings is the utilization of passive systems. The use of passive systems has a long history; they have been employed in building designs for centuries. In recent years, growing issues related to fuel supply and environmental pollution have increased the importance of these systems.

Figure 1 illustrates the research methodology used to optimize channel configurations and enhance the user experience. The objective of this research is to evaluate and maximize the effectiveness of passive architectural elements—specifically, channel configurations connected to central atriums and adjacent zones—in improving thermal comfort in two distinct climates: hot and dry, and cold and dry. To achieve this, the study analyzes the dimensions and layout of these channels in buildings located in Yazd and Tabriz. It investigates how modifying these parameters can enhance the thermal conditions within atriums and adjacent zones, aiming to manage airflow and heat transfer more effectively. The findings aim to inform the design of atriums and adjoining areas in buildings situated in regions with similar climatic conditions, with the overarching goal of enhancing occupant comfort.

The scientific gap in this study is the indirect connection model between adjacent spaces and the atrium. This model can help control energy loss in hot and dry climates. The study examines the dimensions and layout of channels connecting the atrium and office rooms. Its goal is to find the optimal channel dimensions. Previous studies have shown that factors such as geometry, layout, height, ratio, and proportions significantly affect atrium thermal conditions. The indirect connection model is a new approach. It can provide natural ventilation during moderate seasons in hot and dry climates. This approach can reduce energy consumption and enhance comfort, thereby making buildings more efficient. Models for this case study were created within the Grasshopper plugin environment, which runs on Rhino software. Honeybee and Ladybug plugins were used to simulate lighting, thermal comfort, energy, and climate analyses. As a result, energy and daylighting analyses are possible in the Grasshopper environment (Sadeghipour Roudsari & Pak, 2013). Using this environment, Honeybee and Ladybug can parameterize building physics simulation algorithms. Simulation variables can be adjusted immediately, facilitating highly flexible simulations (Pilechiha et al., 2022). Fig. 2 illustrates the various research tools employed in the process, highlighting the functionalities of each tool and its contribution to the overall approach.

By linking energy-related simulations to openStudio and EnergyPlus, Honeybee and Ladybug plugins serve as a

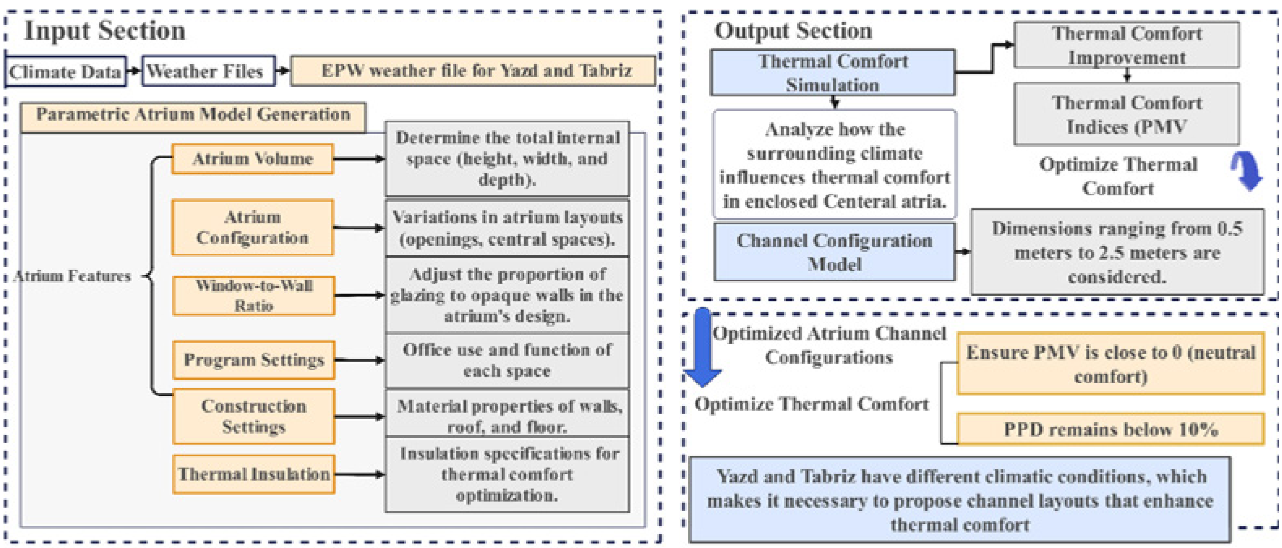


Fig. 1: Research Methodology

bridge to energy and thermal comfort simulation software. Transitioning to tool accuracy, Ashdown et al.'s comparative study (Ashdown et al., 2006) shows that radiation analyses yield high-accuracy results, providing confidence in the outcomes. In a similar vein, Reinhart and colleagues have demonstrated that simulation of PMV is as accurate as the experimental model, highlighting the reliability of the data (Zhou et al., 2023). The research tools utilized for this study are summarized in Fig. 2. When examining plugin capabilities, the Legacy Honeybee plugin can simulate basic thermal comfort variables and perform standard analyses. In contrast, Honeybee Plus enables calculation of annual thermal comfort indices for specific periods and cross-sectional studies. This enhanced version also allows calculation of indices over shorter timeframes, such as a single day, facilitating more detailed temporal analyses. Shifting to the regional context, this study finds that Yazd experiences moderately warm springs (March to May), cool autumns (September to November), hot summers (June to August), and cold winters (December to February). Tabriz experiences hot summers (July and August) and cold winters (January to March). Moderately hot periods occur in May and June, while September is mildly cold. These unified seasonal classifications provide clarity when understanding environmental conditions in these cities.

Model Definition: Using 5x5 modules divided into nine equal sections with the atrium in the center, the study attempts to use 5x5 modules divided into nine equal sections. The dimensions and material types for each variable are presented in Table 2 for default interpretation. Figure 3 illustrates the atrium's thermal performance through indirect channel connections in both warm and cold seasons. In winter, the model emphasizes heat retention and heat loss. Convective currents transfer warm air generated inside downward during this season, minimizing the intake of cold air from the outside. The design of the openings prevents heat from accumulating on the upper floors by evenly distributing it throughout the interior. Consequently, expensive heating systems are reduced, and thermal efficiency is improved. Table 2 presents the simulation results assuming fixed values, while Table 3 lists the materials used in the model. In this study, an indirect connection model is used for the central atrium. To enhance thermal comfort and improve the performance of the solar chimney, the dimensions of the channel—particularly its width—will be examined. Varying the channel width from 25 cm to 2.5 meters is expected to influence airflow, solar gain, and overall effectiveness, thereby affecting thermal comfort within the building.

Atriums can become warmer in the summer if the windows are closed, which reduces the need for air conditioning. Atrium windows allow natural ventilation to exit through the atrium by default, regardless of whether HVAC systems are on or off. The effectiveness of natural ventilation in regulating atrium temperature is directly related to the width of the ventilation channel. As shown in Table 3, the model incorporates various construction elements critical to the study.

An indirect connection between the atrium and office zones is provided by a channel, as shown in Fig. 4. By designing it this way, air and thermal energy can flow freely between the two rooms without interfering with each other directly. In addition to promoting natural ventilation, the channel also regulates temperature. The atrium and office zones have

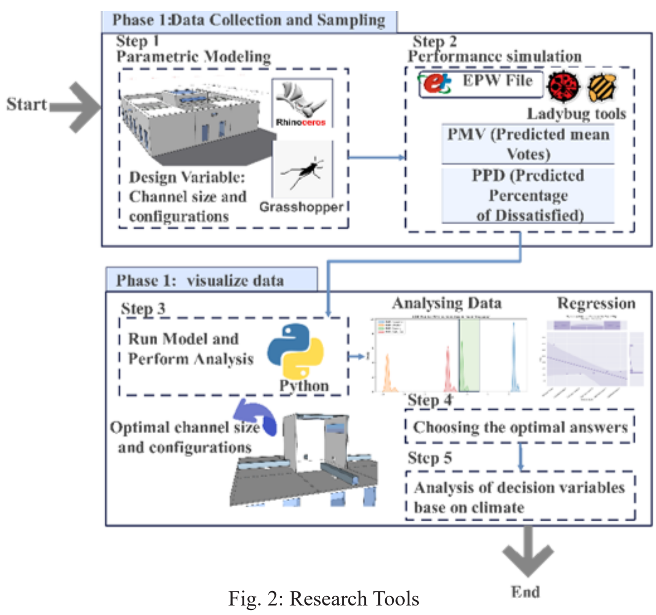


Fig. 2: Research Tools

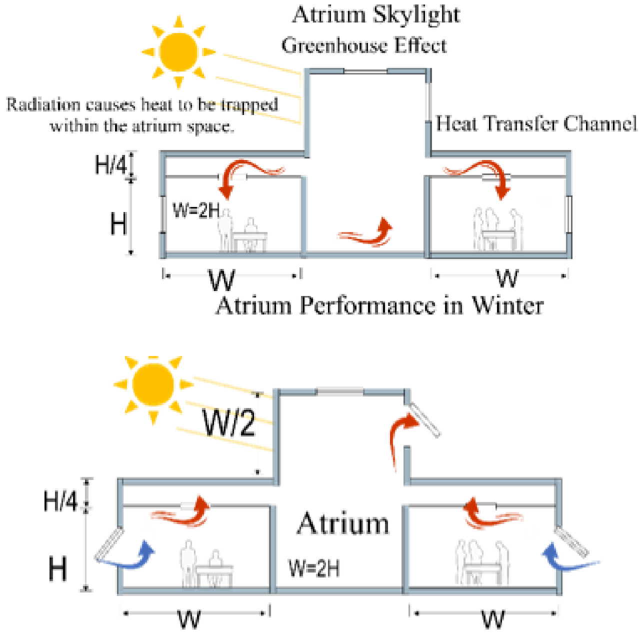


Fig. 3: Study Model (Indirect connection by using Channel)

Table 2: Values during the simulation

Parameter	Value
Location / Climate zone	Yazd, Iran/BWh, Tabriz, Iran/BSk
Floor area	225.00 m2 (15.00 m× 15.00 m)
Channel length	5 m
Zones height	3.50 m
Room Window	0.9×1.92 m2
Atrium height	5.00 m
Schedule	Saturday to Wednesday (9:00 to 17:00)
HVAC settings	Always off
Infiltration rate per area	0.0003 m3/S.m2
Number of people per unit of area	0.10 People/m2
Output intervals	Annual

different air pressures and temperatures. By improving both thermal comfort and airflow, the indirect connection enhances the building's energy efficiency. Maintaining an optimal indoor climate can be achieved by reducing reliance on mechanical HVAC systems. This research aims to examine the impact of channel configuration Sizes in central atriums of office buildings on thermal comfort in BWH and BSk climates.

Climate Analysis of Yazd: Table 2 shows key climate and environmental data for Yazd, Iran. Yazd falls under the Arid Desert (BWk) category in the Köppen system. It is also considered Hot (2) in the ASHRAE system. The city experiences a wide range of temperatures. January is the coldest month, while July is the hottest. The most frigid week of winter in Yazd occurs from December 22 to January 5. The hottest week of summer is from July 13 to July 19. The representative winter week is defined as February 10 to February 16. The representative summer week is August 17 to August 23. Yazd has an average annual temperature of 19°C and an average

Table 3: Materials used in the model (Hoseinzadeh et al., 2022).

	Structure (m)	Thickness	Thermal Conductivity (W/m.K)	Specific Heat (J/kg.K)	Density (kg/m³)
External Wall	Plaster	0.025	0.7	1000	1400
	Brick	0.2	0.39	840	866.67
	Uninsulated Lecca Block	0.05	0.0229	923	520
	Plaster	0.025	0.7	1000	1400
Internal Wall	Brick	0.03	0.39	840	866.67
	Plaster	0.025	0.7	1000	1400
	EPS Insulation	0.07	0.0385	1200	30
	Plaster	0.025	0.7	1000	1400
Floor	Heavy Concrete	0.15	1.06	1000	2000
	Ceramic Tiles	0.01	1.3	840	2300
	EPS Insulation	0.1	0.0385	1200	30
	Plaster	0.025	0.7	1000	1400
Roof	EPS Insulation	0.03	0.0385	1200	30
	Asphalt	0.05	0.7	1000	1200
	Plaster	0.2	0.0385	1000	1400
	Heavy Concrete	0.02	1.06	1000	2000
Window	U 0.5 SHGC 0.34 Simple	0.01	520	2297	923

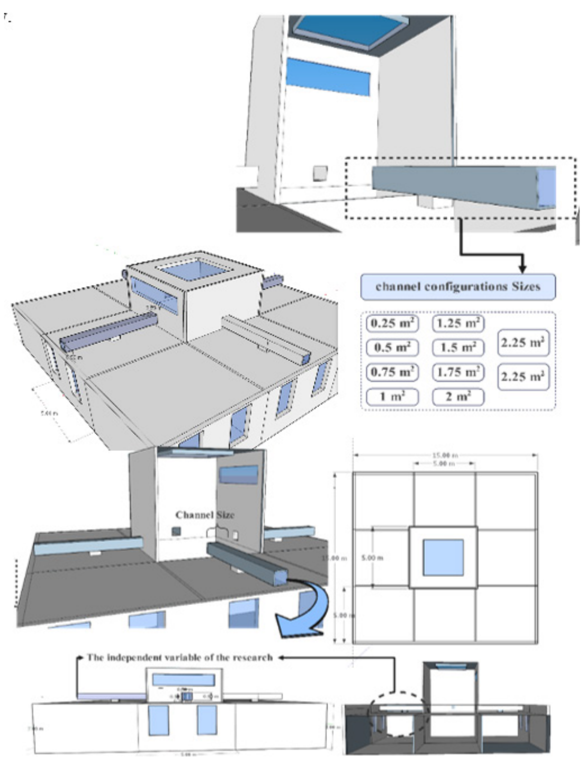


Fig. 4: Indirect connection Atrium and Office Zones By Channel

wind speed of 2 meters per second. The city receives 2030 kilowatt-hours per square meter of solar radiation annually. High solar exposure and low wind speeds have a significant impact on local climate and urban environmental conditions. Table 4 outlines the climatic parameters of Yazd. It provides key information, including the Köppen Climate Zone (Arid Desert cold, BWk), the coldest month (January), and the average annual temperature (19°C), among other details. These parameters are crucial for understanding the local climate conditions. Building on this, following the overview of climatic parameters, Fig. 5 illustrates the psychrometric chart in Yazd.

Climate analysis of Tabriz: Tabriz's climate is influenced by several climatic systems located in the northwestern region. Its proximity to the Zagros Mountain range results in cold, snowy winters and mild, relatively warm summers. Winter in Tabriz brings snowfall and temperature drops, especially in December and January. A clear seasonal temperature fluctuation also occurs in the city. A summer's night is usually more fabulous, and the heat is less intense. A sudden change in temperature, especially at night, can be very extreme. The absolute minimum temperature at Tabriz station is -9°C, and the absolute maximum temperature is 40°C. Temperatures at maximum, minimum, and average are shown in Table 5. Tabriz's psychometric charts, Fig. 6 shows the Psychrometric chart in Tabriz.

PMV (Predicted Mean Vote): There are two primary methods for evaluating thermal comfort: laboratory and adaptive methods. Fanger evaluates thermal balance through laboratory experiments and the adaptive process. Sensory sensations are directly related to temperature regulation, as demonstrated by the thermal balance model. This analysis uses the PPD and PMV indices. (Fanger, 1970). Shaeri et al. developed a thermal comfort model based on ISO 7730 (Shaeri & Mahdavinejad, 2022). The PMV index measures thermal comfort. Table 6 shows the PMV's seven-level comfort rating. Six factors—metabolic rate, clothing insulation, air temperature, relative humidity, air velocity, and mean radiant temperature.

Table 4: Climatic Parameters of Yazd

Köppen Climate Zone	Arid Desert cold (BWk)	Coldest month	
ASHRAE Climate Zone	Hot (2)	Coldest week	January 12/22-1/5
Average annual temperature	19	Typical winter week	2/10-2/16
Annual total solar radiation	2030	Hottest month	July
Average annual wind speed	2 m/s	Hottest week	7/13-7/19
		Typical Summer week	8/17-8/23

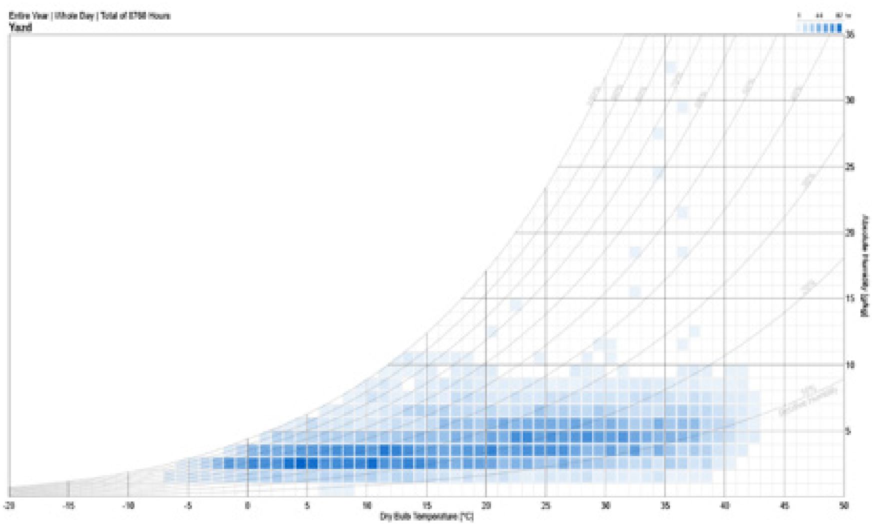


Fig 5. Psychrometric chart in Yazd

Table 5: Climatic Parameters of Tabriz

Köppen Climate Zone	Arid Steppe cold (BSk)	Coldest month	January
ASHRAE Climate Zone	Cool (5)	Coldest week	1/13-1/19
Average annual temperature	10	Typical winter week	12/15-12/21
Annual total solar radiation	1935	Hottest month	August
Average annual wind speed	2 m/s	Hottest week	8/11-8/16
		Typical Summer week	6/22-6/28

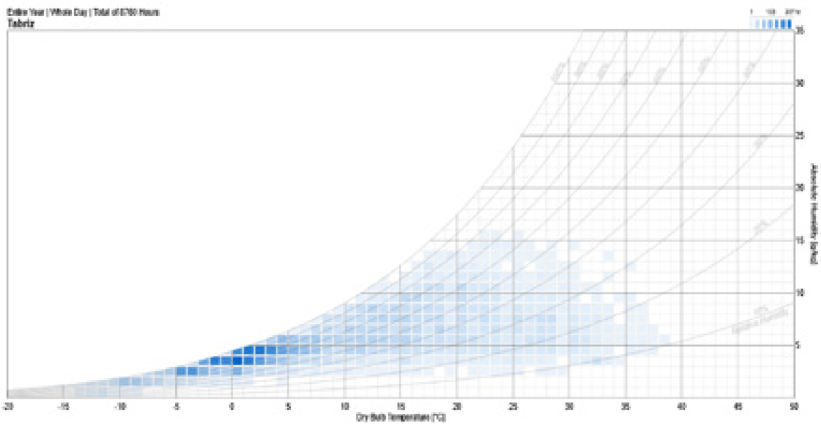


Fig. 6: Psychrometric chart in Tabriz

Table 6: Thermal perception scales with the PMV index (ASHRAE, 2017).

Scales	Thermal perception
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

RESULTS AND DISCUSSION

Predicted Mean Vote in Yazd: Based on the analysis of seasonal variations and the impact of channel dimensions on thermal comfort (PMV) in connected atriums under Yazd's specific climatic conditions, a 1-meter channel width consistently maintains the PMV within the desirable range of -0.5 to 0.5 (ASHRAE, 2017), ensuring optimal comfort throughout the year As winter gives way to spring, Yazd experiences moderate temperatures that are cooler than those in summer. In this period, a 1-meter channel width effectively maintains thermal comfort and keeps the PMV (Predicted Mean Vote) within the desired range. This width ensures sufficient ventilation, steady indoor temperatures in the atrium, and avoids insufficient airflow. As summer approaches, Yazd's temperatures climb sharply. The focus shifts to reducing PMV to near zero and maximizing ventilation; channel widths of 2 or 2.5 meters improve this, but a 1-meter width remains

Table 7: PMV Values for Different Channel Dimensions Across Seasons in Yazd and Tabriz

Channel Dimensions	Yazd				Tabriz			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
0.25 meters	-0.22	2.24	-0.89	-3.75	-1.42	-0.515	-0.946	-5.30
0.5 meters	-0.22	2.22	-0.89	-3.75	-1.42	-0.509	-0.95	-5.30
0.75 meters	-0.233	2.23	-0.89	-3.76	-1.439	-0.505	-0.955	-5.31
1 meter	0.0041	2.41	-0.62	-3.43	-1.13	-0.72	-0.966	-4.94
1.25 meters	-0.24	2.23	-0.903	-3.77	-1.45	-0.497	-0.964	-5.32
1.5 meters	-0.24	2.22	-0.90	-3.77	-1.45	-0.492	-0.969	-5.33
1.75 meters	-0.249	2.22	-0.908	-3.77	-1.46	-0.489	-0.972	-5.33
2 meters	-0.25	2.22	-0.91	-3.78	-1.46	-0.485	-0.976	-5.34
2.25 meters	-0.258	2.22	-0.916	-3.78	-1.475	-0.478	-0.983	-5.34
2.5 meters	-0.25	2.22	-0.914	-3.79	-1.478	-0.478	-0.982	-5.349

adequate when extreme ventilation isn't needed. After the summer heat, the onset of autumn cools temperatures again. In autumn, a 1-meter channel width again optimally maintains thermal comfort, ensuring the atrium's temperature remains balanced. As autumn turns to winter, temperatures in Yazd can drop significantly. A 1-meter channel width performs optimally in these conditions. This width helps retain internal heat and prevents cold air from entering the atrium.

As a result, the predicted mean vote (PMV), which measures occupants' thermal comfort, remains at its lowest negative value and maintains the desired comfort level. Given Yazd's climate, a 1-meter channel width keeps the PMV within the comfort range in all seasons. It provides balanced ventilation and temperature regulation for connected atriums throughout the year. A 1-meter channel width ensures PMV remains in the comfort zone, with sufficient ventilation and minimal temperature fluctuations. Table 7 illustrates how PMV varies with different channel widths across seasons in Yazd and Tabriz.

Yazd experiences extreme summers and cold winters, necessitating careful selection of channel dimensions in connected atriums to maintain thermal comfort, as measured by Predicted Mean Vote (PMV), throughout the year. The hot, dry climate requires an effective ventilation system in all seasons. Channel width selection is critical for achieving indoor comfort. During winter, minimizing heat loss and preventing cold air infiltration are top priorities. Channel widths of 0.5 or 0.75 meters provide adequate ventilation while reducing heat loss. In summer, wider channel widths, such as 2 or 2.5 meters, increase airflow, facilitating the removal of hot air and maintaining comfortable atrium temperatures. In autumn, when temperatures are milder, a balanced ventilation strategy is necessary to avoid significant temperature fluctuations; channel widths of 0.75 or 1 meter are recommended.

In spring, moderate temperatures require sufficient ventilation without excessive cooling or heating, making channel widths of 1 or 1.25 meters optimal for maintaining stable indoor conditions. Considering seasonal temperature variations, a constant channel dimension of 1 meter is identified as optimal for maintaining year-round thermal comfort in Yazd's connected

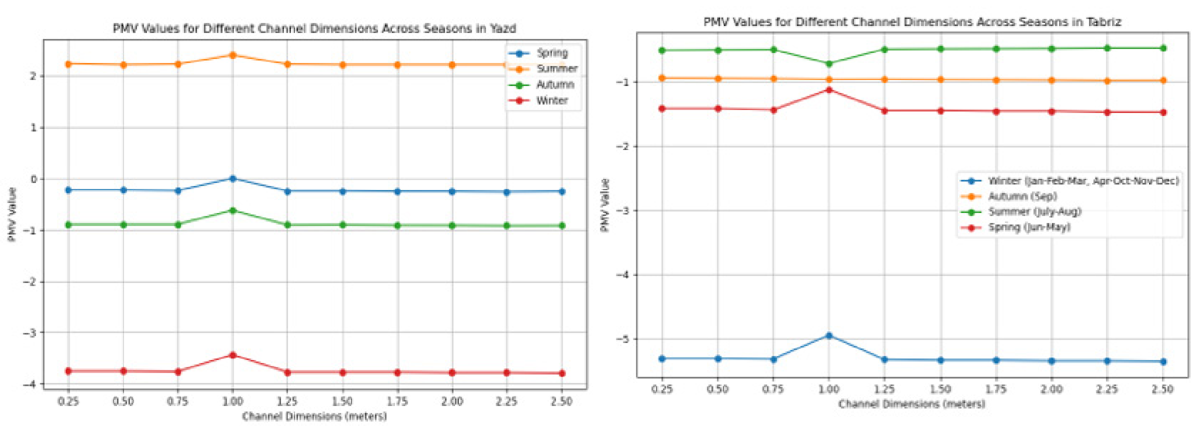


Fig.7: PMV values across seasons according to channel dimensions in Yazd and Tabriz

atriums. This dimension consistently maintains PMV within the comfort range. Although wider channels, such as 2 or 2.5 meters, are more effective during extremely hot summers, a 1-meter width provides the most balanced performance across all seasons. Figure 7 presents the seasonal variation of PMV values in relation to channel size for both Yazd and Tabriz.

Correlation Coefficients: Based on the correlation coefficients presented in the table for both Tabriz and Yazd, a noticeable relationship exists between channel width and PMV (Predicted Mean Vote) across the different seasons. However, the strength of this relationship varies. The correlation coefficients for the seasons in Tabriz and Yazd are presented in Table 8. As shown in the table, there are different levels of correlation between channel width and PMV in each season for both cities.

In Tabriz, the correlation coefficient for Autumn is -0.98, indicating a strong negative correlation. This means that as channel width increases, PMV decreases significantly, resulting in improved thermal comfort. In winter, the correlation is -0.31, indicating a weak negative correlation. This implies a modest improvement in comfort as channel width increases, but the relationship remains weak. In Summer, the correlation is 0.34, representing a weak positive correlation. This suggests that increasing channel width slightly reduces PMV, but the effect is minimal. In Spring, the correlation coefficient is -0.36, indicating a slight negative correlation, which reflects a minor improvement in thermal comfort with wider channels. For Yazd, the correlation coefficients are generally weaker than those in Tabriz. In Winter, the correlation is -0.29, suggesting a modest negative correlation and effect on PMV from increasing channel width. Similarly, in Autumn, the correlation is -0.28, indicating a weak negative correlation, with little substantial change in thermal comfort from channel width adjustments. In Summer, the correlation coefficient is -0.25, suggesting a weak negative correlation, where wider channels reduce PMV slightly.

In Spring, the correlation is 0.33, indicating a moderate positive correlation; as channel width increases, thermal comfort improves noticeably during this season. In both Tabriz and Yazd, a relationship exists between channel width and PMV; however, the strength of this relationship varies across different seasons. In Tabriz, the most pronounced effect is observed in Autumn, with a high negative correlation, while in Yazd, the effect is most noticeable in Spring, with a moderate positive correlation. Overall, while a correlation exists, it is generally weak or moderate in both cities, suggesting that PMV is not solely dependent on channel width; other factors likely play a role in determining thermal comfort. In Figs. 8 and 9, the Joint Plot with Regression in Yazd and Tabriz shows a noticeable relationship between channel width and PMV, with a strong negative correlation in autumn, indicating that increased channel width significantly reduces PMV; correlations in other seasons are weaker.

The PMV values for Spring range from -0.25 to 0.0041, indicating generally good thermal comfort, though smaller channel widths (0.25 and 0.5 meters) may cause a sensation of coldness. In Summer, PMV values between 2.22 and 2.41 indicate uncomfortable heat, which is exacerbated by narrower channels, while larger widths may improve ventilation. Autumn values range from -0.916 to -0.62, reflecting comfortable conditions typical of autumn, and widths of 1 meter or more help maintain this comfort. In Winter, PMV values from -3.75 to -3.79 indicate a cold environment, where wider channels help retain heat and reduce the influx of cold air. The PMV values for Tabriz mirror those for Yazd, but due to the distinct climates, they exhibit seasonal variations. In Winter, PMV values span from -5.30 to -5.34, indicating a frigid environment. Channel widths of 1 meter or more substantially minimize heat loss, preserving comfortable indoor temperatures. In Autumn, PMV values range from -0.983 to -0.972, indicating that autumn falls within the comfort range. Wider channels facilitate efficient ventilation and thermal comfort this season. Summer PMV values shift from -0.72 to -0.478, indicating a slight increase in heat. These values remain within the comfort range, but increased ventilation through wider channels can further ease heat perception. In Spring, PMV values range from -1.42 to -1.13, indicating moderate coldness and satisfactory thermal comfort. Broader channel widths promote stable indoor temperatures. Channel width consistently influences thermal comfort in Yazd and Tabriz across all seasons, moderating cold ingress in Winter and Autumn and enhancing ventilation in Summer and Spring. The collected data enable the establishment of a regression between channel widths and

Table 8: Correlation Coefficients Between Channel Widths and PMV Across Seasons in Tabriz and Yazd

Season	Tabriz PMV Correlation	Yazd PMV Correlation
Winter	-0.31	-0.29
Autumn	-0.98	-0.28
Summer	0.34	-0.25
Spring	-0.36	0.33

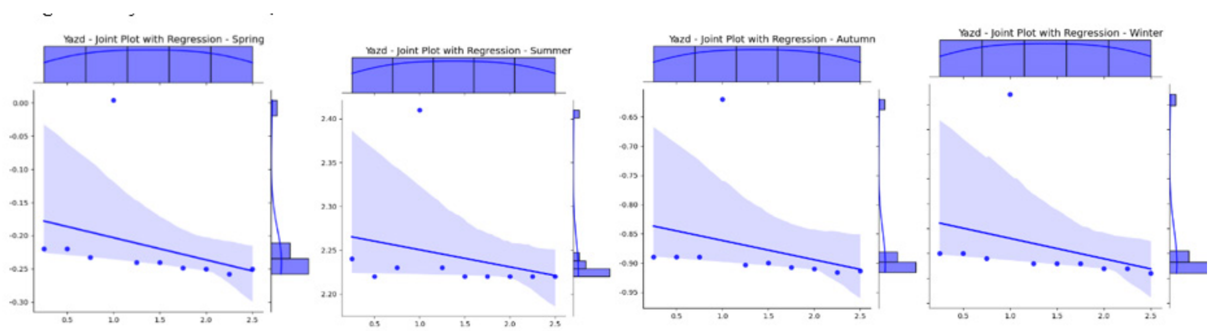


Fig. 8: Joint Plot with Regression in Yazd

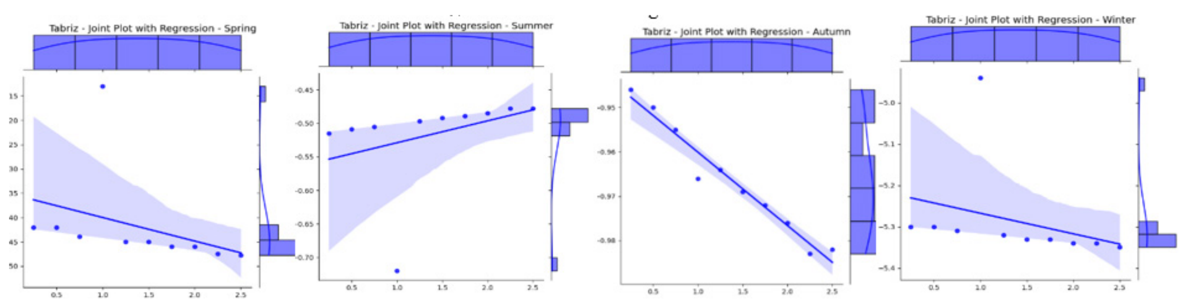


Fig. 9: Joint Plot with Regression in Tabriz

PMV per season in both cities, quantifying the effect of channel width on thermal comfort.

PPD (Predicted Percentage of Dissatisfaction): In building design and ventilation, the Predicted Percentage of Dissatisfaction (PPD) is crucial for assessing indoor thermal comfort. Based on the Predicted Mean Vote (PMV), PPD guides engineers in designing comfortable environments by utilizing HVAC and ventilation systems. Values under 10% suggest comfort for most, while higher values indicate discomfort. Yazd and Tabriz, with unique climates, were evaluated using PPD. By analyzing air vent dimensions, optimal channel widths for comfort in varying weather can be determined. For Yazd, a 1-meter channel provides the best comfort balance: in winter, PPD drops from 99.99% (less than 1 meter) to 99.93% (1 meter)—a slight improvement, as wider channels reduce cold air. Larger widths offer minimal added benefit. In autumn, PPD falls to 13.06% at 1 meter, compared to 21.72% at 0.25 meters; increasing the width further yields little change. In summer, narrower channels (0.25–0.5 meters) lower PPD to 10.55%, while a channel 1 meter wide raises it to 15.91%, offering a practical balance between ventilation and comfort. Table 9 shows PPD values for various channel widths by season, highlighting their effect on year-round comfort.

In spring, PPD improves significantly at 1 meter, achieving 31.9%, compared to 46.58% at 0.25 meters. This demonstrates that 1 meter provides optimal comfort by balancing ventilation needs and fluctuating outdoor temperatures. The 1-meter width reduces PPD more than smaller channels, ensuring improved comfort without excessive airflow. In winter, the PPD for Tabriz remains 100% for all widths, indicating that cold is the dominant issue; however, a 1-meter width still offers efficient air circulation and limits cold air infiltration. In autumn, PPD decreases at 1 meter, dropping from 24.96% (at 1.75 meters) to 24.71%, representing improved comfort. Channel widths beyond 1.25 meters bring little benefit, confirming that 1 meter is optimal in autumn as well. In summer, PPD rises from 10.55% for 0.25 meters to 15.91% for 1 meter, which remains acceptable as it continues to provide adequate ventilation without excessive heat accumulation. Overall, a 1-meter channel width is optimal for delivering balanced ventilation and thermal comfort throughout the year in Yazd and Tabriz, as shown in Fig. 10, which illustrates the relationship between channel width and comfort in all seasons. The Optimal Channel Dimensions (1 meter) provide the best thermal comfort across different seasons, balancing both ventilation and temperature control.

Table 9: PPD Values for Different Channel Widths Across Seasons in Yazd and Tabriz

Channel Width (meters)	Yazd Spring PPD	Yazd Summer PPD	Yazd Autumn PPD	Yazd Winter PPD	Tabriz Spring PPD	Tabriz Summer PPD	Tabriz Autumn PPD	Tabriz Winter PPD
0.25	46.58	10.55	21.72	99.99	46.58	10.55	23.9	100
0.5	46.58	10.42	21.72	99.99	46.58	10.42	24.06	100
0.75	47.6	0.331	21.72	99.99	47.6	10.33	24.26	100
1	31.9	15.91	13.06	99.93	31.9	15.91	24.71	100
1.25	48.19	10.16	22.22	100	48.19	10.16	24.63	100
1.5	48.19	10.06	22.1	100	48.19	10.06	24.83	100
1.75	48.73	10	22.41	100	48.73	10	24.96	100
2	48.73	9.91	22.49	100	48.73	9.91	25.12	100
2.25	49.54	9.77	22.72	100	49.54	9.77	25.41	100
2.5	49.71	9.77	22.64	100	49.71	9.77	25.37	100

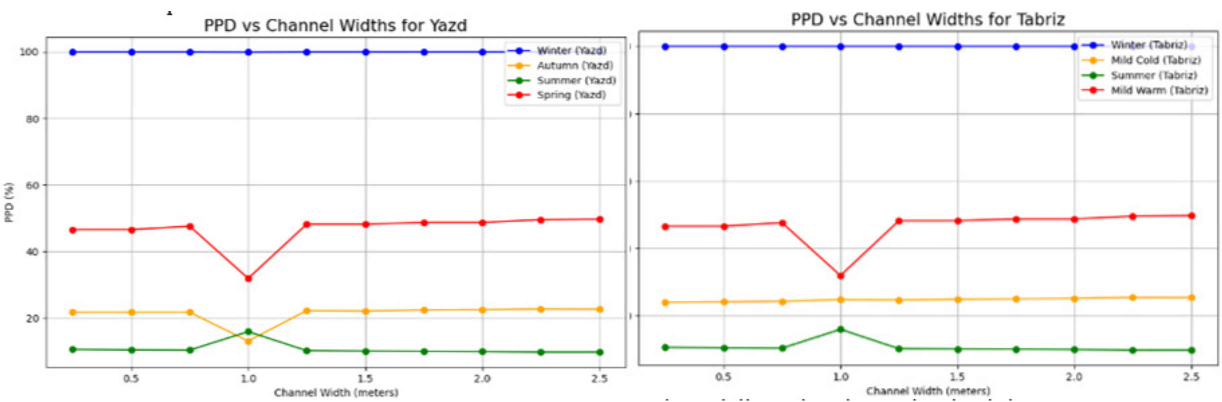


Fig. 10: PPD values across seasons according to channel dimensions in Yazd and Tabriz

To test the first hypothesis, the dimensions of the atrium channel, which is indirectly connected to the office space, were analyzed and compared across different seasons in Yazd and Tabriz. The objective was to assess how changes in channel dimension influence thermal comfort (PMV) in both cities throughout the year. Pearson's correlation coefficient was used due to the characteristics of the data. In Pearson's test, the null hypothesis states there is no significant relationship between the variables, while the alternative hypothesis asserts a significant relationship exists. If the significance level is below 0.05, the null hypothesis is rejected, indicating with 95% confidence that a substantial relationship is present. Pearson correlation coefficients for Yazd and Tabriz revealed a clear relationship between channel width and PMV by season. Table 9 summarizes the coefficients for each season in both cities, highlighting seasonal
diffReferences in the strength of the width-PMV relationship. Autumn, a correlation coefficient of -0.98 indicates a strong negative correlation, meaning that wider channels significantly decrease PMV, thereby enhancing thermal comfort. In Winter, a coefficient of -0.31 indicates a weak negative correlation, meaning wider channels modestly improve comfort. In the Summer, a correlation of 0.34 suggests a weak positive correlation, indicating that increasing channel width has a minimal impact on PMV.In Spring, a correlation coefficient of -0.36 reflects a slight negative correlation, indicating minor comfort gains with wider channels. In Winter for Yazd, a coefficient of -0.29 indicates a modest negative correlation, suggesting that increasing channel width has a limited impact on PMV. In Autumn, a coefficient of -0.28 indicates a weak negative correlation, meaning that changes in channel width result in slight variation in comfort. In the Summer, a correlation coefficient of -0.25 suggests a weak negative correlation, indicating that wider channels slightly decrease PMV. In Spring, a coefficient of 0.33 demonstrates a moderate positive correlation, indicating that increasing the channel width noticeably enhances thermal comfort. As presented in Table 10, the optimal channel dimensions are specified in meters,

with a focus on achieving the best performance in the model. A relationship exists between channel width and PMV in both Tabriz and Yazd, but its strength varies by season. In Tabriz, the effect peaks in Autumn with a strong negative correlation; in Yazd, the effect is most potent in Spring with a moderate positive correlation. Overall, the correlation is generally weak or moderate, indicating PMV depends on additional factors beyond channel width. The value of Pearson's correlation coefficient is calculated using the following formula. Figure 11 illustrates an indirect method of transferring heat to Yazd's atrium. In this diagram, solar heat is absorbed through a skylight in the building's atrium and channeled into the central space via a channel, illustrating the building's clever utilization of solar energy.

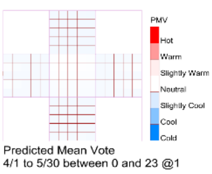
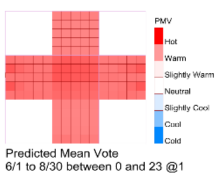
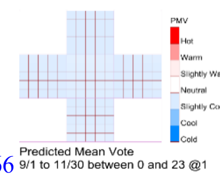
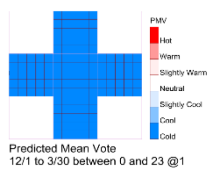
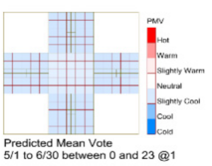
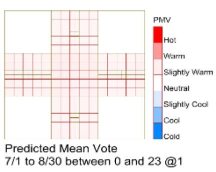
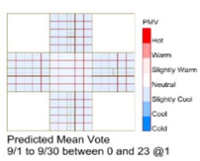
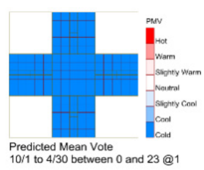
Equation (1) shows the correlation coefficient relationship.

$$r = \frac{\sum xy - n\bar{x}\bar{y}}{\sqrt{\sum x^2 - nx^2\sqrt{\sum xy^2 - n\bar{y}^2}}}$$

In this system for Yazd, which operates as a cooling system in the summer, the solar chimney plays a crucial role. Due to the sun's radiation, the skylight on the atrium traps heat inside the building. As a result, the room's heat rises during the summer and moves upward. This hot air is then directed through a channel connected to the atrium, where the trapped heat is released. The heat is vented out through an eastern window beside the atrium, allowing the hot air to escape from the atrium window. This process facilitates the natural ventilation of warm air from the building, thereby cooling the interior space. The cooling effect achieved through this mechanism reduces the need for mechanical air conditioning, helping to maintain a comfortable indoor temperature in the hot summer months in Yazd. In this system, the skylight window allows natural light and heat to enter. When sunlight strikes the glass, some solar energy is converted into heat and becomes trapped within the building. The glass acts as a barrier to heat exchange. It allows sunlight to pass through but stops heat from escaping easily. This effect is beneficial during cold months, as it retains solar energy inside and creates a greenhouse effect, contributing to thermal comfort. Heat trapped in the atrium—the building's central space—is transferred to the office spaces via ducts. This heat then moves into other parts of the building through natural air circulation.

As a result, the ambient temperature rises, enhancing thermal comfort. This technique is called passive ventilation. It uses less energy and reduces reliance on mechanical heating systems, while promoting comfort within the building. Tabriz has cold winters and hot summers. This makes using solar energy in winter especially helpful. Capturing and storing solar heat inside can lower the energy needed for heating, ensuring a comfortable indoor temperature. During cold months, this

Table 10: Optimal Channel Dimensions (1 meter)

Spring	Summer	Autumn	Winter
	Yazd		
 0.0041	 2.41	 -0.66	 -3.43
	Tabriz		
			
-1.13	0.72	-0.62	-4.94

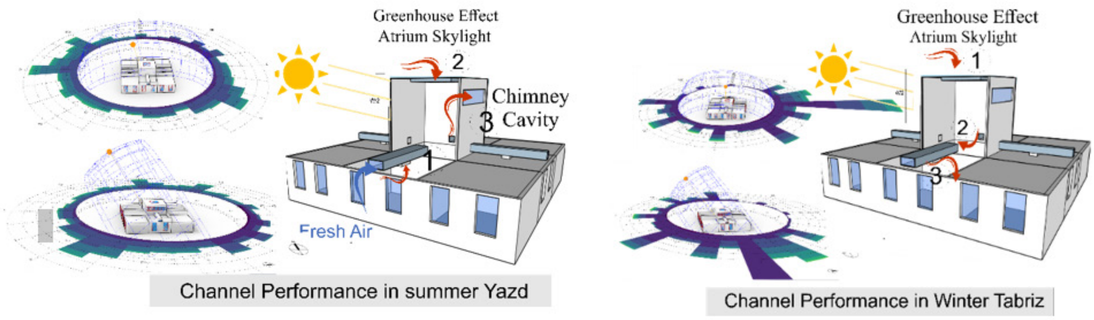


Fig. 11: Climate Diagram by indirect Channel to Atrium in Yazd and Tabriz

stored heat helps maintain optimal thermal comfort.

CONCLUSION

This study investigates the impact of channel configurations on thermal comfort, as measured by Predicted Mean Vote (PMV), in connected, enclosed atria in Yazd and Tabriz, two cities with distinct climates. The research aims to optimize channel dimensions to improve year-round thermal comfort and reduce dependence on mechanical heating and cooling systems. The results demonstrate that channel dimensions are crucial for achieving energy-efficient thermal comfort, highlighting the necessity of integrating climatic and architectural considerations. In Yazd, which experiences hot, dry summers and cold winters, a 1-meter channel width consistently achieves optimal thermal comfort in both summer and winter. During the hot summer, this configuration provides sufficient ventilation. It utilizes the solar chimney system to enhance natural airflow, thereby lowering PMV and maintaining comfortable conditions without the need for mechanical air conditioning. In winter, the same channel width effectively limits heat loss, stabilizes indoor temperatures, and supports thermal comfort. This dual benefit reduces energy consumption year-round while supporting both comfort and energy efficiency. In Tabriz, where winters are cold and summers are hot, the seasonal influence of channel width on thermal comfort differs. In Autumn, a strong negative correlation between channel width and PMV means that wider channels significantly improve comfort by increasing ventilation during cooler months. In Winter and Spring, wider channels have only a mild effect on PMV, as internal heating and passive solar gain play a larger role in comfort. In Summer, while wider channels can enhance ventilation, a width of 1 meter is optimal, balancing the need for airflow with prevention of excessive heat gain and supporting energy efficiency.

The study also revealed that the strength and direction of the correlation between channel width and PMV depend on the season and location. In Tabriz, a stronger negative correlation is observed in Autumn, enhancing comfort with wider channels. In Yazd, spring exhibits a moderate positive correlation, favoring wider channels for improved comfort. These findings demonstrate that the impact of channel dimensions on thermal comfort is not static but shifts in response to seasonal changes and local climatic and architectural factors. Designing energy-efficient spaces thus requires considering how these influences vary across different times of the year. The Predicted Percentage of Dissatisfaction (PPD) further supports the use of a 1-meter channel width, indicating that it provides a favorable balance between ventilation and comfort across all seasons. Larger channel widths increase summer ventilation, but the 1-meter width offers consistent energy efficiency and comfort year-round.

In Tabriz, the most pronounced negative correlation is observed in Autumn, with a coefficient of -0.98. This result indicates that increased channel width substantially reduces the Predicted Mean Vote (PMV) and enhances thermal comfort. In Winter, a weaker negative correlation of -0.31 demonstrates a moderate improvement in comfort with wider channels. During Summer, the correlation shifts slightly positive to 0.34, suggesting that increasing channel width has a negligible effect on PMV. In Spring, a minor negative correlation of -0.36 is recorded, reflecting only marginal improvements in comfort. A channel width of 1 meter is identified as optimal for achieving the highest overall thermal comfort throughout the year, as it effectively balances ventilation and temperature regulation. For Yazd, the correlation is more modest. In Winter, a coefficient of -0.29 indicates a limited impact of channel width on PMV. In Autumn, the effect is even weaker with a coefficient of -0.28. In Summer, a correlation of -0.25 suggests that wider channels slightly reduce PMV. However, in Spring, a positive correlation of 0.33 indicates that wider channels have a moderate positive effect, significantly improving thermal comfort. As illustrated in Figs.

15, the climate diagrams for Yazd and Tabriz demonstrate how solar heat is transferred through the building designs in both cities. In Yazd, the solar chimney system operates as a cooling system in the summer, utilizing the skylight to trap heat, which is then vented out through an eastern window, naturally cooling the interior. In Tabriz, the skylight acts to trap solar heat during the cold months, creating a greenhouse effect that enhances thermal comfort by transferring the trapped heat into the building. This passive ventilation reduces reliance on mechanical heating and cooling systems, contributing to a comfortable indoor environment. In summary, channel width influences the Predicted Mean Vote (PMV) in both cities, with effects that differ by season and are shaped by architectural and climatic factors.

Optimizing channel configurations, especially those with a 1-meter width, is crucial for achieving thermal comfort in enclosed atriums in Yazd and Tabriz. These findings underscore the need to account for seasonal variations, local climate, and passive ventilation strategies in designing energy-efficient indoor environments. This research informs future designs aimed at enhancing comfort and reducing energy consumption across diverse climates. Future studies should investigate additional factors influencing thermal comfort, including building materials, structural components, and advanced HVAC systems, to develop more targeted recommendations for sustainable, energy-efficient buildings. The findings of this study provide valuable guidance for architects, urban designers, and developers seeking to optimize thermal comfort in buildings situated in climates similar to those of Yazd and Tabriz. By integrating passive ventilation systems with optimized channel dimensions, these professionals can design more energy-efficient buildings that reduce reliance on mechanical heating and cooling. The results suggest that incorporating a 1-meter channel width in the design of connected atriums can significantly enhance indoor thermal comfort while ensuring energy efficiency across different seasons. This approach can be particularly beneficial in both new and retrofitted buildings, enabling sustainable and climate-responsive urban designs that improve occupant comfort and reduce operational energy costs.

AUTHOR CONTRIBUTIONS

P. Javid conducted the literature review, designed the experiments, analyzed the data, and wrote the manuscript. N. Nikghadam performed the experiments, compiled the data, and contributed to the manuscript. A. Karimpour interpreted the data and edited the manuscript. J. Sabernejad supported the literature review and completed the final revisions.

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CONFLICT OF INTERESt

The authors declare that there are no potential conflicts of interest concerning the publication of this work. Furthermore, all ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication or submission, and redundancy, have been fully addressed and confirmed by the authors.

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