

Atrium Design in Hot and Dry Climates: Understanding the Influence of Architectural Form Variation on Indoor Thermal Conditions

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Abstract

The atrium is becoming more prevalent in desert regions as a key architectural and functional element in the urban landscape. In southern Algerian cities, we are observing an increasing integration of centralized atriums in public buildings. However, this integration may have an impact on the indoor environmental conditions of the buildings. This study investigates the influence of architectural aspects on the indoor thermal behavior of an existing centralized and enclosed atrium in the hot and dry climate of Laghouat. The study analyzes the influence of two parameters, namely height and glazed area ratio, during summer season. The EDSL-Tas software for dynamic thermal simulation modeling was used. The results revealed that the vertical temperature distribution in the atrium varies depending on its design, as a result of incoming solar radiation.

Keywords: Centralized Atrium; dynamic thermal simulation; hot and dry climate; architectural aspects; vertical temperature distribution.

1. Introduction

In a context of global warming, scientists are observing the evolution of the climate in all regions of the planet and throughout the climate system. According to the latest report of the Intergovernmental Panel on Climate Change (IPCC) published on August 9, 2021. Under the effect of global warming, the cycle of seasons is likely to be significantly modified by the middle of the century, with longer, hotter, drier summers, shortening winters, springs and autumns (L. San, 2023). However, Algeria, being a country with the highest solar deposit in the world, and a dry zone representing almost 95% of its territory (Halitim, 1988). Has also experienced in recent years, a significant and particular evolution in electricity demand during the summer period, reaching significant consumption peaks. This sharp increase in demand is a direct consequence of the change in consumer habits and the improvement of their comfort and quality of life, as well as the impetus given to the economic and industrial sector. Moreover, according to the energy balance of the year 2021 published by the Algerian Ministry of energy in 2022. The resumption of economic activity and the gradual lifting of health measures related to the Covid-19 epidemic generated a rebound (+8.0%) in national energy consumption (B.E.N, 2021).

Energy efficiency and User comfort and are two major concerns when evaluating the performance of building system controls. Ensuring thermal comfort is a key and effective parameter in building design (Aram and Alibaba, 2019). Likewise, the basic requirement in the design of a building is to provide shelter from the environment and its external conditions. However, the designer will also have to ensure the comfort of the user, while ensuring that the impact of the building on the environment is minimized.

With this in mind, among the architectural solutions adopted in modern buildings, was the integration of the atrium, practically and generally in regions with a temperate climate. Nevertheless, this method of construction is even beginning to spread in regions characterized by a hot and arid climate, such as that of the city of Laghouat in southern Algeria. Where we find many of modern buildings incorporate a variety of atrium configurations. These structures often showcase large glass surfaces and simple, streamlined forms. Since people spend significant time indoors, architects also design spaces for recreation and social interaction (Ratajczak and al, 2022).

The atrium concept was partially inspired by the yard as a traditional method of controlling the climate. Atriums functionally are very similar to courtyards and solar chimneys. Their similarities with yards include natural ventilation, natural lighting and shadings, spaces for social interaction, and better visual spaces (Heydari and al, 2023). The emergence of the atrium in southern Algerian cities often represents a transformation or replacement of the traditional courtyard that characterizes these regions, and with increasing urbanization and the introduction of new construction technologies (Amen & Nia, 2020; Aziz Amen, 2022; Auwalu & Bello, 2023; Gaha, 2023), It has become integrated into public buildings, protecting from external elements, especially excessive heat and dust that characterize the dry and hot regions.

The design of the building atrium is often carried out at the program stage, and the design of the atrium space at the program stage has a significant impact on the energy efficiency of the building (Kunwar, 2021). An appropriate atrium design can not only effectively reduce energy consumption, but also improves indoor thermal comfort (L and al, 2019; Mohammad Yusoff, 2021; Wahiba, 2020; Amani, 2018).

Similarly, numerous studies have shown that the Thermal performance of the atrium is largely determined by its geometric characteristics (Wu and al, 2021; van Dijk, 1995).

It is in this spirit that before approaching the design of a building, the architect must take the climate into account in his design approach to integrate elements such as solar radiation (carrier of heat and light) , wind, rain, cold, etc., in its design process. These natural factors have a direct impact on the perception of shapes, materials, comfort, atmosphere and economy of a building (Liébard and al , 2007).

During the design stage of a building, optimizing the building's orientation, structure, and layout can significantly enhance the thermal utilization efficiency of solar energy and reduce the building's heat load (Su and al,2022). When designing building with an atrium, it is important to consider the geometry of the atrium (Pang and al ,2023; Heydari, 2023), orientation and skylight area ratio (Wang and al, 2024), shapes and proportions (heydari, 2023; Khayami and al, 2023), depth and height (Rajapaksha,2020; Pang and al, 2023) as well as the type and configuration of the roof glazing (Mohammad Yusoff, 2021). As atriums serve as hubs connecting indoor and outdoor spaces, skylights are an essential part of their envelope structures (Acosta and al, 2018).

Simulation studies on energy consumption indicate that reducing the skylight area and atrium height which represented by The section aspect ratio (SAR) can improve the thermal environment. Atriums are dynamically coupled by multiple factors, including radiation and convective heat transfer (Wu and al, 2021). Thus, it directly leads to a high surface temperature on the glass roof and a large temperature gradient in both vertical and horizontal spaces of the atrium (Lu and al, 2020; Calcagni and Paroncini, 2004). Also thermal stratification generally occurs in high spaces (Mei and al, 2018). Likewise thermal stratification was observed in the non-air conditioned atrium with clear vertical gradients and largely influenced by climate (Dai and al, 2022; Jin and al, 2024). From the point of view of thermal environment, complicated thermal and fluid dynamics phenomena could take place in these confined spaces (Ferrucci and al, 2022).

As described above, most existing international studies, addressing the effect of atrium configuration on thermal comfort and energy consumption, often focuses on regions with temperate climates, while research on hot and arid regions is very rare.

Today, the arid environment is facing urban growth, where the building sector is one of the leading sources of energy consumption and one of the main contributors to greenhouse gas emissions (Berghout and Forgues, 2019).

The arid zone of a hot summer climate in Algeria includes most of its territory, characterized by a hot and dry summer where the average temperature in summer can reach 49°C. Despite this, large glazed surfaces can lead to excessive solar heat gain in summer and to heat loss in winter, as well as air stratification, especially in summer, which can affect the comfort of building users, as well as energy performance (Hussain Shafakat and Oosthuizen, 2012). On this, this research focuses on analysing atrium thermal behavior using the analysis and selection of atrium design suitable for buildings in an area with a hot and dry climate. This leads us, in fact, to ask the following question: What is the influence of atrium configuration on indoor thermal conditions for hot and dry climate regions?

Therefore, the main objective of the present study aims to present an attempt to obtain a configuration based on the geometric architectural parameters most effective in optimizing the thermal environment during summer by testing two geometric variables glazed area ratio and height (SAR index).

2. Material and Methods

The study employs a structured approach comprising two principal stages as shown in Figure 1. The initial stage involves selecting and identifying the atrium building, to subsequently characterizing atrium building typologie, which features a centralized atrium and desired characteristics for the hot and dry climate . The subsequent stage entails Dynamic Thermal Simulations assessment, using the EDSL Tas software version 9.4, in which the thermal behavior of the study case is evaluated, and different models configurations are analyzed among diverse atrium designs. This stage aims to evaluate the impact of design and dimensions of atrium on environment thermal, based on two architectural variables: Height (SAR index), and glazed area ratio .

The following are the evaluation criteria:

2.1. Stage 1 : Selection of a representative atrium building and typologie classification

The building selected as an experimental case study is "the faculty of social and human sciences", located in the western part of the Laghouat city with an average altitude of 750 meters, latitude 33°46'N and longitude 2°56'E; it has a hot dry climate. It was built in 2012. This building serves as both an administrative and institutional building. A choice duly motivated by the central atrium with a sloping roof located at the heart of its central hall which is used for circulation and distribution purposes to adjacent spaces, as well as the advantage of offering easy access to the public, as part of a public institution. The building has a compact shape with several blocks, oriented towards the East (East-West axis), and rises on three levels. The plans of the ground floor, first and second floor are almost identical with different spaces between, offices, classrooms, lecture halls and other spaces (figure 1). the atrium is a 17 x 8 metres rectangular in shape and 12 meter in height, naturally lit only from the top by a huge glass roof inclined at 10° towards the South, and which covers the roof of the atrium at 100%, without any solar protection or openings.

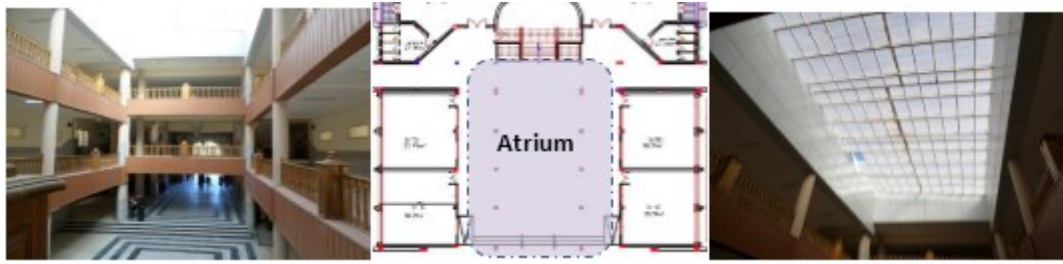


Figure 1. Interior views of the study case and the ground floor plan of the atrium

Given the unlimited number of type and configurations of the atrium, different academicians have sometimes classified the same shapes but with different names, this classification was initially written by "Richard Saxon" in "Atrium buildings: Development and Design" and "Bednar" in the "New Atrium", as well as by other authors such as: "Yashino", "Hasting" and "Baker" (Gemi, 2007).

According to the atrium typologies cited by the different authors, we can classify our atrium according to its shape and configuration as a centralized atrium, of a rectangular shape and of large volume with a depth or height Average (Table 1).

Knowing that :

$$\text{SAR index} = \text{Height} / \text{width} = 12 / 8 = 1,5$$

$$\text{PAR index} = \text{width} / \text{length} = 8 / 17 = 0,47$$

the SAR is defined as the height of the atrium (H) divided by the north to south width of the atrium (W), as given in Eq. 1

$$\text{SAR} = H / w \dots\dots \text{Eq. 1}$$

Table 1: Typology Classification of the selected atrium building

Typology Classification				
Hasting Typologie	Saxon Typologie	Yoshino	SAR index	PAR index
	/		1 < SAR < 2	0.4 < PAR < 0.9
Centralized atrium	/	Large volume with large floor area	Medium Atrium	Rectangular atrium

2.2. Stage2 : Dynamic Thermal Simulations and Analysis

In the first part of the research, the building was simulated in Laghouat , southern Algerian City, which is classified as a hot and dry climate (latitude 33°46'N and longitude 2°56'E, characterized by a very hot and dry summer, and a very cold winter with reduced humidity. In the Laghouat city climat, from June to August has the highest average temperature (27,9 °C–32,1 °C), with a maximum of 39,4°C in July. The cold season is from December to February (8,4° C – 9,5°C), and the minimum average is 1,7°C in January °C. Generally, An increased humidity during the winter season with values between 52% and 65%. However, the summer season records a range of 27% to 35%. We can report a difference of 38% between the coldest month (January) and the hottest month (July), which suggests that the climate of the city of Laghouat is cold in winter and quite dry and hot in summer.

The simulation covers summer period. A representative July day was taken for the analysis, characterized by an average wind speed of 2.5m/s, and an average temperature equal to 33°C, with a maximum of 41°C and a minimum temperature of 30°C.

The simulation and analysis were carried out using the EDSL Tas software version 9.3.3 . The 3-D geometric model of the building was created based on the available "DWG" architectural drawings of the actual building (Figure 2). However, for greater convenience, the model has been simplified by ignoring interior and exterior stairs, small corners and by combining a few spaces into a single zone. The model was defined into zones within each floor for thermal simulation purposes, so three main groups of zones were divided as follows:

- Atrium zones: (ground floor atrium, 1st floor atrium, 2nd floor atrium, Roof)
- Corridor areas: (ground floor corridor, 1st floor corridor, 2nd floor corridor)
- Adjacent spaces zones: (Adj ground floor space, adjacent 1st floor space, adjacent 2nd floor space)

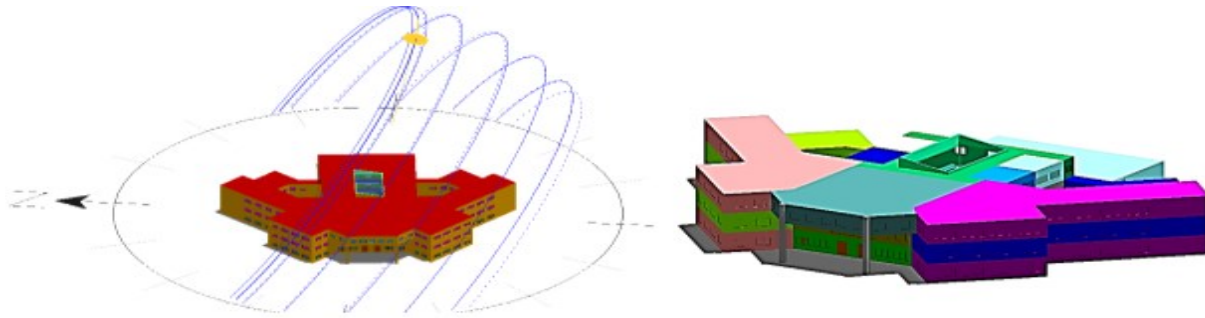


Figure 2. Base model of the atrium building case

The model set-up via the TAS software includes: setting out location and weather data, creating construction material for walls, floors, roof, windows, creating occupancy scenarios, internal gains, air exchange, and aperture type. For internal conditions, we have excluded any kind of gains related to lighting, occupants and equipment, in order to maintain the same internal conditions of the building, except the infiltration specifications for each zone.

The building is accepted for occupancy from 8:00 a.m. to 5:00 p.m. weekdays, exception weekend based on information from actual building opening hours

Referring to the actual situation, the Glazed roof is set as a single-layer clear glass (6mm), with heat transfer coefficient of $K = 5,682 \text{ W/m}^2 \cdot \text{°C}$, light transmittance of 0,890, and solar energy transmittance of 0,844.

The model analysis was conducted for six (6) simulations including the basic case, and divided on two simulation model groups:

Groupe 1 The height (SAR): On this case, the simulation is carried out on three (3) SARs, so three (3) dimensions of height (H) chosen with equation (H/w) according to these SAR configurations cited above, while keeping the atrium width (8 m) and the ratio of glass coverage to floor area (100%). (Table 2)

- 1) $H < w$ $H = w/2$ $H = 8/2 = 4$ —————→ **SAR = 0,5**
- 2) $w < H < 2w$ $H = w$ (Basic case)..... $H = 12$ —————→ **SAR = 1,5**
- 3) $H > 2w$ $H = 3w$ $H = 3 * 8 = 24$ —————→ **SAR = 3**

Groupe 2 Glazed area ratio: Includes three ratios (10 -0,430% (basic case), 75% and 50%) are carried out for the three configuration tested in the first group. each height (SAR) is simulated with the three ratios (Table 2) .

Table 2: EDSL Tas models with different heights (SARs) and area ratios.

Groupe 1 Height variable	SAR= 0,5 ($H = w/2$)	SAR= 1,5 $H = W$	SAR= 3 ($H = 3w$)
Groupe 2 Glazed area Ratio variable	Ratio 75%	Glazed ratio: 100%	Ratio 50 %

3. Results

The presentation of the results of the simulation of the study model proves necessary to be able to propose improvements to the configuration of the atrium for better temperature prediction. Also, the Tas simulation had the advantage of predicting the temperature indoor air near the glass roof.

To strengthen our results, particularly for the vertical air temperature distribution inside the atrium space, for specific moments. A CFD simulation is carried out using the “Ambiens” module of the “Tas” program which allows simple modeling and rapid simulations. For this reason, our atrium is modeled as a 2D section and simulated for one chosen times of the day, the most critical occupancy and solar penetration hours of the day (3 p.m)

3.1 Thermal environment with different SARs:

The simulation results show a different temperature distributions in the atrium section, roof surface and floor surface with different SARs (Table 3). The different temperatures in the vertical direction are specifically presented with different SARs. Also the graphs in the figure 3 represent a comparison between the overall average interior temperatures calculated for the three atrium configuration cases tested.

The average interior temperatures calculated in the atrium for the three cases tend to decrease with increasing height. Hence the “SAR =0,5” marks the lowest temperatures, with a peak of 39.73°C at 3:00 p.m. However, the average temperatures of both “SAR=1,5” (basic case) and the “SAR =3” remain approximately the same with peaks being respectively: 36.66°C and 36.76°C at the same time. This reveals the effect of height (SAR =3) on reducing the amount of energy received, and consequently on reducing indoor air temperatures.

Table 3: CFD simulation results of the different heights (SAR variable)

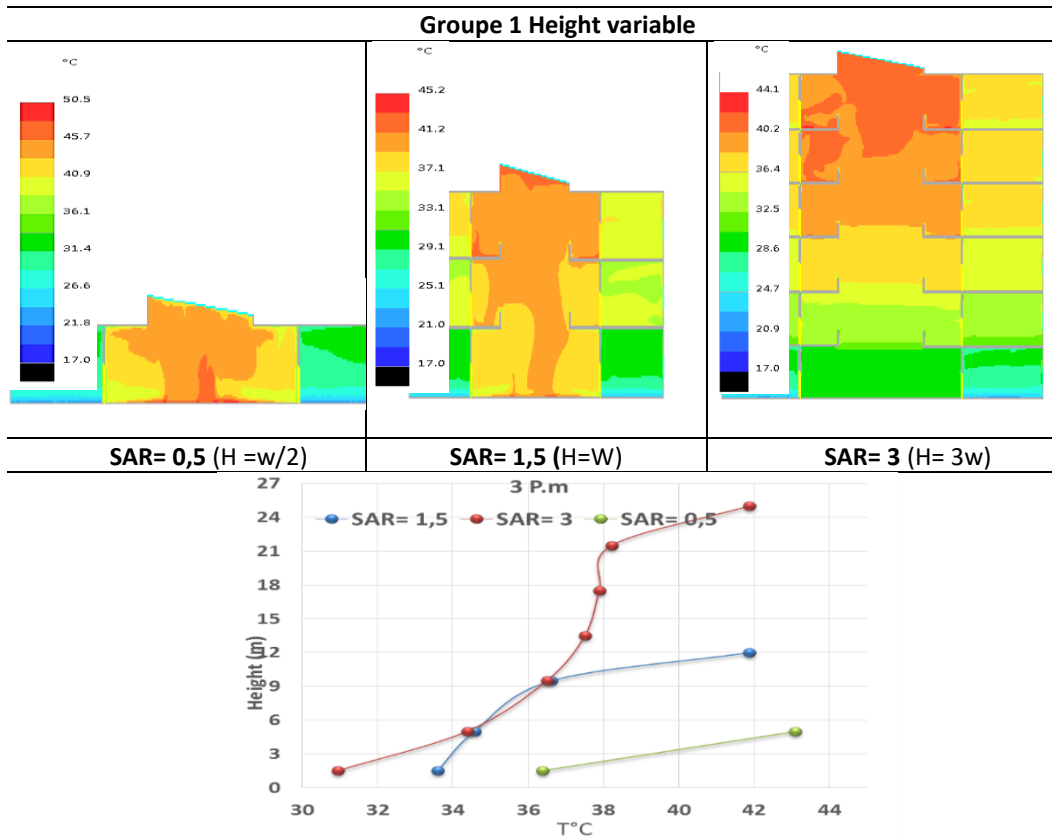


Figure 3 . Effect of different heights (SAR) values on the indoor vertical air distribution

More pronounced stratification is observed, when “SAR =1,5” and “SAR= 3”, presenting a non-linear profiles, with differences of 8.3°C and 9.3°C, respectively (Figure3). While noting that for the “SAR=3” ,a Stratification from the third level to the fifth level occurs gradually and linearly with height. Beyond that, a change in the appearance occurs suddenly up to the upper part of the roof, to be more accentuated, which means that it is in this part that the sunspot is located, and at a certain height (estimated at 13.5m) the temperatures remain noticeably close and stable. In the “SAR= 0,5”, this point of transition in behavior is marked from the second level to the very high part of the roofing. This is mainly caused by the shadow caused by height. In the case of the “SAR= 0,5” the stratification is done linearly, with a difference of 6.7°C. The wide distribution of the sunspot favors a uniform distribution of heat in the volume as well as good mixing of the air probably favors such behavior.

3.2 Thermal environment with different Ratio:

The different temperatures in the vertical direction are specifically presented with different ratios in Figure 4. It shows that the thermal gradients for the different glazed area ratios respond at identical rates with each of the configurations of the SAR variable, which means that the decrease in the ratio didn’ affect the vertical thermal distribution.

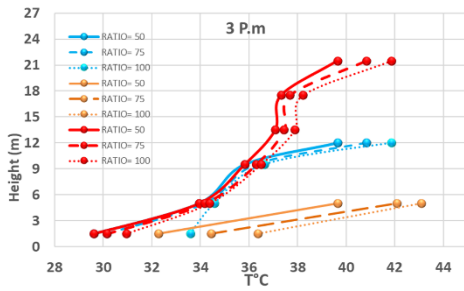


Figure 4. Effect of different area ratios values on the indoor vertical air distribution

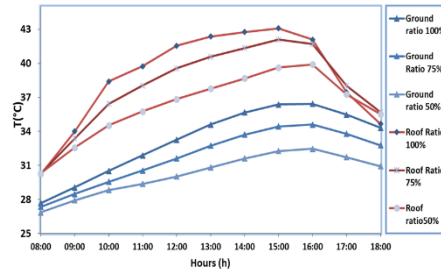


Figure 5. Effect of Glazed area ratios on different temperatures obtained at the floor and roof levels for the SAR=0,5

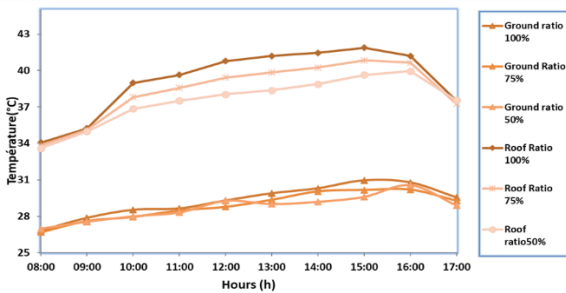


Figure 6. Effect of Glazed area ratios on different temperatures obtained at the floor and roof levels for the SAR=3

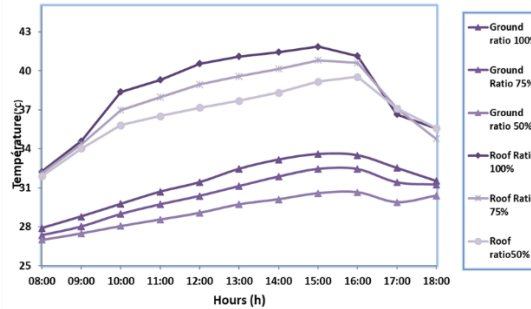


Figure 7. Effect of Glazed area ratios on different temperatures obtained at the floor and roof levels for the SAR=1,5

Figures 5,6 and 7 show the simulation results of the different temperatures obtained at the floor and roof levels, for the different Glazed area ratio tested (100%, 75%, 50%) according to the three SAR tested during the summer day:

- **SAR = 0,5:** Reducing the ratio has a significant effect on reducing indoor temperatures. We report a maximum difference of 4.1°C at 3:00 p.m on the ground floor, between the initial ratio (100%) and the ratio 50%. However, for the upper part (Roof level), the temperatures of the 50% ratio record a maximum difference of 4.6°C with the 100% ratio. Furthermore, the temperatures of the 75% ratio record a maximum difference of around 1.9°C at 12:00 p.m. compared to the largest ratio (100%) .
- **SAR = 1,5** (basic case): We first notice that reducing the ratio relatively reduced interior temperatures. the 50% ratio records a maximum temperature difference of 3°C at 3:00 p.m. compared to the 100% ratio (initial ratio). However, the temperatures of the roof level were reduced compared to the initial ratio (100%) with a maximum difference of 3.4°C at 12:00 p.m.
- **SAR =3:** Overall, we see that there is not a big difference between the three ratios (100%, 75%, 50%). In addition, the reduction in the ratio for this case has less impact on the reduction in interior temperatures, in comparison with those of the first two cases “SAR 0.5” and “SAR 1.5”. However, the reduction in the ratio is more influential at the very high level of the roof, where the maximum difference between the initial ratio (100%) and that of 50% is 2.8°C at 1:00 p.m., and 1.37 °C at 12 p.m between the 100% and 75% ratio.

4. Discussions

The analysis of thermal gradients of temperatures in relation to height (SAR), between the three cases of the simulated configurations, shows us that the degree of heating which is due to penetrating solar radiation, varies according to the different SARs of the atrium:

An atrium with a small SAR (0.5) is overheated more substantially than a higher atrium with a larger SAR (3) and medium one(1,5). This is because the Atrium of a small SAR receives more of the solar radiation, and the sunspot is more extensive in volume. the deep or tallest atrium with large SAR (3) receives less solar radiation which relatively reaches the lower levels and the ground. However, intense solar radiation at the top of the atrium would result in higher stratification and, therefore, higher convective fluxes useful for passive cooling (Samant,2011), which provides an advantage in reducing interior temperatures. Although it presents an overheating problem in its upper part. For the Atrium at medium height of SAR=1.5, it behaves similarly with the “High Atrium” of SAR=3 for all levels, particularly the upper levels. The analysis of how changing atrium geometry effects thermal stratification in a building has been studied by (Jones and Luther, 1993). They conclude that tall, narrow atriums have more localized direct solar impact,

less air mixing and less emitted radiation, and therefore more stratification compared to shorter and wider atriums (John Ashley, 2001).

Since the small atrium (SAR=0,5) receives more of the solar radiation, and the sunspot is more extensive in volume, reducing the glazed area ratio can have a greater impact on reducing the indoor temperatures, which the simulation results improve it.

For the higher Atrium with SAR=3, the change in the ratio remains negligible. In addition, the reduction in the ratio for this case has less effect on the reduction in interior temperatures, in comparison with those of the first two cases "Short" and "Medium Atrium". The reason lies in the fact that the atrium being higher, it becomes self-shaded by receiving less amount of solar energy, so reducing the ratio will not have a significant effect for the deeper atrium (SAR=3). However, the reduction in the ratio is more influential at the very high level of the roof, since the latter receives more quantity of solar energy. Furthermore, changing in glazed area ratio had little effect on the thermal environment for the case of deeper atrium with SAR =3. Consequently, as was confirmed by (Wu and al, 2021) in his study, it is not true that changing glazed area ratio can have always effect on atrium thermal environment.

5. Conclusions

This research focuses on the relationship between the architectural design parameters of a centralized fully enclosed atrium and indoor thermal conditions in hot and dry climate of Southern Algeria cities, and this is during hot summer. The impact of the different architectural configurations of atrium namely: Height variable with presented by the index SAR, and the glazed area ratio variable were analysed via numerical CFD simulation. The following conclusions can be obtained.

It is proven that architectural configuration is an important factor to consider in atrium design in hot and dry climate, it influences both conditions of indoor thermal environment and thermal stratification obtained at the atrium center. In such a way that the decrease or increase in the glazed area ratio remains influenced by the height (SARs) of the atrium.

The overheating problem is present in the atrium at SAR=0.5 (small SAR), and in the roof level for both medium SAR=1.5 and SAR = 3. Therefore, the higher is the atrium (large SAR), the less severe is the overheating.

The variation in the glazed area ratio has a greater impact on temperatures, for an atrium at small SAR. For a large SAR, the change in the ratio remains negligible.

In fact, the research presented the air temperature always decreased with increasing SAR. However, reducing the Glazed area ratio has a certain effect on indoor thermal environment in some situations.

It demonstrated that for the hot and dry climate zones, the atrium at Medium SAR is favorable with decreasing in its glazed area ratio. However Atrium at large SAR is more favorable. The atrium at small SAR remains the most unfavorable even by reducing its glazed area ratio.

Furthermore, the issue of atrium space design cannot be solely confined to considerations of thermal temperatures or the examination of only two variables. Indeed, the findings of this study may be regarded as being in the preliminary phase of conceptualizing an atrium that is more or less proper for hot and dry climates. Future research endeavors ought to incorporate additional parameters, notably: Shading devices, skylight glazing materials, atrium area ratio, roof inclination, and other atrium shapes.

Likewise, the integration of all the following aspects seems interesting: Thermal comfort Energy consumption, natural lighting, natural ventilation, and air conditioning and heating control strategies.

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Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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