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ORIGINAL RESEARCH PAPER

Design an optimized model to improve natural ventilation thorough the roof orientation

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ABSTRACT: Natural ventilation is among those effective methods that is useful in hot dry climates. One of its important uses is in the atrium spaces in the office buildings. Although, as a passive solution, it has a significant impact on the reduction of energy consumption, the control of inlet and outflow of air as well as the control of air current temperature has always been a challenge for architects and engineers. This study aims at designing a model to reduce energy consumption and increase airflow inside the atrium. In so doing, the present study reviews the existing solutions in the inactive area. In this way, using computer simulations, the designed model in the energy software is analyzed and compared. The Design Builder Software is used to analyze the natural ventilation inside the building. The results clearly show that the use of a suitable form in the atrium ceilings with the aim of increasing the absorption of direct sunlight can have a direct effect on natural ventilation and thus reduce energy consumption in hot dry areas.

KEYWORDS: *Atrium design; Roof Orientation*; *Energy efficiency; Solar passive design*

INTRODUCTION

The decision of designing a highly transparent house with a central atrium considered the advantages of enhancing daylight in buildings. This is a fundamental aspect of sustainable buildings, which is increasingly recognized in sustainability assessment systems (Berardi, 2012; Abaeian *et al*., 2016). For example, LEED assigns credits to daylight in areas ranging from "Energy and Atmosphere" to "Indoor Environmental Quality". Opportunities to obtain higher rates in sustainability rating systems through daylight and atrium design have recently been shown (Yoon and Moeck, 2005; Sharples *et al*., 2007).

Atrium is defined as a space added to the buildings with at least one transparent facade which commonly is high (Rundle *et al*., 2011). It is an architectural feature in different building types such as office buildings, shopping malls and educational spaces in warmer climates in the architecture of ancient civilizations, such as the Romans, Greeks, Chinese and Iranian cultures (Edwards, 2006). Atrium provides an internal space and protects it against outdoor unfavorable weather conditions. The internal area can be used as a circulation path above the ground level. This feature is important for social life through interaction during variety of social activities like working and gardening within a sheltered environment (Dempsey, 2006). Social interactions provide opportunities for social ties which in turn are beneficial for the psychological well-being of individuals (Kawachi *et al*., 2001) with a sense of the "right to belong" (Talen, 1999). Advantages of atrium are not limited to this feature, and its environmental benefits encourage designers and owners to add it to their buildings. Providing adequate solar gain and daylight as well as improving thermal comfort features have been mentioned are some of the benefits of atrium (Abdullah and Wang, 2012) and it is part of the natural

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ventilation system as it acts as an air channel to enhance convective airflow through and around the adjacent buildings (Khan *et al*., 2008).

However, designing and controlling the thermal conditions of the atria are not easy due to numerous characteristics of the space such as walls with large areas, small usage zone ratio, high ceiling and so on (Qin *et al*., 2012). The top glazed surfaces allow deeper daylight to bring the pleasant internal spaces while reducing proper conditions for achieving thermal comfort (Douvlou *et al*., 2000). Also in tropical climates, excessive solar radiation through glazed surfaces may worsen internal thermal conditions especially during working hours (Pan *et al*., 2010) and lead to increase energy demand of buildings (Ahmad and Rasdi, 2000). Among these items, overheating is the major problem of atria in hot climates contributing to thermal comfort reduction (Ahmad and Rasdi, 2000).

Overheating is the excessive solar radiation penetrating into the atrium through the glazed surfaces. Thus, controlling the solar radiation is an essential parameter, which increasingly can be done by attaching shading devices and evaporation cooling systems (Abdullah *et al*., 2009). The impacts of these approaches are remarkable when they are taken into account during the design process (Athienitis, 2013). Knowing the types and thermal performance of atrium are essential for designers to prevent unintentional problems due to excessive solar radiation and overheating.

Meanwhile, natural ventilation of the atrium can decrease negative impacts of overheating in internal spaces. In naturally ventilated buildings, the heat at the top of the atrium exits by the wind driving force and stack effect. Indeed, the stack effect lifts air from the lower part of the atrium to the top section and removes it through the openings located at the atrium roof or sides. Although the hot air at the top of the atrium improves upward airflow, at the same time it causes unpleasant thermal conditions for occupants of the top floors. As a result, stack effect on natural ventilation reduces air conditioning load, and the greenhouse effect on the thermal environment reduces heating energy consumption under some design conditions which affect social activities and comfort for people in the atrium (Mei and Kang, 2012).

This study investigates the integration of heated atrium design in multi-storey apartment buildings in arid climates to enhance both environmental and social sustainability. To do this, we have provided an early effort to improve natural ventilation through the atrium at arid area cities of Iran using energy simulations. The paper is organized as follows; it first describes the climate characteristics in the Esfahan, as a selected place of arid area in Iran. Next, it elaborates on the proposed model for estimating the natural ventilation throughout the building, then the daylighting and solar loading simulations are investigated. The later session discusses the different results of the simulations, including different lighting metrics, glare metrics and blind movements; finally, some conclusions about the design of an atrium house will be reported, together with suggestions for further research.

Literature Review

Recently, Atria has become common in commercial and service buildings around the world and it is expected that it continues to be developed in different degrees and it is applied on modern architecture mostly the largescale buildings (Wall, 1996).

Several studies have analyzed the Atrium design in certain service buildings, such as offices and school buildings nd shopping centers. They mostly focused on the control of the controls of daylight-linked lighting (Chow *et al*., 2013; To and Chan, 2006), passive cooling (Pfafferott *et al*., 2004; Abaeian *et al*., 2017), thermal comfort (Laouadi and Atif, 1998; Harris, 1997), shopping and socializing (Zacharias, 1993), and spatial integration (Kiliç-Çalgici *et al*., 2013). Aldawoud and Clark (2008) conducted a comparison for the energy performance between an office building having unheated centralized atrium and the same building with an open courtyard in Holland. Their results were that high-rise buildings having enclosed atria are better in energy performance as compared to low-rise buildings. A commercial office building with centralized atrium design having different length were analyzed by Aldawoud (2013) to the width ratios and different height. He concluded that: an atrium with square shape is more efficient in energy consumption, for cold and temperate climates the low-rise atrium buildings are more efficient, and in hot dry climates the high-rise atrium buildings are more efficient. Harris (1997) made a comparison in the energy performance of two school buildings with atria; one of the atriums was heated while the other one had a floating temperature. He concluded that heating demand is increased by the atrium; however, in winter time, this also result in comfortable conditions. The two buildings and their atria had nevertheless different designs and geometries. Laouadi *et al*. (2002) conducted a study on the thermal and energy performance of semi enclosed, centralized, and linear atria in cold climates. They concluded different alternatives, namely glazing types, glazing area, together with skylight shape. They revealed that the glazing type and glazing area have huge impacts on both heating and cooling demands in the atrium, but there were provided no details for the adjacent building or the effects the atrium leave on the heating and cooling demands in the adjacent buildings. Moreover, no comparison was made to non atrium buildings and it is not clear whether an atrium cause increase in a building's total energy efficiency as compared to buildings without atrium design.

Few studies have investigated the energy performance of atria-designed residential buildings. Taleghani *et al*. (2014) analyzed the effects of enclosed atrium spaces and open courtyard on energy performance in Holland and the indoor thermal comfort of terrace buildings. They showed that heating demands are reduced by glazed roof atrium during the heating season, but it increases the number of discomfort hours in the summer as compared to open courtyard.

Wall (1996), in Sweden, investigated a multi-story apartment building with unheated atrium design, a terraced building with unheated atrium design, and street with glazed roof. The investigated parameters were the atrium indoor temperature and the energy demand in the adjacent buildings enclosing the atrium. She ended up with the results that an unheated atrium with adjacent buildings on its three sides was the best for collecting and retaining solar heat gains; however, during the heating season, it would not achieve thermal comfort conditions. It would leave minor effects on the energy demand in the adjacent atrium buildings in case it is used as a climate buffer zone or to preheat the supply air to the adjacent buildings.

As Wall (1996) puts it, in case atria is heated to thermal comfort conditions in Nordic climates, there is an increase in the overall final energy demand of the building, i.e. both for the atrium and adjacent buildings". He calculated 65 kWh/m2/year net increase heating demand for an atrium having adjacent buildings on three sides.

However, both Taleghani *et al.* (2014) and Wall (1996) analyzed atria, which were designed to have floating temperature, i.e. the atria were not intended to be heated to thermal comfort conditions during the cold season. Common factors, which influence the two or more aspects of physical environment, have then been identified along their tendency of influence. It is expected that the results will help to optimize the physical environment at the early design stage.

Calcagani and Paroncini (2004) showed 90 percent of office workers prefer window sitting and offices with more sunlight, it is believed work time tends to be longer when there is appropriate sunlight. The shape of the atrium and its orientation to the sun, together with the transmittance of the roof, the reflectivity of the atrium surfaces and the glazed areas are among the important parameters in the day lighting of atrium buildings that affect the daylight conditions in the adjoining space and the atrium floor (Calcagni and Paroncini, 2004). Studies show that daylight has certain advantages in terms of work efficiency, sustainability, energy efficiency, and human health (Leslie, 2003; Lim *et al.*, 2010).

Ahmad and Rasdi (2000) and Abdullah *et al*. (2000) discussed different atrium forms and examined atrium in certain selected shopping malls in Malaysia. Advantages and disadvantages of the side-lit atrium were given by them and they suggested it for tropical climate. Abdullah and Wang (2012) examined different form of atrium roof a tropical climate. They put the atrium roof form as a critical parameter considering thermal comfort and running cost.

This way, one can investigate the influential factors affecting the peripheral properties of atrium. These factors are classified into five categories of material properties, geometry, form, ceiling structure, and specifications of the extensional spaces. Their effects have been studied on the intensity of daylight, acoustic specifications, natural ventilation, and temperature aspects. There have been conducted various studies in each of these areas. This study classifies the existing studies into the categories of plan and section in the field of the effects of geometric properties of atrium on temperature specifications of space. The results of this study indicate that:

Sectional shape affects the thermal environment in atria. "A" form sectional shape can provide shade for lower layers, and at the same time, it increases the stack effect. "V" form can increase the solar radiation which could be used as atrium form in buildings in cold regions of China (Chuan *et al*., 2004; Wen and Wang, 2006).

As increased height and smaller plan area are key factors for the stack effect, the buoyancy-driven ventilation is much more apparent for atria in high-rise residential buildings. However, the relationship between size and ventilation should be considered in common public buildings, as the atrium area is much bigger than it is in residential buildings. The "A" form or "V" form has the advantage of stack effect or greenhouse effect separately; however, it is not considered the sectional form influenced on the daylight or acoustics in atria. For ventilation, the opening area of skylights is an important element affecting ventilation (Zhao *et al*., 2015).

MATERIAL AND METHODS

In this paper, two atrium roof forms are examined in naturally ventilated conditions utilizing simulation with annual energy consumption. Different methods have been proposed to study natural ventilation and air movement in buildings such as empirical, small-scale experimental, full-scale experimental, multi-zone, Zonal and CFD models (Chen, 2009). Among these, CFD is one of the most popular methods due to lower cost and controllable conditions in comparison with other approaches. Although CFD was introduced for industrials proposes, it now becomes a common method to evaluate ventilation and environment of buildings (Asfour *et al*., 2007). Design-Builder is used in this research as a simulation program for calculating atrium performance.

The applications of CFD models are not limited to ventilation aims in buildings, and it is known as a method to predict different parameters of thermal comfort, indoor air quality, fire safety, HVAC system performance and more in different types of buildings (Chen, 2009). CFD modeling is employed in the design process and provides accurate and cost effective results (Ji *et al*., 2007; Laouadi and Atif, 1998; Tan and Glicksman, 2005; Wang *et al*., 2009). It is a useful tool for engineers and designers to calculate the inside and outside conditions of buildings, and acceptable results have been achieved in terms of energy usage and airflow based on CFD modeling (Chien *et al*., 2011).

Although CFD methods bring various advantages, users and developers of this software come up against new issue by developing the computer simulation and CFD usage. They should know how they can rely on the simulation results. Verification and Validation (V&V) are the primary methods in response to this issue (Oberkampf and Trucano, 2002). Numerous parameters affect the accuracy of the CFD results for natural ventilation studies such as user's knowledge of fluid dynamics and experience with skill for using numerical techniques. However the major parameter with critical impacts is the appropriate selection of CFD approach and turbulence model (Zhai *et al*., 2007). The selected software for the research is DesignBuilder version 3.1.0.080 using EnergyPlus 7.2 for simulation and standard k-e turbulent model for CFD.

On the other hand, EnergyPlus is the official building simulation program of the United States Department of Energy, promoted through the Building and Technology Program of the Energy Efficiency and Renewable Energy Office (Fumo *et al*., 2010). Crawley *et al*. (2001) demonstrated EnergyPlus and compared it with previous programs in this field. He mentioned numerous advantages and benefits of EnergyPlus for building purposes. Numerous studies have used EnergyPlus in various fields (Ng *et al*., 2013). Zhai *et al*. (2011) employed EnergyPlus to calculate hybrid and natural ventilation in a building. Also, the validation of Design-Builder for related studies has been reported by the authors (Baharvand *et al*., 2013).

Model Specifications

As mentioned, this research studies two different atrium roof forms in the hot and arid climate of Iran. The first model is a model designed using fermented properties and change in materials and it uses sustainable processes inside the building; the second model also includes a space with the same dimensions as the normal specifications. They are simulated under the same environmental conditions. The formic dimensions and attributes of this type of atrium are as shown in Figs. 1 and 2.

In order to define a structure for the exploitation of this pattern in the office buildings, a building was simulated as a sample. The physical and material specifications are available in the Table 1.

The model was simulated in the Energy Plus software. The desired output is the average monthly temperature in the space. These results are compared with the same area and conventional atrium. The purpose of this work is to analyze the results of this study with the state-of-the-art.

The following are the main characteristics of modeling and weather conditions applied in the simulation model:

- Building activity is defined as an office building with only natural ventilation for cooling aims.
- The building plan is rectangular with 30m length in south and north and 21m in west and east direction.
- The building includes three levels with 3.4 m height per each floor (Fig. 1).
- The atrium plan is rectangular along the length of the building with a 21m × 9m dimension.
- The width of circulation area around the atrium is 1.5 m.
- The building is assumed to be in an excellent mode of infiltration.
- All simulations are run for the period from 18th to 23rd of March.
- CFD calculations are run at “2:00 PM” on 21st of March.

All zone doors and windows are closed and they are only ventilated through the vents. There are three types of opening allowing for airflow during simulation. Two west and east exterior doors (low level openings) and vents in the ground floor which are entirely open over calculation in both models and provide 10m^2 opening area for ventilation. Although models have different windows at the top of the atria, both of them provide the same opening areas for airflow, which is 5m^2. Fig.1. (a) Side-Lit Atrium Section and (b) Top-Lit Atrium Section.

The weather data of Isfahan is used for simulation. This data file includes temperature, wind velocity and direction, solar altitude, solar azimuth, atmospheric pressure, direct normal solar and diffuse horizontal solar data. Previous studies showed temperature has been increased in the city center while this growth is not significant in rural or suburban area, thus updated weather data would be needed for simulations. However, the modeled building is a low rise building, and it is assumed to be in a suburban area, so the weather data file is used without changes. 21st of June is chosen for CFD mentioned as the hottest design day in Isfahan.

Fig. 2 indicates external wind velocity and air temperature employed for simulations from 18th to 23rd of March. The external wind direction is unstable and its 160, 117, 110, 183, 109 and 236 degree for 18th to 23rd, respectively. Also, the CFD grid structure of these models included 301 000 cells and 9 monitoring points defined within the atria and adjacent rooms.

Design

Based on the research methodology, the atrium was designed to enhance thermal and humidity properties based on the following two factors:

- Moisture increase: In order to increase relative humidity in the interior space, the use of recycled water might be effective. Based on the weather information

Table 1: Building Details summary

Set-point cooling	20 ℃
Set-point Heating	24 ℃
Equipment gain	3 w/m^2
U-value of external wall	0.24 to 0.47 w/m^2.k
U-value of Roof	0.14 w/m^2.k
U-value of Intermediate floor	2.5 w/m^2.k
U-value of Windows (doubled glazed with air gaps of 13.5 mm)	2.67 w/m^2.k
Lighting gain	6 w/m^2.k
Occupied Floor area	3546.4 m^2
Window to wall ration (WWR):	
- North(315 to 45°)	0.15
- East (45 to 135°)	0.21
- South (235 to 225°)	0.45
- West(225 to 315°)	0.2
Building type	Office building
No. of modeled thermal zones	10
No. of stories	3

Fig. 1: Floor plan (above) and cross section (below) of the atrium

center of the city of Isfahan, Iran, the temperature can be cooled up to 16 degrees Celsius in warm seasons using relative humidity in an indoor climate in the city of Isfahan (Synoptic weather station of Isfahan, 2015). Therefore, due to water scarcity as an influential source, it is suggested to maintain and conserve water in the office space in the basement. Generally, water used in an office space is mostly form the light gray type because it is mainly used for drinking or washing purposes and it is less rich in minerals. Hence, the use of these waters for recycling can be effective with the addition of disinfection and chlorination filters. Water systems in the atrium walls are also used to prevent stagnation of water and decrease the probability of decaying. These systems, like a cooling tower system, evaporate through the roof and cools the remaining water to flow. This cool water after crossing the green walls, walls, which include plants designed to enhance moisture and shade in the summer days, will double the cool air inside the building.

- Increasing the natural ventilation rate: in general, in an atrium space, there are two ways to increase the natural ventilation in an office space: 1- Using the difference in air pressure at the two points of the atrium at the beginning and end points of the atrium; and 2- Using the temperature difference at those two points. In this design, various alternatives were examined in this field, where ultimately the following solutions were used to increase the airflow:

- In order to increase the difference in air pressure from the upper point of the atrium to the low air in the basement, the height of the atrium was raised several meters above the height of the upper floor.

- In order to increase the temperature difference in the interior of the atrium, the surface is such designed to contact the direct sunlight as much as possible. In other words, the horizontal angle of the slabs with angles equal to the angle of the sun's radiation in the winter days was designed for 34 degree. This increases the absorption of heat from the sun in the ceiling, resulting in a difference in the temperature inside the space and the suction of air upwards. In addition, in cold seasons, it leads the direct radiation of the sun into the interior atmosphere, which greatly contributes to the heating process.

Based on the features of the area, the desired specifications were designed and several models were made. The final model was selected based on several factors, such as environmental sustainability and social suitability for office space functions. The main ideas of this project are shown in the Fig. 3.

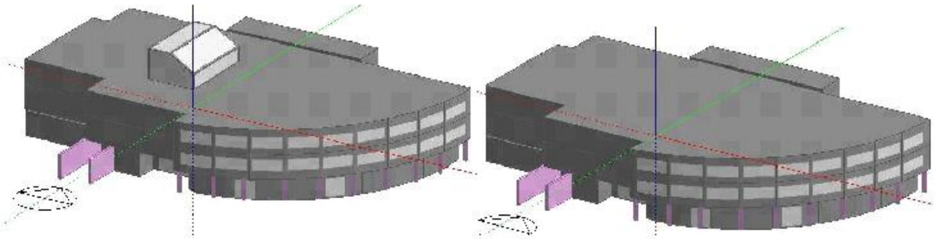


Fig. 2: Physical characteristics of models; With regular (Right) and Atrium(Left) Design

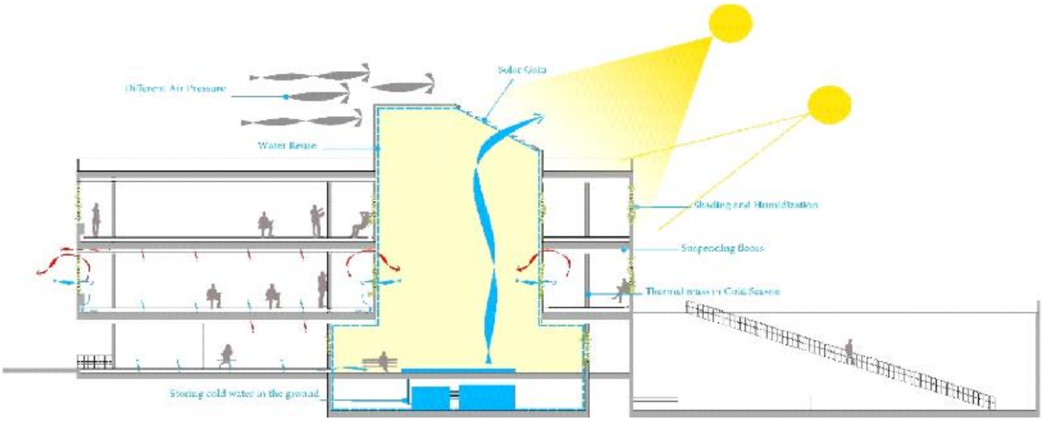


Fig. 3: Functional Diagram of the design

RESULTS AND DISCUSSION

In order to identify the design factors in the existing model, the simulated model is compared with an initial design (Fig. 2). According to the simulated results, the designed model can be used in summer and in hot days by using two airflow factors, which are absorbed by airflow suction from the top of the atrium, as well as the evaporation of the reflux of the recycled waters in its walls. In addition to the effects of cooling, it increases the stability due to the irrigation of plants. The Fig. 4 shows simulation results of the design model in the Designer Billboard Software simulated on a hot summer day, June 15. According to these results, the air inside the atrium is flowing up. In addition, due to the use of green walls and water recycling in the walls, there is more airflow around the walls. Following these results, the air is flowing in the entire space.

However, in normal states, according to the Fig. 5, the airflow in the outer walls is faster. While this amount is less in atrium and in the interior space, which ultimately leads to a scattered stream towards the outer walls of the walls. Under this process, residents' comfort conditions will be faced with dry and stagnant air during hot days.

Figs. 6 and 7 provides details of the numbers and results in different models. According to these results, it can be observed that the average temperature difference in the warm days of July between the two designs is about 4 degrees. This is about 2 degrees in the cold days of the year. It is worth noting that in the present project, the effects of mechanical and heating systems are not considered, and the simulation is based only on inactive solutions and geometric proportions and has been proposed in this paper.

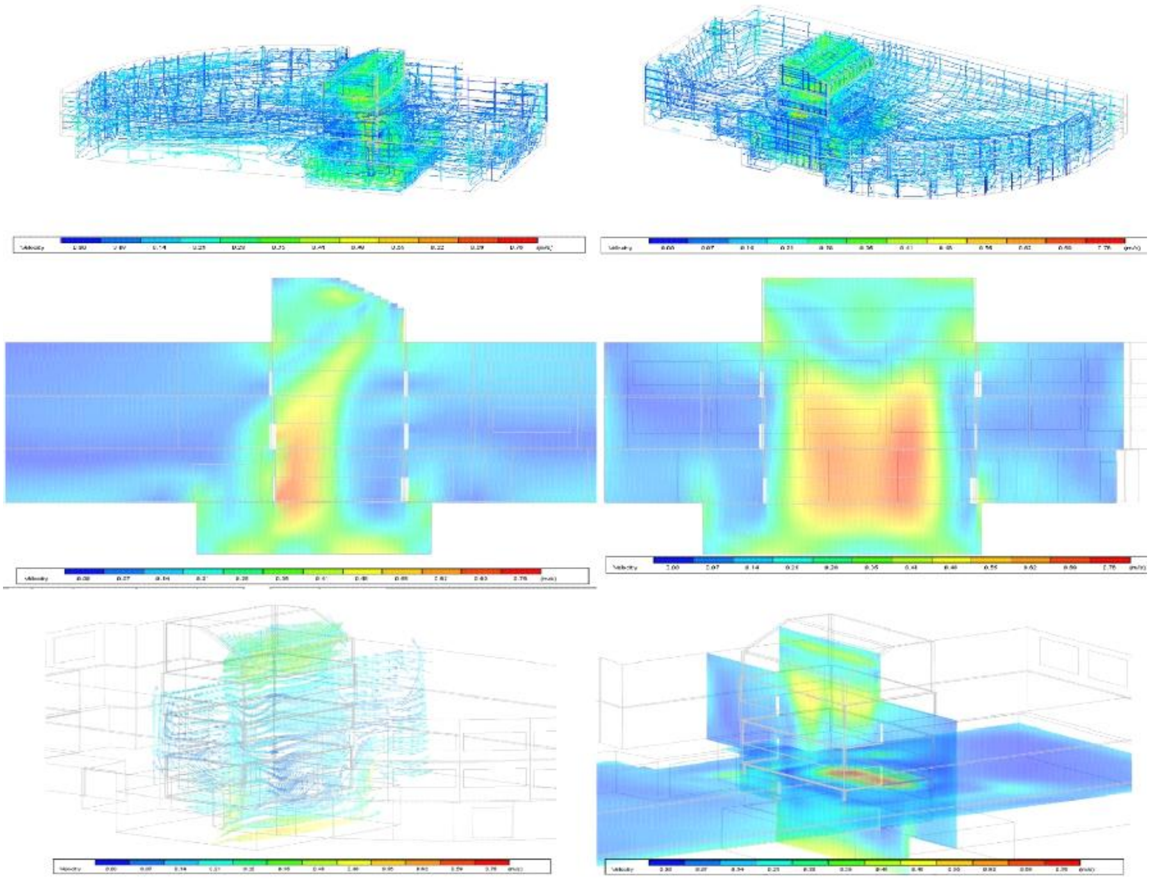


Fig. 4: CFD simulation results of proposed Design

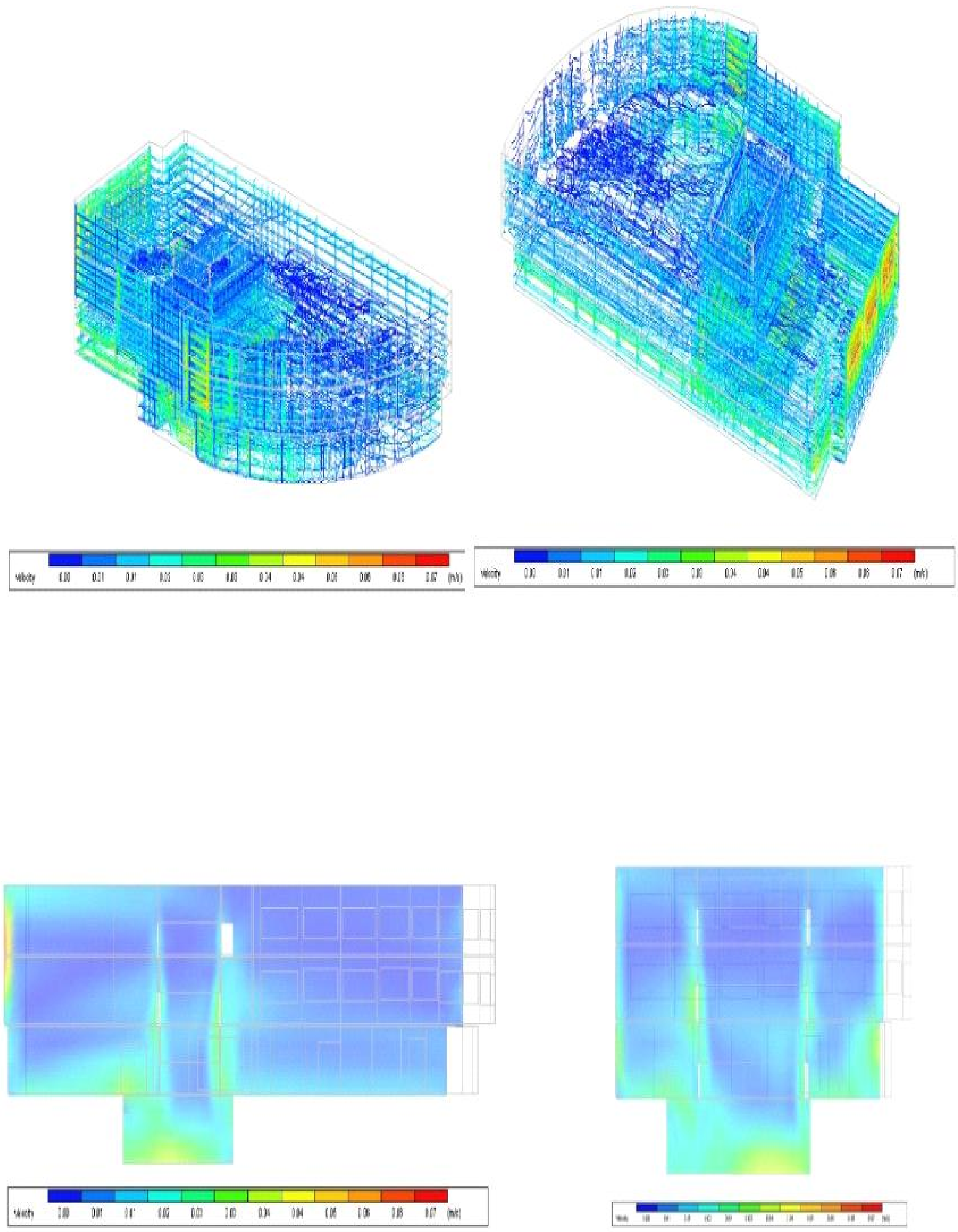
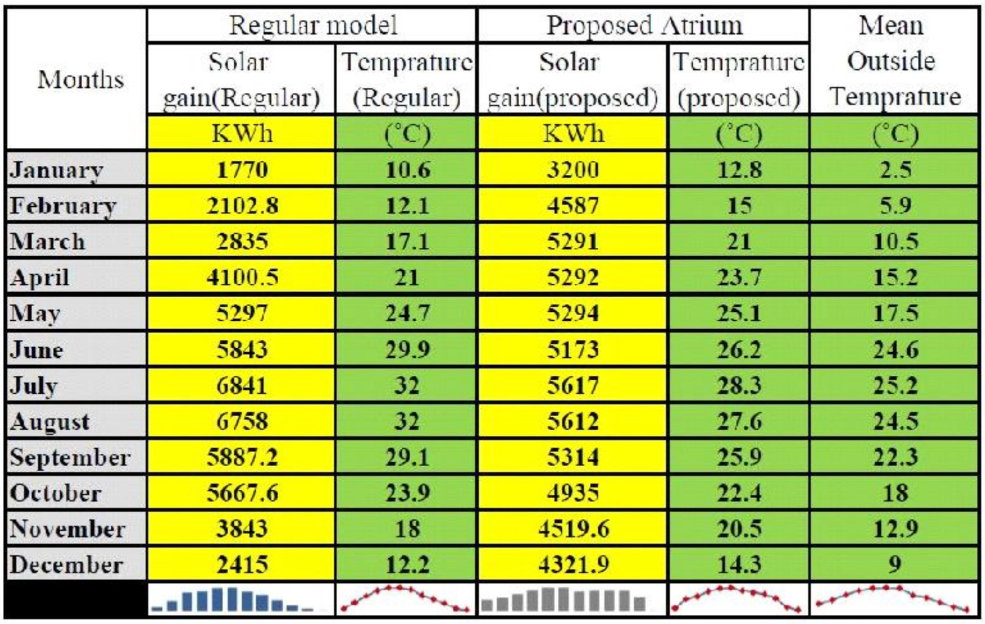


Fig. 5: CFD simulation’s results of regular model



Months	Regular model		Proposed Atrium		Mean Outside Temprature
	Solar gain(Regular)	Temprature (Regular)	Solar gain(proposed)	Temprature (proposed)	
	KWh	(°C)	KWh	(°C)	(°C)
January	**1770**	**10.6**	**3200**	**12.8**	**2.5**
February	**2102.8**	**12.1**	**4587**	**15**	**5.9**
March	**2835**	**17.1**	**5291**	**21**	**10.5**
April	**4100.5**	**21**	**5292**	**23.7**	**15.2**
May	**5297**	**24.7**	**5294**	**25.1**	**17.5**
June	**5843**	**29.9**	**5173**	**26.2**	**24.6**
July	**6841**	**32**	**5617**	**28.3**	**25.2**
August	**6758**	**32**	**5612**	**27.6**	**24.5**
September	**5887.2**	**29.1**	**5314**	**25.9**	**22.3**
October	**5667.6**	**23.9**	**4935**	**22.4**	**18**
November	**3843**	**18**	**4519.6**	**20.5**	**12.9**
December	**2415**	**12.2**	**4321.9**	**14.3**	**9**

Fig.6: Comparison of temperature and solar gain between different models

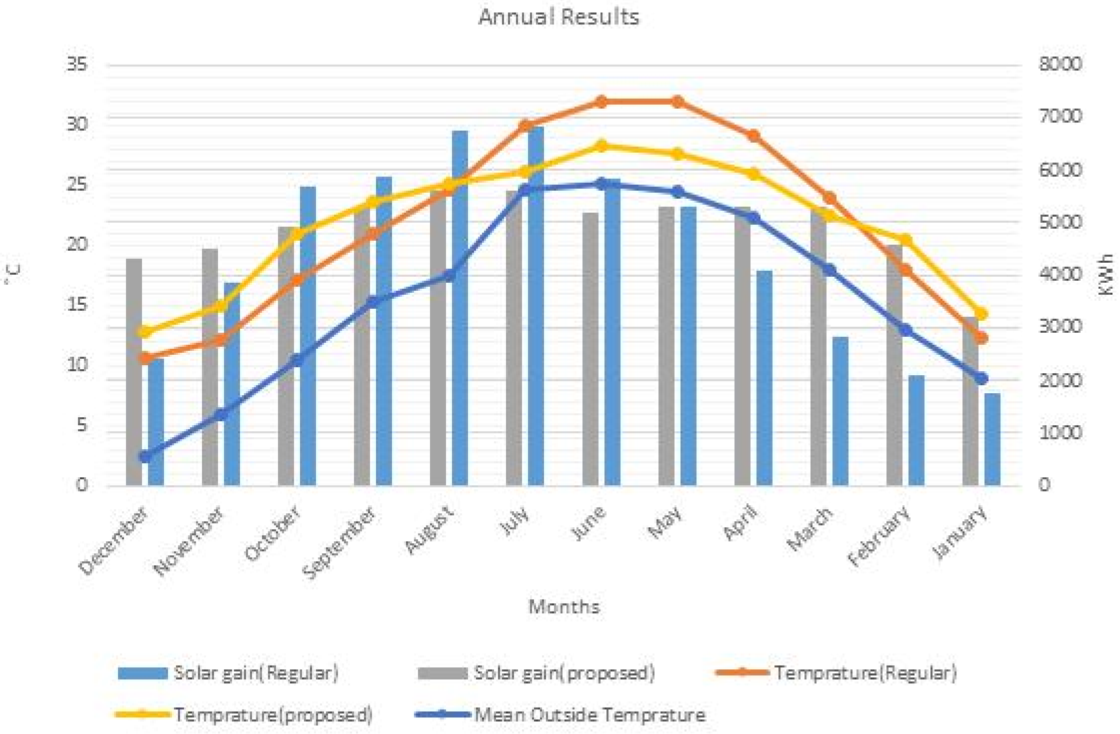


Fig.7: The diagram of comparison of temperature and solar gain between different models

CONCLUSION

The use of daylight by an atrium is one of the best ways to enhance the energy efficiency and improve the indoor environment against external harsh conditions (Boyer and Song 1994) and it can radiuses electrical energy and need to artificial lighting in adjoining spaces (Lau and Duan, 2008).

Surface property affecting the physical environment should be assessed including surrounding spaces and roof structure.

- Depending on the openness of surrounding spaces for enclosed, adjoining, and open type, different considerations should be given in terms of the effect on physical environment at ground level and other spaces.
- The roof structure and skylight type should be considered for the effect on sound and thermal environment.
- The geometry and surface properties should be considered for the effect on comprehensive physical environment (Zhao *et al*., 2015), as this study developed a framework for optimizing the roof orientation for the office buildings.

By increasing the entrance angle of the sunlight into the atrium ceiling, it not only will enhance the interior space but also creates a warm surface with a high temperature difference to the lowest point of the atrium, which greatly increases the airflow inside the space. In areas with warm and dry climates, using the recycled water in the same space can reduce the temperature and facilitate the comfort of the residents as it increases the relative humidity.

This study examines the factors affecting the shape of the atrium ceiling, the effective factors on the ceiling for and the degree of interior air comfort. Future researches can be directed towards the comparison of the effects of other architectures on this space, such as the level of openings on walls, materials, and wall surfaces in fixed constants on airflow rates.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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