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Sustainable energy saving alternatives in small buildings

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Abstract

Day lighting significance in architectural designs is well established for enhancing visual comfort, energy-efficiency and low carbon buildings development. Practicing the atrium element in the modern architectures has been increasingly popular in recent years because of the fact that the transitional space with good environmental elements can improve the quality of the buildings and reduce extra energy utilisation. The present study explores the advantages and effect of atrium on the energy performance of small buildings, a case study of 'The Azuma Row House'. Based on local micro-climate data Autodesk Ecotect Analysis was performed to calculate the daylight factors and the energy demand of the building. A comparison was made with atrium and without atrium in the building to evaluate overall energy savings. The results show a higher annual heating energy demand with atrium 3,443 kWh compared without atrium 2,526 kWh. The annual cooling energy demand without atrium 2,516 kWh is significantly greater than with atrium 912 kWh. The total energy requirements under no atrium case is about

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5,042 kWh which is considerably higher than the total annual energy demand with atrium 4,355 kWh. The total amount of energy saved is about 15.7% per year by introducing the sunlight through the atrium. Along with the increasing issue of the energy crisis, environmental problem and the beautiful design of atrium, the development of atrium in modern architecture designing is feasible to have a good future.

Keywords: Sustainable Energy, Low carbon buildings, Solar energy, Atrium, Transitional spaces, Simulation and Autodesk Ecotect.

1. Introduction

Buildings are responsible for a large amount of energy consumption because of heating ventilating, and air conditioning (HVAC) systems [1-3] for different weather conditions during the year. This energy is mostly coming from fossil fuels such as coal, oil and natural gas. According to predictions, the energy consumption in this sector continues to increase [4] and this increase will clearly raise the global carbon dioxide (CO_2) emissions. Energy saving technologies have, therefore, become more popular from last few decades with decreasing the energy sources and increasing the negative effect of CO_2. Additionally, reduction of the energy using in buildings is to utmost importance in achieving to reduce CO_2 and other GHGs emissions [5]. The atrium has become a popular architecture form to bring sunlight into the building and to enhance the sense of spaciousness [4, 6-8]. In the construction industry, it can be predicted that the atrium could have a good developing foreground in future.

The atrium is a transitional space widely used in the architecture design. The design feature Atria gives a "feeling of space and light" in a building. The atrium was introduced in the 19th century, with the industrial revolution in iron and glass manufacturing techniques. It became a popular practice after 1970's energy crisis [9]. Nowadays, the modern architecture designers practice the atrium widely in large-scale commercial buildings. Despite the aesthetic advantages other potential benefits of this feature are low carbon, energy saving, solar gain and natural ventilation. It is, therefore, considered that the good characteristics of the atrium can save energy consumption and can widely be used in the modern world's buildings [6]. In the 19th century, the atrium in buildings appeared for the first time, due to the progress of construction technology in the manufacturing [9]. Then in the 20th century, Sharples and Lash [9] considered that the atrium has lost some concerns, perhaps because of the increasing attention on lighting potentialities and air conditioners. However, after 1970's energy crisis, atrium again attracted by lots of people due to its sustainable advantages [9]. In recent years, designing of the atrium in modern architecture has become very popular at small and large-scale commercial buildings [10].

There are many key factors which influence the energy performance of atrium building such as; the geometric shape of the atrium, orientation to the sun, penetration of daylight into adjoining space, reflectivities of the atrium's surface and transmittance of the atrium roof and latitude [4, 11-15]. These parameters should be carefully considered to design an effective energy saving atrium. Previous studies revealed that atrium geometry has a strong relationship with the daylight factor [4, 12, 16-18]. Aizlewood and Maurice [19] have documented the several forecasting techniques to assess the average of the daylight factors and also mentioned the significance of atrium position in the building. The atrium position is a critical characteristic for the quantification of a complex daylight factor, i.e. the daylight of the atrium spaces and its adjacent spaces [20]. Latitude has a significant effect on solar radiations an through atrium in buildings. The optimum tilt angle of the roof can be changed in different latitude in order to get required solar radiation which is confirmed in previous literature [21, 22].

In fact, the design and location of the atrium are based on the local climatic conditions, expectations of thermal comfort level, building function and the experiments of architecture. Aldawoud [4] has investigated the response of different atrium forms and geometries in under various conditions. The results of the study demonstrate that the total energy consumption is significantly affected by the shape of the atrium. According to Moosavi et al. [18], the most important objective of the atrium is for daylight factor and ventilation. In addition, Moosavi et al. [18] have also pointed out that the atrium position and shape design in a building is the main factor which determines the advantages of the atrium in the building environment. Different shapes of the atrium are categorised as; centralised, semi-enclosed, attached and linear as shown in Fig. 1.

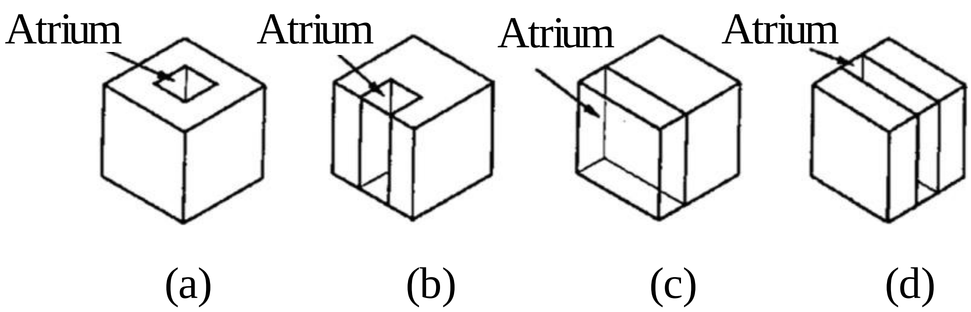

Fig. 1. Four different general forms of atrium; (a) Centralised, (b) Semi-enclosed, (c) Attached and (d) Linear [23].

The atrium position in the building is the main factor which determines the advantages of the atrium in the building environment. Ahmad [24] has mentioned that the horizontal top-lit form atrium is not suitable for tropical regions. Furthermore, Ghasemi et al. [13] have assessed the daylight performance in the adjacent spaces of the vertical top-lit atrium in the tropical climate regions with reference to Malaysia. The findings demonstrate that by providing sufficient daylight in the adjacent spaces of the vertical top-lit atrium, a model of the atrium with atrium's section aspect ratio 1, atrium's plan aspect ratio 1/3, and 3/8 atrium clerestory to atrium height is the most proper model of atrium [13].

Different kinds of daylight factors distribution in the atrium have a relationship with a geometrical shape index [17]. Kim and Boyer [16] presented relationships and dependencies between the centre of the daylight factors in open atrium spaces and atrium shapes. Aizlewood [19] pointed out several forecasting methods and techniques to assess the average of the daylight factors, as well as considered the parameter influences within the daylight of the atrium spaces and its adjacent spaces. It is always complex and hard to predict that the daylight of the atrium in a building. The atrium as a transition space not only presents the atrium space itself but also offer natural light to adjacent spaces [20]. Through exchanging inside and outside air, the building atrium also offers natural ventilation and daylight [25].

Buildings consume a lot of energy and resources, the atrium is the main potential source to offer daylight into buildings and provide other environmental factors; such as the reduction of energy consumption, solar gain and natural ventilation. The present study investigates the benefits of the atrium in small buildings and to explore main characteristics of the atrium which lead to energy saving. The focus is given to the linear shape atrium to investigate the advantages of the atrium, as well to know how much energy could be saved through introducing sunlight through atrium by using a sample case of the Azuma Row House (Osaka, Japan). Furthermore, the study evaluates the effect of the atrium on the energy consumption and demand of the building. Autodesk Ecotect tool has been employed to calculate the average Daylight Factor (DF) and to analyse the energy demand of this unique style of architectural practice. “Ecotect was developed by Square Research Ltd and Dr Andrew Marsh. Ecotech software is an energy simulation tool and it is compatible with BIM software, for example, Autodesk Revit Architecture. Several studies are carried out which demonstrated high accuracy of Ecotect simulation to perform preliminary building energy performance analysis [26, 27]. It offered a wide variety of simulation and building energy functionality analysis which helps to visualize and simulate building performance especially day lighting simulation. The software for analysis combines an intuitive 3-D design interface with the performance analysis function set the interactive display of information[28]. This also provides Acoustic, thermal and lighting analysis. It includes monthly space loads, acoustic reflection, the impact of environment, cost of the project and artificial/ natural lighting level [29]. Although its modelling and analysis capabilities handle geometry of any complexity and size, the main advantage is to focus on feedback at an initial stage of building process design. In addition to the table and standard graph based reports results of the analysis can be mapped over the surfaces of the building and can be directly displayed within the spaces such as spatial and volumetric results analysis visualization. In building Ecotect simulation helps in achieving design by different architectural practices, in turn, reducing global warming potential. Secondly, it also helps in reducing building operating cost [30]. Since the release of 5.6 versions, Ecotect added the support for gbXML and IFC schemas. Ecotect can import CAD software like Revit, 3Ds Max and AutoCAD. It exports to a wide range of other programs and is supported by GBS, Energy Plus and Equest [31]". The results provide very useful findings to compare energy consumption in the Azuma Row House with atrium and no atrium under the same circumstances. This study is a good example to demonstrate the energy saving and sustainability in small and narrow houses buildings.

2. Methodology and data analysis

The experimental program was divided into a few analysing steps. Initially, the time duration and mode of the daylight enters the interior spaces were analysed. The daylight factor was tested in the overcast sky of the whole year. The energy consumption of the Azuma Row House with the factor of the atrium was measured. Design modifications were then carried out by adding a roof at atrium position and measuring the energy consumption without atrium. The Ecotect Analysis tool was employed to calculate daylight factor, illuminance level and energy consumption by incorporating a global weather information database [32].

2.1 The daylight factor

Daylight Factor (DF) is the most common index and easy to measure the light in buildings. It is the instant proportion of inside light level in the measuring points, to the outside light level in the same horizontal plane under a standardised CIE overcast sky [11] and is defined as follows:

$$DF(\%) = (\frac{E_{di}}{E_{do}})*100 \qquad (1)$$

where E_{di} = indoor horizontal illuminance measured under the diffuse sky and E_{do} is outdoor horizontal illuminance from the diffuse sky from the diffuse sky.

The daylight factor is used in building and architecture design not only for evaluating the interior natural daylight illuminance on the surface but also for ensuring whether there will be enough space for habitats to do their normal works [11]. It is a complex and repeated process to calculate the daylight factor, and thus it is necessary to use some software products, such as Ecotect, Radiance, DAYSIM and DIVA. These are a set of tools to present daylight simulation, including renders and many other features to measure simulated daylight levels. In these tools, radiance is one of the most popular and powerful daylight simulation products [33]. More specifically, radiance should be able to predict the internal luminance and illuminance distributions in any sky conditions, and it has been widely validated during the past 20 years [7]. Ecotect simulates the performance of building with the context of the environment. The Ecotech inbuilt tools are used to present daylight simulation, including renders, radiance and many other features to measure simulated daylight levels [7, 33].

The daylight factor is often measured in an artificial sky or under an overcast day [11]. According to the British Standards Institution (BSI, BS 8206) [34], when a space with an average daylight factor of less than 2% is considered as dim and dark, it means most of the day needs electric lighting. When the daylight factor is between 2% and 5%, there is a good balance between thermal and lighting aspects, as well as a little or no additional lighting is required during the daytime, moreover, supplementary artificial lighting is necessary. When the average value of the daylight factor is more than 5%, space appears strongly light, it seldom needs to use artificial lighting during the daytime.

Three simple steps to estimate and calculate the daylight factors in the centre of the atrium spaces are as follows [35-38]:

First, compute the Well Index (WI) by considering the represented values of height, width and length of the atrium.

$$WI = height * \left(\frac{width + length}{2}\right) * length * width \tag{2}$$

Second, compute the horizontal DF (%) for unglazed roof. (Open atrium without roof).

$$DFunglazed = 100 * e^{-WI} \tag{3}$$

Third, estimate the transmission factor (ρ) for a glazed roof and multiply the calculated DF with it.

$$DFglazed = \rho * DFunglazed \tag{4}$$

2.2 The Azuma Row House

The Azuma Row House (also known as Sumiyoshi by Japanese) was designed by Tadao Ando in Osaka, 1976 [39, 40]. The Azuma Row House is located in Osaka. The latitude and longitude of Osaka are 34° 40' 0" N and 135° 30' 0" E respectively. The house is a narrow concrete rectangular house with covered area 70 m^2, with rooms back and forth connection through the outdoor bridge. The floor plan of the house and the sun lights which pass through the atrium are illustrated in Fig. 2. There is a living room, a kitchen-dining room on the ground floor, separated by an external atrium and stairs to the two bedrooms on the floor above. The central atrium space is the sole source of natural daylight throughout the whole house. It is a small and narrow house in a rectangle area, with rooms back and forth connection through the outdoor bridge in the centre of the atrium. The Azuma Row House is chosen in the present study to highlight the effectiveness of atrium at small scale level where space is limited.

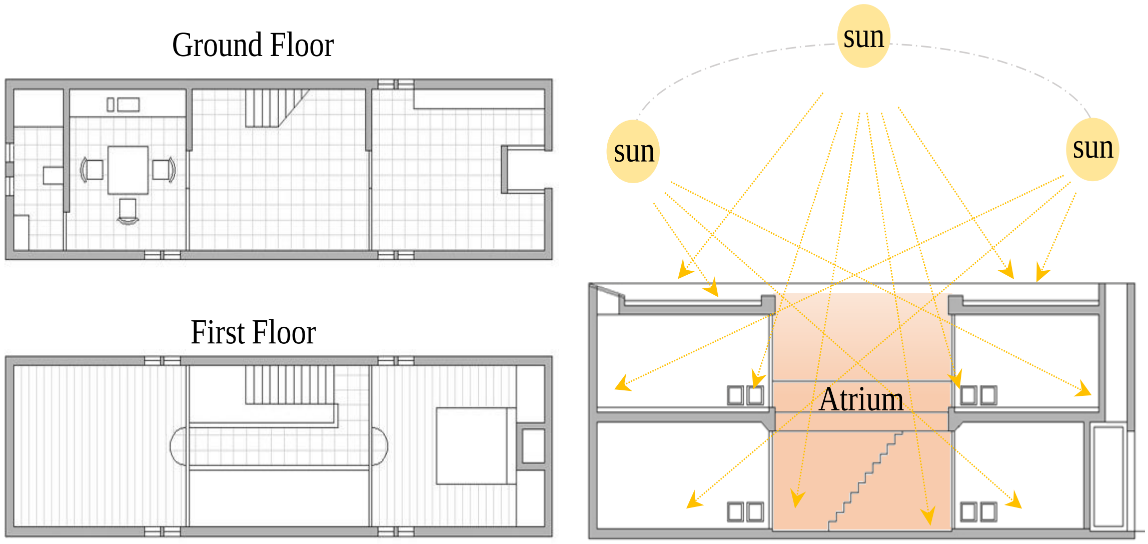

Fig. 2. The Azuma Row House floor plan and sunlight distribution [39, 40].

An external atrium is located in the central space between the rooms. It is a linear-shaped atrium type. There are three reasons to choose the Azuma Row House to test the daylight factor and to calculate the energy saving for the atrium. Firstly, Tadao Ando is an architect of light, focusing on using natural light and ventilation for his architecture design. The second reason is that the Azuma Row House contact with light, rain, air and other natural elements. Almost the whole daylight goes through the atrium spaces, however, the one through several small windows is quite small. The last reason is that there is no air-condition in the simple and narrow house. Moreover, the Azuma House as a researching sample is easier to test and more convenient to analyses the importance of atrium in energy saving as compared to other modern buildings with an atrium.

2.3 Testing and calculations

The testing can be divided into few steps as; the first step is to use Ecotect for analysing when and how long the daylight enters the interior spaces under the condition of no change. The second step is to calculate the energy consumption of the Azuma Row House with or without the factor of the atrium in this testing. With the purpose of research, the role of this atrium, a roof which can prevent daylight through Azuma Row house has been made in this atrium. In this way, it can be calculated how much energy should be used under the condition of a roof and without a roof. Autodesk Ecotect Analysis with a comprehensive concept-to-detail method is architectural design software to analyse sustainable building design. The tool is applied to calculate daylight factor and illuminance level at any point through the model, as well as to calculate the energy use of the whole building on annual, monthly, daily and hourly basis.

2.4 Distribution of daylight factor

The Azuma Row House is located in Osaka, Japan. The latitude and longitude of Osaka is 34° 40' 0" N and 135° 30' 0" E respectively. According to the latitude, it is easy to present solar angle in different seasons and different time using Sun-Path Diagram, as shown in Fig. 3. The Azuma Row House was roughly divided into four main areas, respective to measure the daylight factors of these four rooms on an overcast day.

Table 1. The solar angle during different seasons and time in Osaka [41].

Seasons	Day	8:00	12:00	16:00
Summer solstice	21st June	37.2°	78.6°	37.0°
Vernal equinox	21st March	23.1°	54.9°	23.1°
Winter solstice	21st December	9.3°	31.7°	7.9°
Autumn equinox	21st September	26.6°	56.1°	23.1°

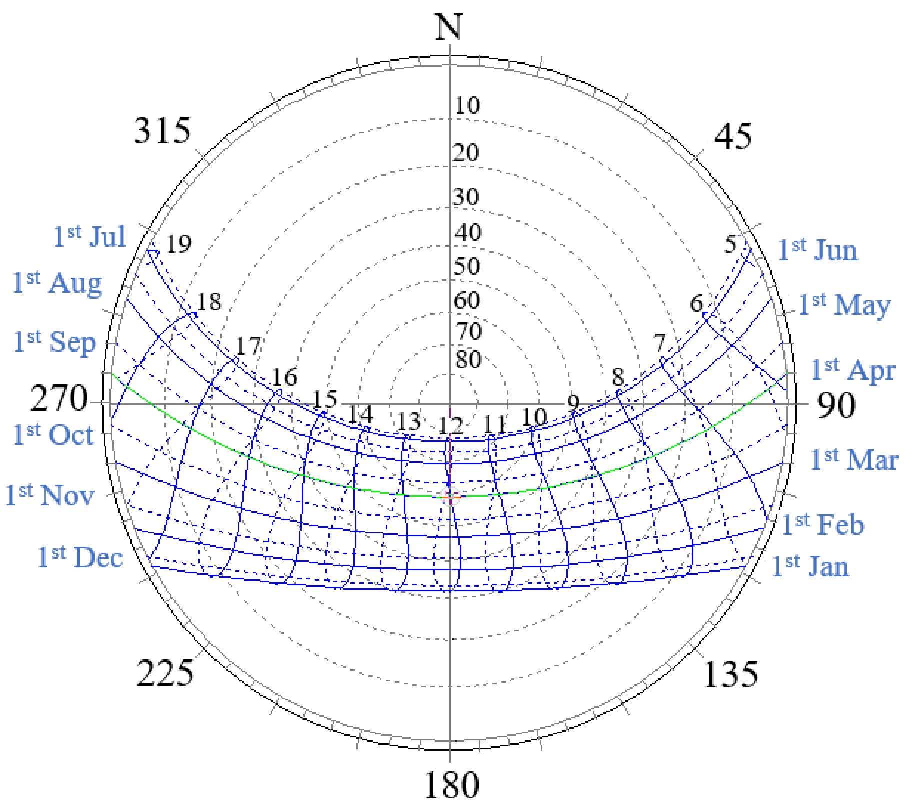

Fig. 3. Sun-path diagram in Osaka along with solar angles during different seasons and times [41, 42].

3. Results and discussion

3.1 Daylight factor analysis

Fig. 4 illustrates the distribution of daylight factor in the interior spaces based on the local weather data analysis. From Fig. 4(a), the first analysis grid it can be seen that the average value of the daylight factor is about 6.30% DF, which is more than the average daylight factor mentioned on the British Standard (BS 8206) [34]. The institution mentioned that the average DF should be at least 2%. If the average daylight factor in a space is at least 5% then electric lighting is not normally needed during the daytime, provided the uniformity is satisfactory [34, 43]. Then in Fig. 4(b), the second analysis grid shows that the average value of the daylight factor is about 5.54% DF in the room, which is located at the front of the building. Although the value is slightly less than the back room still it is not necessary to use artificial lighting on most of the daytime. In this testing, the value range of the daylight factor is from 0.0% to 15.0%.

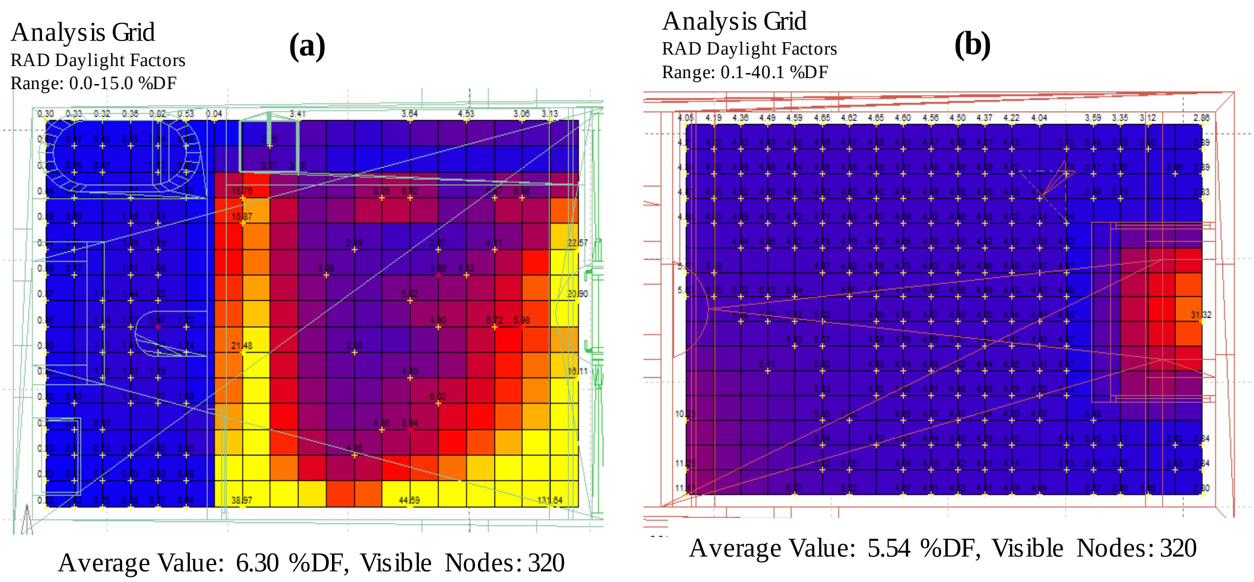

Fig. 4. The distribution of DF at a height of 800 mm above the ground floor; (a) Behind the building, (b) Front of the building.

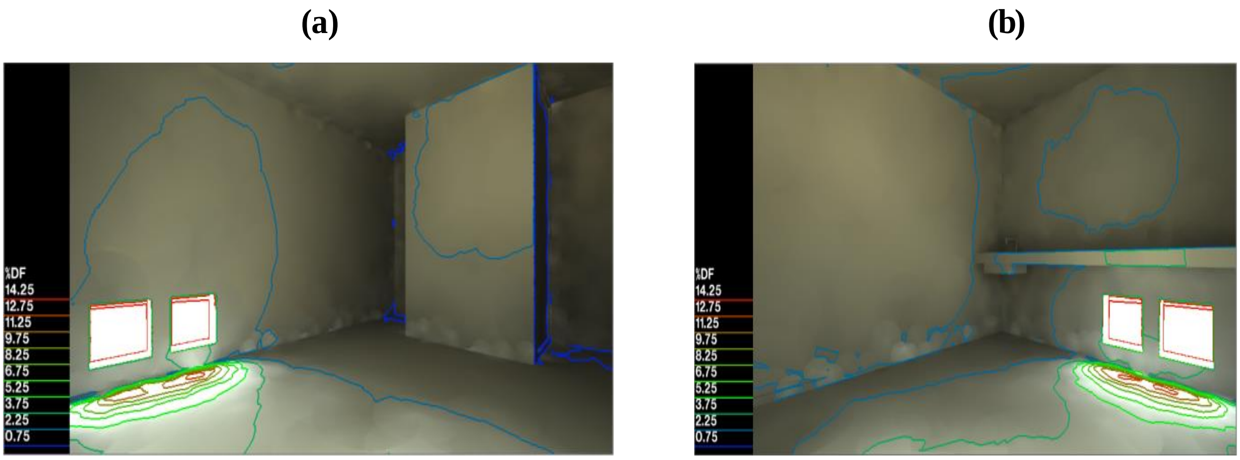

Fig. 5. The ground floor room arrangement rendering in Ecotect; (a) Behind the building, (b) Front of the building.

The contour lines for ground and first floors are presented in Fig. 5 and Fig. 7, respectively. The different colours of the contour lines represent different levels of daylight factor. The blue contour lines represent the lowest daylight factor, on the contrary, the red contour lines represent that the highest daylight factor. Although there is an uneven distribution of the daylight factor, it can still be found from the figure the light source mainly comes from the atrium and small low-level windows.

Similarly, Fig. 6 indicates the daylight factor distribution in the first floor spaces at the height of 800 mm. From the analysis grid Fig. 6(a), it can be seen that the average value of the daylight factor is about 8.82% DF, which is strongly light and it seldom needs to use artificial lighting during the daytime as it is much higher than the standard average DF mentioned in BS-8206 [34, 43]. Then the analysis grid Fig. 6(b) shows that the average value of the daylight factor is about 5.05% DF for the room which is located at the front of the building at first floor. Although the values are less than the back room, it is still unnecessary to use artificial lighting on most of the daytime. In this testing, the daylight factor values range from 0.0% to 20.0%.

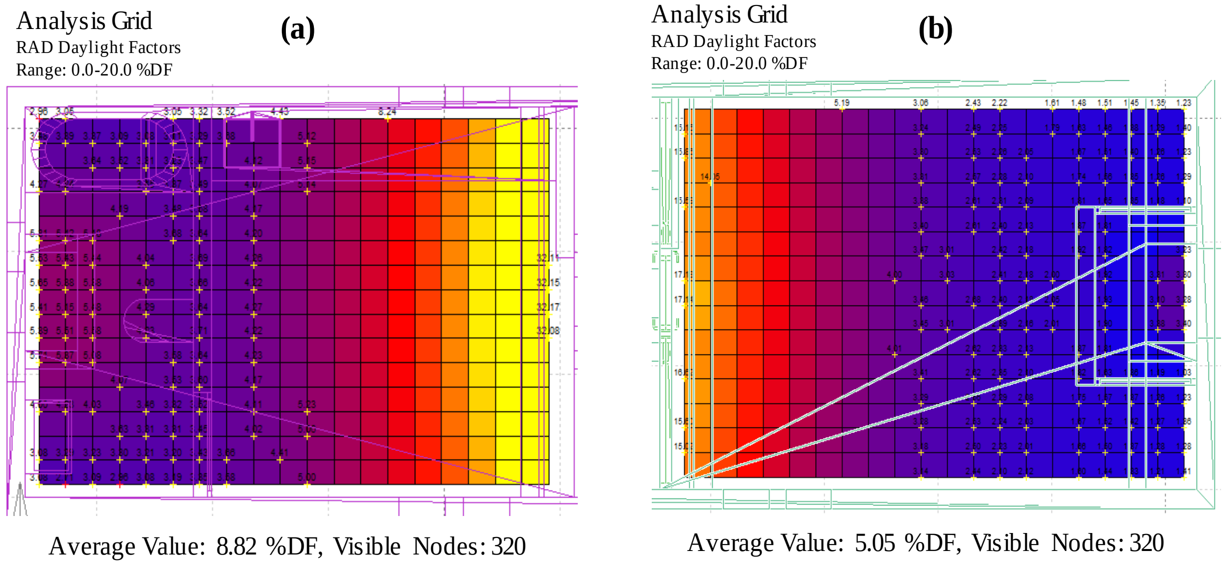

Fig. 6. The distribution of DF at the height of 800 mm above the first floor; (a) Behind the building, (b) Front of the building.

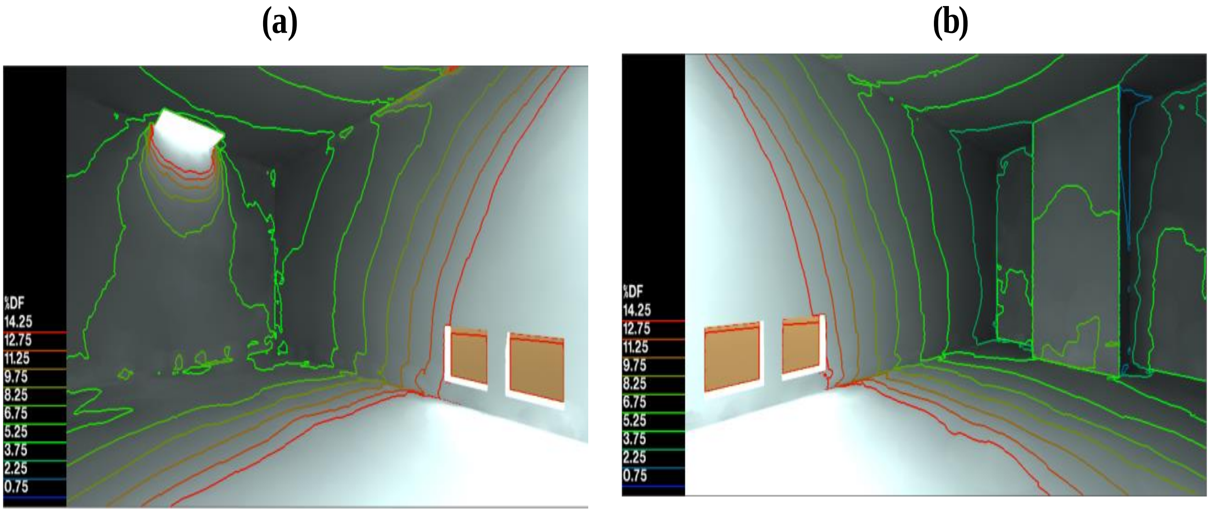

Fig. 7. The room of the first-floor arrangement rendering in Ecotect; (a) Behind the building, (b) Front of the building.

The average daylight factors computed for front and behind rooms at ground floor were 6.30% and 5.54% DF respectively, while 8.82% and 5.05% DF at first floor. The analysis shows that there is 40% more daylight on the first floor i.e. on the front room. According to BSI, the range lies between the theoretical limits specified to use extra light energy (i.e. DF<2% considered dim and dark) [34, 43, 44]. Therefore, even in the overcast day, it is not necessary to use extra artificial lighting during the daytime and to reduce energy consumption.

3.2 Heating and cooling energy demands

All of the results from Ecotect simulation (radiances) have been analysed and interpreted. The testing comes out mainly from the illustrated heating and cooling energy demand of the whole year with or without atrium in the Azuma Row House. These results help to predict that how much energy can be saved by constructing atrium as a major source of daylight. Firstly, Fig. 8 displays result under the condition of no atrium, the heating and cooling loads for the whole building from January to December, measured in Watts (W). The red bars represent when need to be heated and blue bars represent when need to be cooled. The total heating (red) and cooling (blue) energy being used by the building. In addition, each bar is divided into two parts, the dark brown bit is for the whole ground floor of the building and the light brown bit is on the first floor of the building.

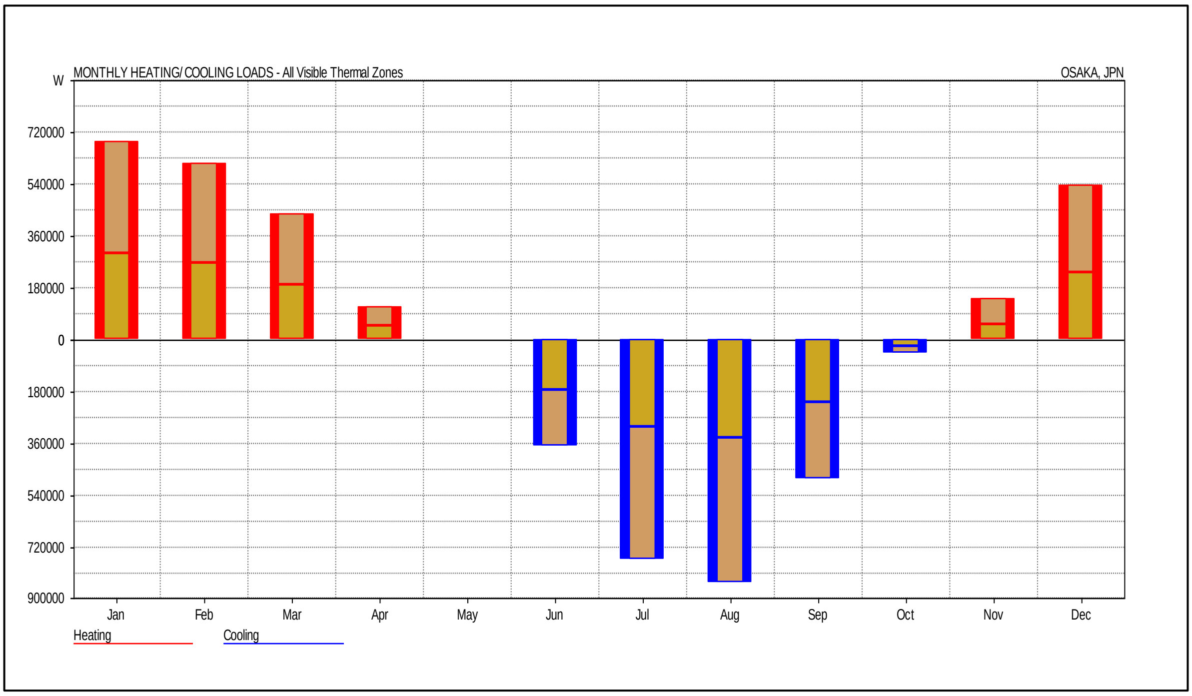

Fig. 8. Annual heating and cooling energy demand with no atrium.

One thing should be concerned, the house is heated if the interior temperature is below 18 °C and cooled if the temperature is above 26 °C. It can be seen that the energy requirement for the first floor is observed higher than the ground floor for each month during the year. The total annual energy demand for heating and cooling for the whole building is about 5,042 kWh, which is separately 2,526 kWh for the heating and 2,516 kWh for the cooling. The highest energy demand month for heating is January, total 675 kWh, and for cooling in August, about 820 kWh. Moreover, July is also the second highest energy demanding months of the year, about 760 kWh. As the first month of the year, January is the coldest month and need the highest energy requirement and the seventh month of the year, July, is one of the hottest months. It is clearly understandable high energy requirement in these months.

As for the case with atrium, Fig. 9, the heating and cooling loads for the whole building from January to December, measured in watts (W). Likewise, red represents a heating load while blue represents a cooling load. The energy demand in a year for heating and cooling in this whole building is about 4,355 kWh, which is separately 3,443 kWh for the heating demand and 912 kWh for the cooling demand under the case of the atrium.

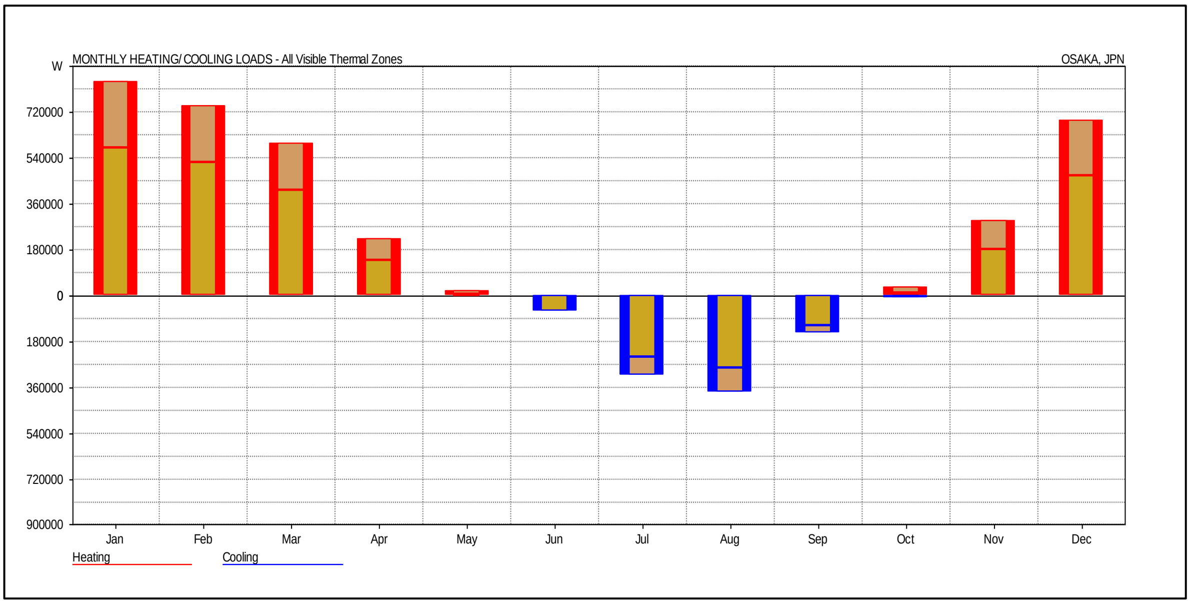

Fig. 9. Annual heating and cooling energy demand with an atrium.

Although the total annual energy demand for heating under no atrium is 2,526 kWh which is little less for the condition with atrium 3,443 kWh total annual energy demand for cooling under no atrium is 2,516 kWh which is considerably greater than energy demand with atrium, 912 kWh. The possible reason behind this is the heat gains are not too much in the atrium space during the cooling term. This may be considered that the exterior air temperatures are higher during the whole year and heat loss does not occur. As a result, the demand of the heating load is relatively lower. Additionally, whereas the energy requirement for the first floor dramatically decreased with the atrium case, it increases for the ground floor. This might be explained by atrium position; while the top of the atrium receives direct light, the ground floor receives much more reflected light rather than direct light as mentioned also by Aschehbough [45]. Moreover, internal obstructions of the house such as walkways and flight of stairs can significantly reduce the daylight available in the ground floor [43]. However, Samant concluded that a progressive increase in the number of openings from upper to the lower floors can lead to higher DFs available at the ground floor [46].

Based on the tested data from Ecotect shown in Fig. 8 and Fig. 9, the energy consumption analysis for both cases, with and without atrium is presented. It is clear that the no atrium case consumed more energy as compared to the atrium case especially in the Summer solstice (21^{st} June). Furthermore, the energy requirements for the first floor without atrium case is also higher than that with atrium case in the other terms; the Autumnal equinox (22^{nd} September), Vernal equinox (21^{st} March) and Winter solstice (21^{st} December). On the other hand, during Winter solstice, the energy demand for the ground floor with atrium case is much higher than without atrium case. As a result, although the energy demand of the total annual for heating under no atrium is 2,526 kWh is slightly less than energy demand in the condition with atrium 3,443 kWh. The total annual energy demand for cooling under no atrium is 2,516 kWh which is significantly greater than energy demand with atrium 912 kWh. If there is no atrium, the annual heating and cooling energy demand is about 5,042 kWh. This value is considerably higher than total annual energy demand with atrium 4,355 KWh.

3.3 Energy savings

The energy savings are computed on monthly basis and are represented in Fig. 10. It can be observed that during cooling period from June to October, it is possible to save quite a lot of energy such as; 500% in June, 120% in July, 110% in August, 220% in September and 20% in October. As mentioned by Moosavi et al [18], atria and courtyards are commonly embedded in some buildings for natural ventilation and cooling purposes. It is clearly seen from this research the atrium on the Azuma Row House has non-negligible results on the energy saving for this purpose. However, during the heating term from November to May, the energy saving is on the negative side. As previously indicated, the measurements are taken in the real atrium of the Azuma Row House, which served as a model, confirms the effectiveness of the presence of the atrium as compared to the no atrium case. The energy performance of the atrium is much better at its first floor where more optimal conditions are produced.

As the solar angle during the winter solstice is the lowest as compared with other terms. However, the annual heating and cooling energy demand for the no atrium case is 687 kWh which is high as compared with the atrium case for the whole year. The probable reason for that is the heat gains are not too much in the atrium space. This may be considered that the exterior air temperatures are higher during the whole year and heat loss does not occur. As a result, the demand of the heating load is relatively lower.

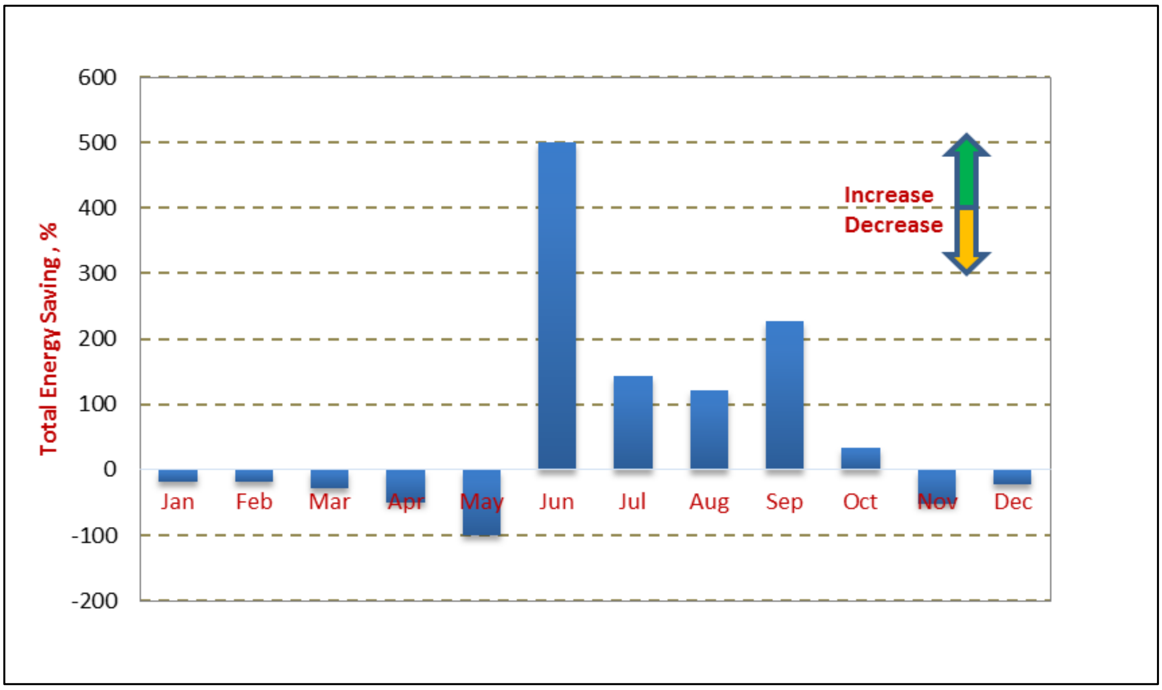

Fig. 10. Total energy saving in the case of with atrium on monthly basis.

A simple atrium can save about 687 kWh, the building energy for a whole year. In other word, nearly 15.7% of the total energy of the building can be saved every year. Therefore, the atrium is effective to save an overall energy of the building, although the saving is small it could be improved by introducing different location, shape and size of the atrium with respect to the architectural design of the building. However, it may have negative effects on the annual energy demands if the location or climate changes. In addition, the results are tested by a model which is making by sketch-up, the predicting daylight factor of the atrium area sometimes can be uncertain and inaccuracy. Furthermore, the consequence may differ under different forms and structures of buildings. For example, there are different shapes of the atrium, centralized, semi-enclosed, attached, and linear etc. [18]. Therefore, for the better performance or higher energy savings, the characteristics of these different shapes of atriums under different weather conditions could be studied.

4. Conclusions

In the present study, the Azuma Row House is taken as the model structure and tested under atrium and no atrium conditions as a sustainable energy-saving alternative. Nevertheless, atrium plays an important role in Architecture designing, especially in daylight factor and energy saving. Ecotect (Radiance simulation) is used to calculate and evaluate the daylight factors. The results showed that atrium has great importance in energy savings and reduce carbon footprints. The atrium can bring sunlight into the interior space of the building to reduce the usage of artificial lighting. Under atrium conditions, the ground floor daylight factor of indoor spaces at behind and front of the building is about 6.30% and 5.54% respectively. Whereas first-floor daylight factor at behind and front of the building is about 8.82% and 5.05% respectively, satisfying the requirement of the function for occupancy. The mentioned above the average value of the daylight factor is more than 5%, space appears strongly light, and it seldom needs to use artificial lighting in the daytime. Therefore, it is can be considered that the energy conservation decreased without using artificial lightings. The energy demand is calculated for linear shaped atrium by using the Ecotect. The overall average energy savings of the Azuma House is about 15.7%. However, future research could be focused on the other characteristics of the atrium. These may contain the shape of the atrium, the attitude of the building, the climate around the building and so on. Along with the increasing issue of the energy crisis, environmental problem and the beautiful design of atrium, the development of atrium in modern architecture designing is conceivable to have a good future.

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