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The Thermal Performance of Residential Building Integrated with Adaptive Kinetic Shading System

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Abstract – In the last decades, development of innovative solutions is considered as a prominent issue for achieving sustainability within the built environment. One of the most paramount methods of saving energy in a building is by deliberate designing its façade. The façade is one of the perfect options for administering the communication between the outdoors and the internal spaces. Also, an intelligent kinetic design presents a creative method for energy conservation in the buildings. This paper reports the experimental results of thermal performance of residential building coupled with smart kinetic shading system. Moreover, the comparison between two identical apartments is accomplished. One coupled with the proposed system. The system fixed on the window the wall south faced. Indoor air temperature and energy consumption are measured and recorded for both apartments simultaneously. The results showed that this system could lead to improved and decreased the internal temperature of the building about 2-3^{o}C. Consequently, the energy saved by 18-20% compared to the standard building without shading system, the improvement in apartment regards indoor environment quality and energy consumption will reflect directly on the building performance. The experiments were conducted on one apartment only due to financial costs. Consequently, implementation the proposed system on the whole building will enhance the energy consumed within the building.

Keywords – Adaptive façades, automated control, energy saving, intelligent building envelopes, residential building.

1. INTRODUCTION

As the twenty-first century approaches, increasing energy prices and fluctuating oil reserves have pushed humankind to think about sustainable energy policies. Kinetic facades have appeared as alternative building envelopes, designed to meet the growing of varying and complicated demands related to user comfort, energy consumption, and cost efficiency. It is widely known that significant amount of energy use in buildings depends significantly on the used criteria for the heating, ventilating, and air-conditioning (HVAC) systems, which controls the comfort of the occupants [1], [2]. Buildings sector consumed about 42% of the total annual world energy consumption as well as accounted for 33% of the carbon dioxide, which is the leading greenhouse gas associated with global climate change [3]. Thus, facades are crucial to energy consumption and comfort within buildings. Incorporating intelligence in their design is an efficient way to achieve low energy consumption buildings [4].

It is noteworthy that Egyptian houses are often designed without sufficient consideration to the climate conditions. Thus, such conditions give impetus toward the incorporating kinetic shades to enhance the natural ventilation and minimize the energy consumption. This concept has been described in given ways, ranging from the usage of innovative components to highly intricate designs and advanced technological application [5].

Nowadays many architectures designers of dynamic building skins that reconfigure themselves in changing conditions have utilized mechanical systems. On the other hand, when designing for dynamic responsiveness, these systems often involve intricate and high-tech mechanistic joints, actuators and control [6]. Some auspicious and inventive building envelopes tend to be more adaptive and interactive with the climate, space functions, indoor environments, occupants and visitors [7] and thus building façades are progressively developed as intricate systems of material assemblies attuned to climate and energy optimization [8].

2. THE DEVELOP INTERSET OF THE KINETIC FACADE

The burst of technology empowered kinetic architecture to make a remarkable comeback and attack traditional architecture, as a result of the dominant combination of manufacturing and use of technologies, sustained by kinetic architecture [9]. Therefore, technological advancements and innovations for designing dynamic architectural skin present new opportunities for designers and architects [10]. Thus building façades are increasingly developed as complex systems of material assemblies attuned to climate and energy optimization [8].

The use of kinetic facades has been adopted since the 1960s. Being one of the first examples responsive building skin of the Los Angeles County Hall of Records, designed by Richard Neutra in 1962 [11]. Another early example of automated climate-adaptive envelopes was Buckminster Fuller's façade for the United States pavilion built for the 1967 Montreal Expo. The skin of this geodesic dome was made of a transparent cladding of acrylic panels, with interior

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canvas sunshades controlled by a computer program that would adjust their position sensitive to the movement of the sun [8], as shown in Figure 1.

In addition, this kinetic response is designed and demonstrated by the famous Jean Nouvel kinetic facades, Monde de Arabe (1980) [10] which hundreds of sliding planes (25,000 photoelectric cells similar to a camera lens) were motorized and placed within the façade. Various sensors measure daylight and open or close the irises as necessary to control lighting levels. The system using complex motorizations and an enormous amount of motorization [12], as shown in Figure 2.

Furthermore, the kinetic facades design involved a substantial mechanical system to actuate the kinetic response. Aedas adopted a similar pattern of design on the Abu Dhabi Investment Council. It designed in Abu Dhabi which the dynamic Mashrabiya includes 1,049 units for the west and east side of the building, which claim to be the world's largest, computerized facade built today for 150 meter high towers. The kinetic facades create a folding and unfolding movement, which adapts to the sun and changing environmental conditions. The kinetic elements are programmed to transform into three kinetic states as entirely closed, mid open and fully open, which refer to the scaling type of kinetic. The control systems of the facade adopt the piston mechanism, which sorts into the sliding form of a kinetic pattern, in molding the facade's movements to adjust the environmental conditions.

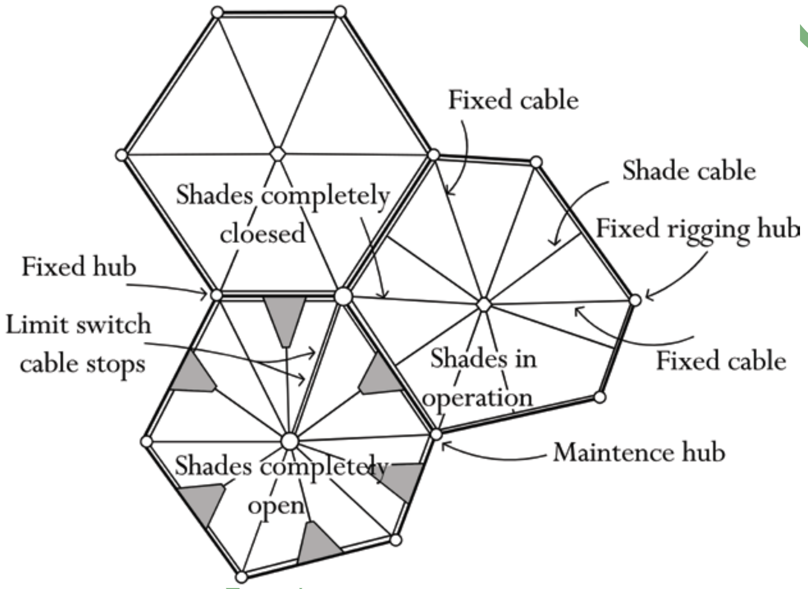

Fig. 1. The canvas sunshades of American Pavillion by Buckminster Fuller.

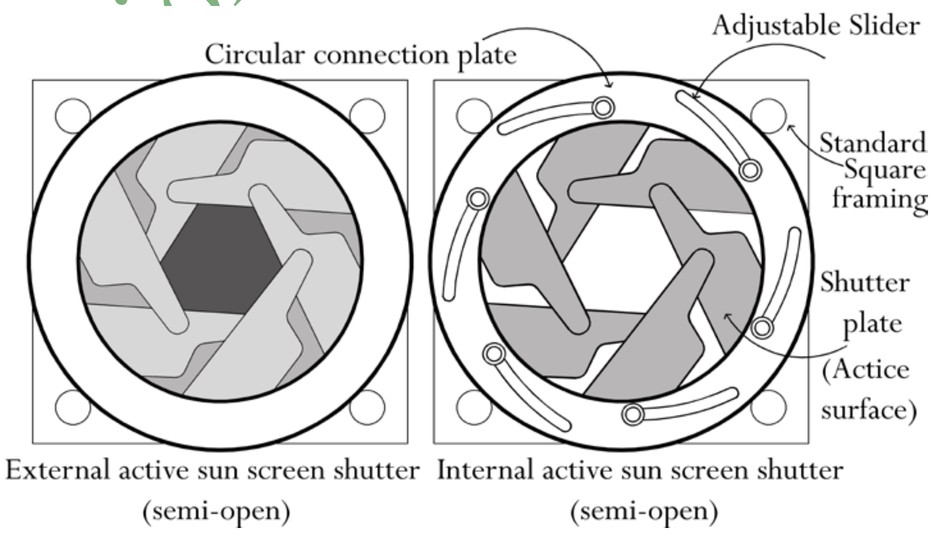

Fig. 2. The six Kinetic Shutters panel of Institute Monde de Arabe which are used to create an open and close performance to respond to the daylight condition.

3. TOWARD KINETIC FACADES: RESPONSIVE KINETIC FACADES FOR ENVIRONMENTAL CONDITION

Nowadays, the application of responsive elements in a building, such as kinetic facades plays an essential part in a building's operation. On the other hand, the architectural construction methods and design principles of kinetic facades have been under-explored [13] which adaptive facades afford opportunities for substantial reductions in building energy use and CO_2 emissions, in the same hand, having a positive influence on the quality of the indoor environment. Many different types of adaptive façade concepts (materials, components and systems) have already been developed, and an increase in emerging, innovative solutions is expected for the near future [14].

Over the past couple of decades, widespread experimental and simulation studies were conducted to investigate the performance of various types of dynamic facades.

Elghazi *et al.* present a simulation study for a south oriented façade of an office room in Aswan, Egypt. They use the dynamic screen to trace the daily, monthly and annually façade response for climate changes to test the usefulness in improving the luminance levels. Their results show that kinetically actuated facade achieved better daylighting performance compared with the static base case [15].

Loonen *et al.* give a new expression called climate adaptive building shells (CABS) which have the ability to change some of its features frequently, behavior or functions over time. This adaptation is a response to change in performance demands and boundary conditions [16]. Moreover, CABS is seen as an outstanding design concept for realizing low-energy building operation while offering potential for ameliorating the indoor environmental quality [17]. Also, Loonen and Hensen discuss requirements, challenges, and solutions for simulation-based design optimization of CABS and the study concentrate on reaching energy savings while enhancing the indoor environmental quality of dynamic daylight performance and thermal comfort [18].

Shen *et al.* compare the energy performance of perimeter zones in two commercial building types: a "traditional building", with brick cavity walls, and a "modern" building, with curtain wall construction for the climates of Chicago and Rome. In addition, the two buildings use the same high-performance glazing, but an extra reflective shade is utilized for the modern building, and the result indicated that the modern building in higher source energy consumption for both climates if simplified controls are used. The influence of open/closed shading control set points was also examined, to underline its significance and impact on daylight autonomy and energy use [19].

Mahmoud and Elghazi made a simulation for daylighting performance studied for the three studied cases; the base case, the rotational and the translational kinetic motions and the results indicate that the Rotational motion improved daylighting by approximately 50% in summer and spring and about 30% in autumn and winter compared to the base case [20].

Kensek and Hansanuwat analyzed the effectiveness of the kinetic systems for four different building elements (folding, overhang, vertical louver, and horizontal louver) and they noticed that all four systems showed consistent improvement over a non-shaded system, showing an energy reduction ranging from 28% to 30% for heating and from 28% to 33% for cooling, in addition, they concluded the study of kinetic systems can keep about 38-55% of the work surface in the recommended light levels, not only reduce the requirement for non-natural lighting, but also keep the space in a comfortable state [21].

Furthermore, engineering firm Buro Happold, in association with deployable structures innovator Chuck Hoberman, have established a smart surfaces unit called The Adaptive Buildings Initiative (ABI). This design unit Has developed some kinetic shading and cladding systems, including the Strata™ System, which contains automated modular dynamic units that can retract into a slender profile as shown in Figure 3. The Strata™ system was the basis for the Helio Trace Façade, developed in collaboration with SOM and Permasteelisa Group, which improves envelope performance about daylight and glare while reducing solar heat gain by approximately 81% [22]. The aluminium perforated shading surfaces work in two separate layers in response to daily sun path. Each square shaped opening/window is entirely covered with four vertical triangular folding shading surfaces. The shading surfaces that fold out horizontally are located at edges of each window [23].

Fig. 3. The Helio Trace Centre window unit by SOM/ABI/Permasteelisa, 2010 [25].

Among strategies and solutions used in discussing the problem of a buildings' energy consumption, the buildings' façade should function as a mediator between the external and internal environments. Facades can be entrusted with multiple vital purposes that dictate the building's energy consumption and which determine indoor environmental quality [24], and thus we measure the influence of the new adaptive kinetic shading system in energy consumption within the residential building during the summer period in this experimental.

This study aims to introduce a method for appraise the impact of dynamic facade adaptation on residential building performance and to improve the indoor environment within these building because many of houses in Egypt are regularly designed without taking the climate into account sufficiently. Therefore, new houses often have a poor indoor environment, which affects comfort, health and building efficiency. In hot and arid climates, the passive cooling system employs non-mechanical procedures to maintain suitable indoor temperature. Thus, we measure the influence of the new kinetic shading system in energy saving.

4. EXPERIMENTAL SET-UP

Experimental investigations of kinetic shading development have conducted during the period from 20th of July to 20th August 2015 on the campus of Egypt-Japan University of Science and Technology (E-JUST), as shown in Figure 4, which located in New Borg El-Arab City Alexandria (30.9°N, 29.6°E).

The field study was conducted on the outer surface of the south oriented window of the apartment which located on the third floor which the other apartment used for comparison assigned for comparison located directly above the apartment of interest (3rd floor). With the same dimensions, orientation, air cooling capacity and the same operation condition. Figure 5 depicts the schematic diagram of experimental set-up consist of aluminum frame window of dimensions 130* 150 cm. The selected window divides into two sections which can be moved vertically and rotationally. Moreover, the central part moved vertically up and down motion using Direct Current (DC) actuator and connected wire, while the minor parts can be moved from 0 to 180° with two servo motor. These actuators controlled by Arduino Board, which had an outdoor temperature sensor, as shown in Figure 6 the stages of the operation of the kinetic system. However, the setting point of the control signal is adjusted to be 28°C. Consequently, Arduino senses the environment by receiving inputs and sending output from sensors. Then, Firefly software tool enables the connection and interaction between analog and digital devices. It provides a direct connection between Arduino microcontroller and the algorithm software, Grasshopper in Rhinoceros environment. Figure 7 indicates the connection between Arduino board and laptop with controlling software and the way of the digital servo and DC motor respond to the computer.

Fig. 4. Exterior view of residential building from the south direction of kinetic shading system.

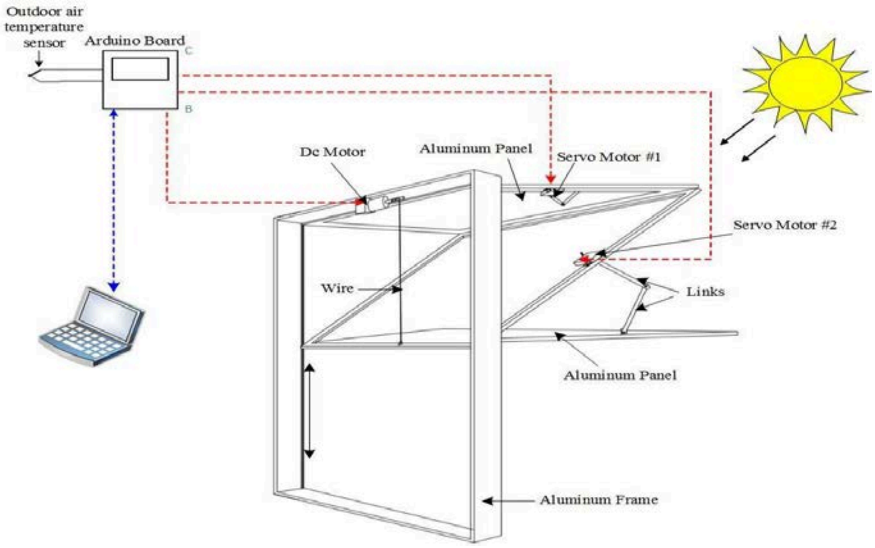

Fig. 5. The schematic diagram of the experimental set-up.

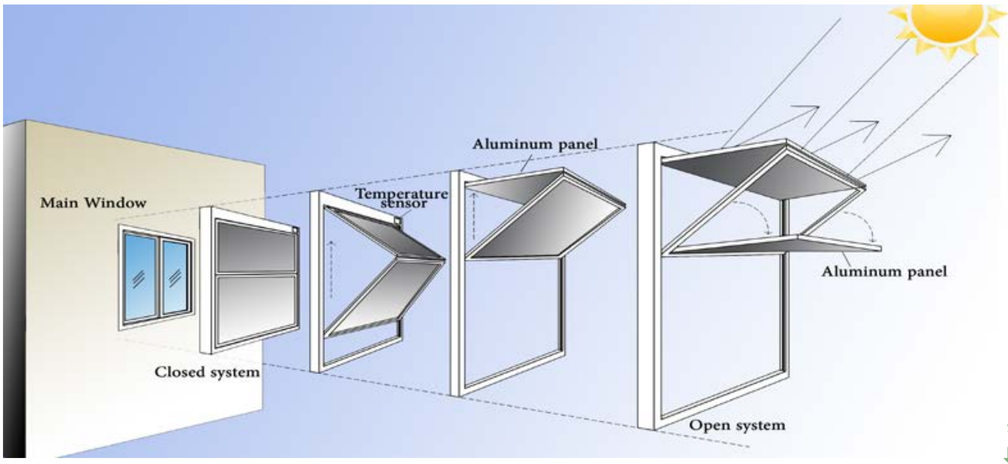

Fig. 6. Stages of the operation of the kinetic system.

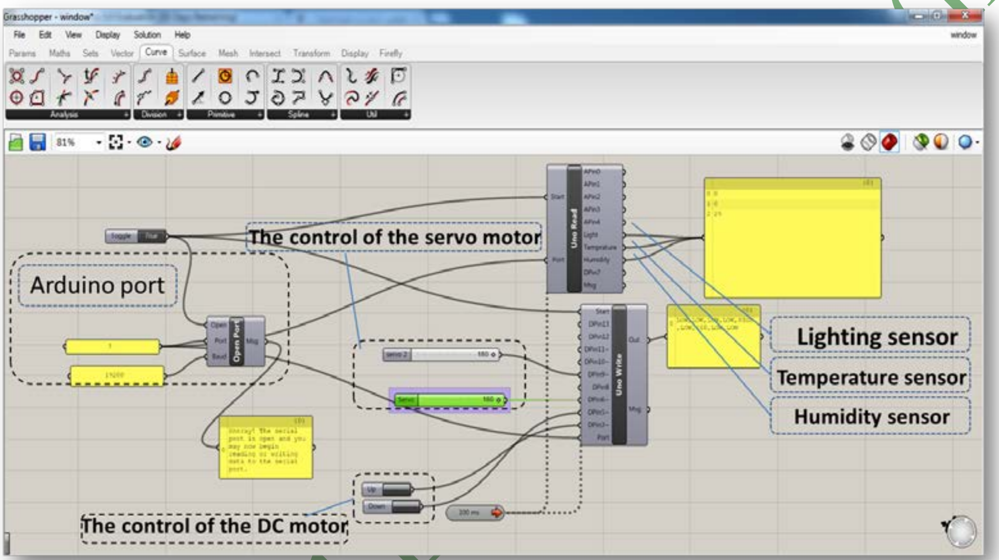

Fig. 7. The connection between Arduino board and laptop with controlling programme software (Rhino and Grasshopper).

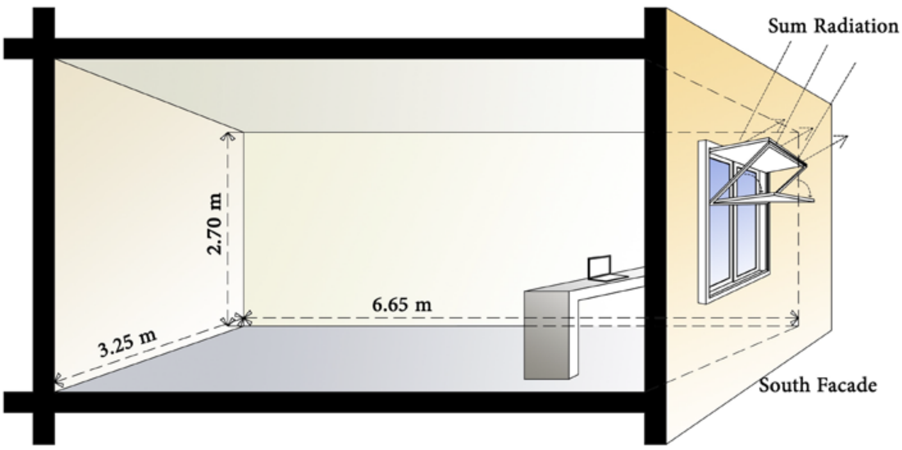

Fig. 8. 3D drawing of living room coupled with automatic shading system.

In this field study, the indoor thermal comfort conditions were investigated within the living room space, as shown in Figure 8, by monitoring environmental parameters; indoor air velocity, indoor air temperature and indoor relative humidity measured by air velocity meter (Hot wire anemometer model number 9545/9545-A). These variables recorded simultaneously with outdoor variables every hour starting from 6:00 am to 6:00 pm which Figure 9 shows the process of transferring the data while examining the adaptive kinetic shading system.

Additionally, this study presents a comparison between two identical spaces, one with the system and the other without a system is conducted to examine the effect of the kinetic system and its influence on energy consumption within the residential building.

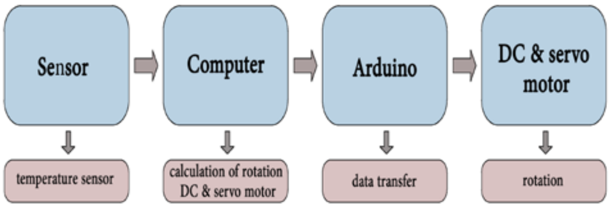

Fig. 9. The schematic diagram of the data transfer at the Kinetic shading system.

5. RESULTS

5.1 Environmental Conditions

Figures 10, 11, 12 show yearly average outdoor temperature values and sunshine duration in Alexandria city in which the study was carried out using Meteonorm 7 software [26]. From the figures, it can be clearly seen that August has an average maximum temperature during the year. The maximum outdoor temperature recorded is about 32 ºC during the daytime (6 AM - 6 PM).

Regarding the indoor thermal comfort evaluation in the presented study was determined by using the Adaptive Comfort Standard (ACS) for naturally ventilated buildings which were employed by ASHRAE Standard 55[28].

For the ACS, 80% and 90% acceptability limits of indoor operative temperature are proposed as a function of mean monthly outdoor air temperature by the following formula [29]:

$$T_{com,} = 0.31(T_{out}) + 17.8$$

Where T_{com} is the optimum comfort indoor temperature in ºC and Tout is the mean monthly outdoor air temperature in ºC. While the 90% acceptability limits of indoor operative temperature were calculated as follows [30]:

$$\text{90\% acceptability limits} = T_{com} \pm 2.5\ °C$$

The measured data clearly in Figure 13 show that there has been an increase of outdoor temperature in the measurement within the ranged from 25.5ºC to 42.6ºC during the day time corresponding to a rise in indoor temperature ranged from 25.5ºC to 35ºC. As depicted in Figure 13, the indoor temperature ranged from 25.5ºC to 28.2ºC while installing the proposed system on the south opening of the building.

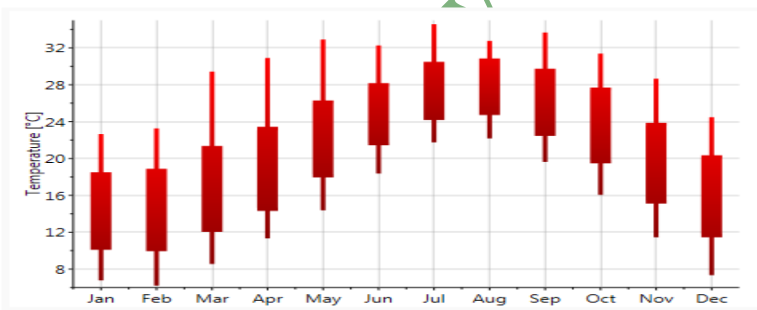

Fig. 10. Alexandria's temperature data based on [26].

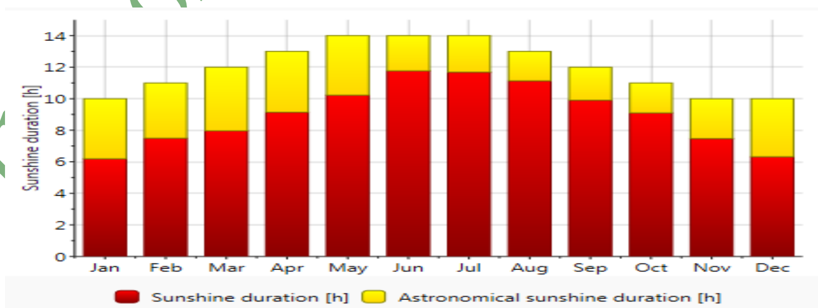

Fig. 11. Alexandria's sunshine data based on [26].

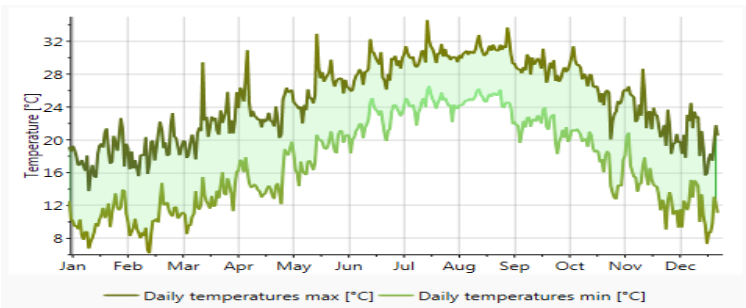

Fig. 12. Alexandria's daily temperature data based on [26].

The indoor and outdoor humidity measured data clearly in Figure 14 indicates that there has been installed system were in the comfort zone recommended kinetic shading installed when we compare that with the base case and the 90% of indoor relative humidity with by ASHREA, on the same hand, Figure 15 indicates that the proposed kinetic shading system prevent of amount of the direct solar radiation to enter the experimental place and thus will improve and decrease the temperature and improve the thermal comfort within residential hall and the kinetic shading system prevent from 15 to 20 W/m^2 of direct solar radiation.

It is clear that the kinetic shading system improves the indoor temperature and almost temperature after using system between comfort ranges and thus will decrease the energy consumption of the air condition and cause ameliorate comfort within this residential space.

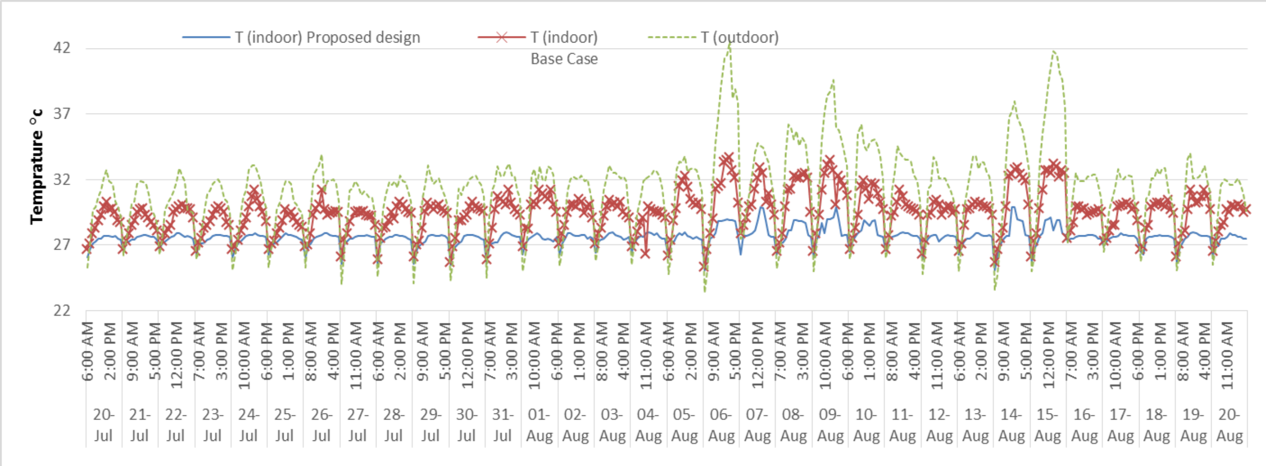

Fig. 13. Hourly indoor and outdoor air temperature.

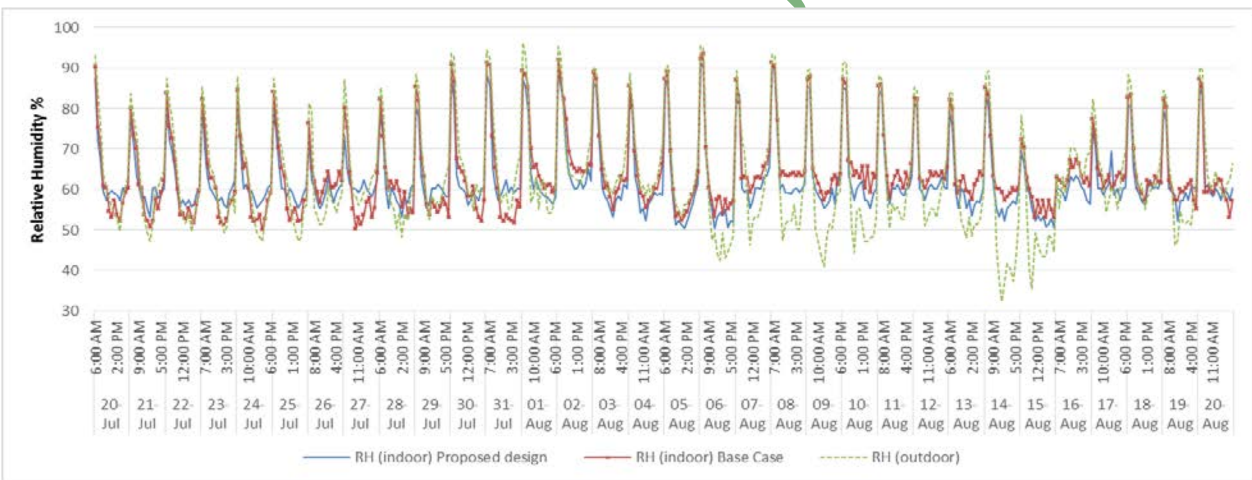

Fig. 14. Indoor and outdoor humidity plotted upon the designated comfort and discomfort zone.

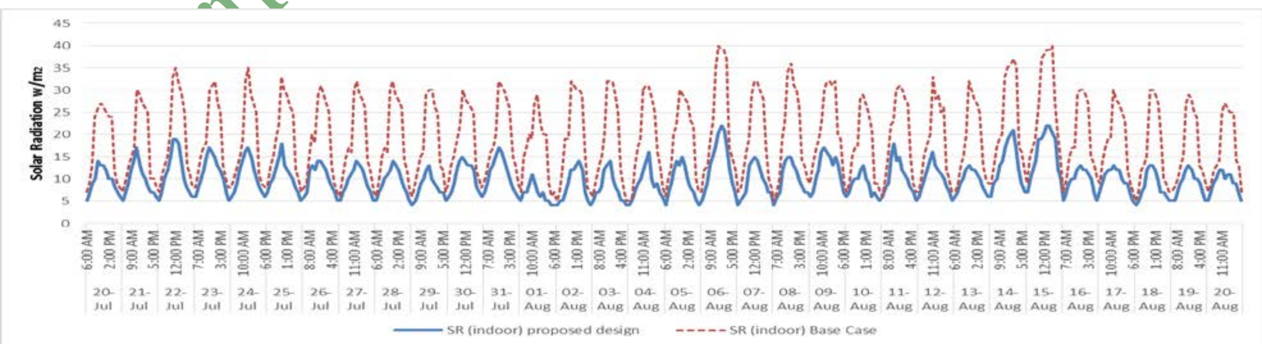

Fig. 15. The direct indoor solar radiation plotted upon the base case and the proposed design.

5.2 Energy Savings

Each zone of the building was physically examined with the aid of the building's operation to take out information and data on the building lighting, equipment, and occupancy. Moreover, electricity utility bills for the whole year 2015 have been collected. For the financial analysis, the cost of the energy consumption was calculated in Egyptian pound (EGP), which is referred to as operation cost. Then, the energy use inside the building was measured using a digital power meter for a studied period.

According to the collected results, the monthly electricity consumption for the building was 450 kWh per month (130 EGP per month). That means the building is consuming five kWh/m^2/month of electrical energy. Figure 16 shows that the electricity consumption in summer months while installing the proposed system is lower than the consumption under actual operation conditions. These savings were due to decreasing the indoor temperature of space, as a result of declining the operation time of air-conditioning during the daytime.

The energy consumption sources of the kinetic shading system are the motors (DC motor and two servo motor) which are used to actuate the system. The system contains three motors, the strongest one used to derive the vertical motion had the rated power of 80 W. The other two servo motors used for rotation motion had rated power of 10 W. While these motors energizes for 1 hour so the total energy consumption was 0.09 Kw.hr which is not comparable with energy saving amount achieved.

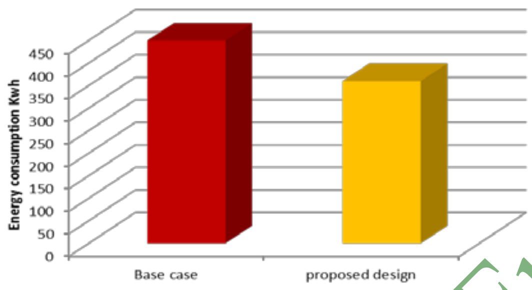

Fig. 16. Electricity consumption with and without the system.

6. CONCLUSION

This paper studies and compares experimentally the indoor air temperature and energy consumption of two identical residential flats at the same building. This building is located in Egypt-Japan University of Science and Technology, New Borg Al-Arab city, Alexandria, Egypt. The first flat (3rd floor) hall window is coupled with a new adaptive kinetic shading system. On the other hand, the other flat (4th floor) has no shading system. The experimental results indicate that such system decreases indoor air temperature by 2-3 o C in the summer season. Consequently, it reduces thermal load leads to saving energy by 20 %. Moreover, the relative humidity declined with 15 %. Finally, it can be concluded that such system can reduce the heat transmission as well as the electricity consumption of the air conditioning system, especially for the buildings located in hot aired area.

The main objective of proposed system is to reduce indoor air temperature by obscure direct solar radiation; it results in decreasing indoor heat gain. Consequently, cooling load decreases leads to decrease the energy required by the air conditioning compressor to carry the desired cooling load. By means of power meter connected to the air conditioning unit electrical input, so the electrical energy consumed by AC measured simultaneously with other measurements. Two power meters used, one for AC in the apartment under consideration and the other in the apartment used for comparison. Finally, the difference in electrical energy consumed for both apartments is the amount of energy saving achieved.

The authors recommended an additional future investigation to enhance façade design and performance. Also, cost analysis is more important in future work.

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