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RESEARCH PAPER

Experimental study on the performance of solar window films in office buildings in Kuwait

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Abstract This work examines the solar performance of double-glazed windows in four offices in ACK buildings with and without solar window film in actual working conditions. Window films are passive thin films stick to the interior or exterior of windows to effect various solar-optical impacts including energy saving, UV reduction, and increased thermal comfort. For this study, the 3M Neutral 20 and 70 are selected which are made of multilayer nanofilms of 220 SAN25/THV 95-nm thick reflective layers. Real-time measurements of temperature, humidity, and luminous were conducted in 5 min intervals over the months of June, July, and August 2019 and data stored through WiFi system in iClouds. Arduino-type microprocessors and various temperature-humidity, and LUX sensors were assembled and programmed to transfer and store data in real time. Exploring and analyzing the data collected for four offices with and without window films in summer of Kuwait, it is evident that window film has good potential to save water by preserving interior humidity to the level of human comfort, decrease interior temperature to save energy and reduce CO_2 footprints, to restrict the solar UV rays to minimum level, and to reduce visual impacts of high solar luminous. The benefits and drawbacks of the selected window films are discussed here for the weather condition of Kuwait.

Keywords Luminous · Office buildings · Solar energy · Thin window films · Thermal comfort

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Introduction

Importance of reducing world energy use has been highlighted in many researches due to the limited available fossil fuel resources and the drastic impacts on nature such as rapid changes of climate and green house effects (King et al. 2015; Pérez-Lombard et al. 2008). The climate change has caused many adverse effects such as dust storms, draught, and lack of drinkable water supply in many countries, while increased floods, tornadoes, and hurricanes in other parts of the world (King et al. 2015). To withstand global warming, a huge reduction in CO_2 footprint is eminently required. This can be achieved either by utilizing sustainable renewable energy resources and/or by decreasing energy consumptions through energy saving methods or improving energy efficiency (Ürge-Vorsatz et al. 2015).

In the developed countries, tremendous research has been focused on energy saving in buildings either residential or commercial because these count nearly 40% of total energy use that can be considerably reduced by using the energy efficiency methods (Hee et al. 2015). In many of developed and developing countries, there is a growing number of establishments that aim at reducing building energy consumption (Carbon Trust 2013). In Europe, buildings count about 40% of the total energy use. This energy use must be reduced to 20% by 2020 and 50% in 2050 compared with the values reported in 1995 according the European Union set goal (Recast 2010). In Europe, a large portion of energy use is for heating in buildings. A large portion of this energy is lost through window and roof glazing. But in hot climates, the large proportion of energy in buildings is used for cooling. Windows are responsible for overheating of interior building due to solar radiation pass through windows. Hence, methods for reducing radiative heat through windows are favorable to lower cooling loads particularly in heating seasons. Such methods may preserve heat in winter time by reducing heat radiation from interior of building to outside through windows. These methods can be either passive or active although passive methods are preferred using low-emissivity materials.

In Kuwait, KGBC (Kuwait Green Building Council) has set the goal of improving energy efficiency of existing buildings without scarifying residents' comfort using approaches such as implementing insulation materials within the building fabric retrofitting and using air leakage free air conditioning (AC) ducts (KGBC 2019).

Window panels are crucial architectural component of buildings which have considerable effects on the visual impact of the buildings and play important role in energy efficiency and residents' comfort of the living place (Li et al. 2015; Wang and Greenberg 2015). Windows are designated in buildings to provide light to residents during the day with visual connection to outside of the building, sustaining thermal comfort, air ventilation, passively obtaining solar thermal energy, and a rescue exit to human safety in fire cases (Cuce and Riffat 2015; Huang et al. 2014). In high-rise buildings, the open scenery through windows is a popular architecture in modern cities (Huang et al. 2014). However, it is believed that windows are responsible for heat loss of up to 60% of heating in cold climates (Jelle et al. 2012) and loss of cooling load of same amount by windows in hot climates (Hee et al. 2015). Although, solar heating through the windows reported 40% of cooling load or AC of a building according to glass federation (Glass and Glazing Federation 2012). Hence it is important to reduce the solar radiation through windows in a cost-effective manner. Window films are a cheap and market-ready solution to remedy solar radiation through windows of buildings. Window films are usually made from polyester thin films that can be stick on window glasses. The polyester thin films are multi layered thin films that are coated or chemically processed with some layers of different metals to improve radiative properties of window films (Plummer 2015). There are many products of window films; however, window films to obstruct certain thermal and UV solar waves are the most common. Window films are used to protect against harmful effects of sun including overheating, fading, glaring, and ultraviolet radiation. Window films also enhance security and increase privacy and visual privacy of the interior of building (Plummer 2015).

Some advanced applications such as reversible airflow windows, tintable smart windows, or solar energy control systems showed to cause disturbance to residents and are not necessarily preferred over window films (Wang and Greenberg 2015). Moreover, application of window films does regulate light and heat penetration to the building and almost prohibit entry of ultraviolet (UV) light without noticeable disturbance to occupants (Wang and Greenberg 2015).

The process includes soft coatings which is addition of several metal layers when the glass is hardened. This usually requires at least one conductive layer of metal with thickness of around 10 nm to be applied by a method of magnetron sputtering. Silver is one of the most favorable metal layers because of its optical characteristics. The next candidates are copper and gold because they absorb short-wavelength under 0.5 μm (Granqvist 2007). These metal layers will eventually be oxidized except gold therefore integrated with dielectric layers which are optically transparent (Mohelnikova 2009). The dielectric layers are made of different oxides, i.e., tin, zinc, titanium, or bismuth, with a minimal thickness of order of below 40 nm. The metal layers give solar and thermal reflection although the dielectric layers do opposite in the visible light spectrum but protect the metal layers from chemical or mechanical damages (Meszaros et al. 2012). Window films are usually made from multilayer thin films of metals and polymers some with preset adhesive to stick surface of a window. Some window films are only designed to be installed on the interior surface of windows because these window films cannot withstand outside weather conditions. These films are usually cheaper and provide an economical solution to many buildings.

Recent literature reveals considerable and various studies on application of window films on energy efficiency of buildings, some of these are cited here. Several feasibility studies on application of window films on energy saving of several types of commercial buildings were conducted (Li et al. 2015; Yin et al. 2012; Yousif 2012). Li et al. (2015) used an experimental and simulation approach to study different window films on windows of commercial buildings in warm climate of Hong Kong. They found the best energy saving in clear glazing (than tinted) windows of office buildings. In another research, the effects of window films were investigated on non-residential buildings in weather condition of hot summer and cold winter using software simulation (Yin et al. 2012). The performance of the building with and without window films reported reduction of 44% and 22% energy if applied on exterior or interior surfaces, respectively. Another study used spectrophotometer to measure glazing performance of two rooms in hot climate throughout the year and concluded that window films have opposite effects favorable in reducing the summer cooling energy demand but increased winter heating energy demand (Yousif 2012). ASHRAE (2001) has provided details of calculating heat transfer and optical performance of glazing in buildings.

Dussault et al. (2012) used smart window methods to examine the energy demand of buildings on a double-glazed window in office building in Canada. Smart window technology uses some controllable multi-layers for absorption, which controls optical or heat properties of windows by controlling solar light and/or heat flux. Their study concluded desirable saving energy of building. Chen et al. (2012) used various window shadings in exterior side for controlling cooling loads of various commercial buildings at five locations in China with different weather conditions. They conclude that flexible shading of opaque type is the most efficient for energy saving in office and hotel buildings.

Various window designs were investigated in terms of effectiveness for energy saving at different weather conditions using simulation methods (Carriere et al. 1999; Huang et al. 2014; Yang et al. 2015). Huang et al. investigated this for cold climate. Huang et al. (2014) concluded that double glazing gives the worst performance while low-emission windows performed better. Carriere et al. (1999) showed through simulation opposite that more glasses reduce cooling energy demand. Yang et al. (2015) investigated to find the best ratio between window and wall of a building and also glazing type in various AC systems for domestic buildings. They found that by increasing the ratio of window to the wall, the overall energy use increased and recommended low-emissivity windows for better efficiency. Vanhoutteghem et al. (2015) investigated the effects of orientation, glazing, and size characteristics of windows for zero-energy buildings in cold climate. Sorgato et al. (2016) used EnergyPlus software to simulate effects of windows in office building for different weather conditions in the USA. They concluded that for optimum condition, HVAC energy can be reduced by 17 to 47% in summer. EDSL TAS software was used in another study to estimate energy consumption (Crawley et al. 2008). The software is approved by several standards (EDSL TAS 2015). Wang and Greenberg (2015) studied how human habits of using windows impact on the HVAC energy consumption in Brazil. They recommended automated ventilation control for reducing HVAC energy consumption. The durability of window films is also reported to have the life span of 10 to 20 years (ATD Solar & Security Window Film 2012). Examples of the studied window films include PR40EX and PR70EX (3M Co. 2017).

From the literature review cited here, it is seen that many studies conducted on commercial office buildings with majority of these in cooling dominant climates. It is therefore justifiable to conduct similar study in dry and hot climate of Kuwait.

Methodology

Application of window glasses in buildings has advantages in architecture of buildings including utilization of sunlight and increase of visibility. In contrast, the glass windows are responsible for heating/cooling losses due to solar radiation from the building. Even in the most recent advanced building architecture, the glass windows are still responsible for 20% energy loss from the building. In summer time, the glass windows are responsible for 75% absorbed heat from solar rays of the building. This will obviously increase the cost of air ventilation and cooling of the building. Many industrial and scientific researches started in 1960 to improve building energy efficiency. The recent development of multilayer coatings and use of window films have reduced these undesirable effects considerably and increased the building energy efficiency. Window films are made of multilayers, for instance, the Reflective Co. (2019) uses 5 layers in their window films. In these layers, polyester with tiny ceramic particles is used. In this technology, the full spectrum of the sunlight is filtered from the heating rays and allows the visible light to pass through the glass window selectively. The different layer mechanisms in the window films provide the following characteristics (Reflective Co. 2019):

1. Reject 78% of the solar radiation heat;
2. Avoid UV penetration by 99% using chemical UV absorbent within the layers;
3. Increase impact resistance and avoid breaking glass into pieces using reinforced polymer layers and the used gluing resins;
4. Protect against greenhouse gases using 2 layers of polyester and a special resin;
5. Easy installation (no need to remove glasses from window frames) and washable.

The newly built building in ACK is a 3-floor building (see Fig. 1) designated offices for faculty and staff in engineering and business schools. Each floor composes of in average 31 offices occupied by 2 staff in each room, one kitchen, 2 washrooms for both genders, two lift compartments, and a secretary room for 3 secretaries (see Fig. 2). There are two exit stairways in the two corners of the building as shown in the figure. Out of 31 offices, 22 of the offices have windows to outside the building. The four offices selected for this investigation are located at the second floor and the third floor in the west side of the building shown in the Google map in Fig. 1b.

For the two selected offices of the building on the third floor, no window films were installed while the two identical rooms under these offices in the second floor were equipped with two types of window films, i.e., M3 Neutral 70 and M3 Neutral 20. All four offices

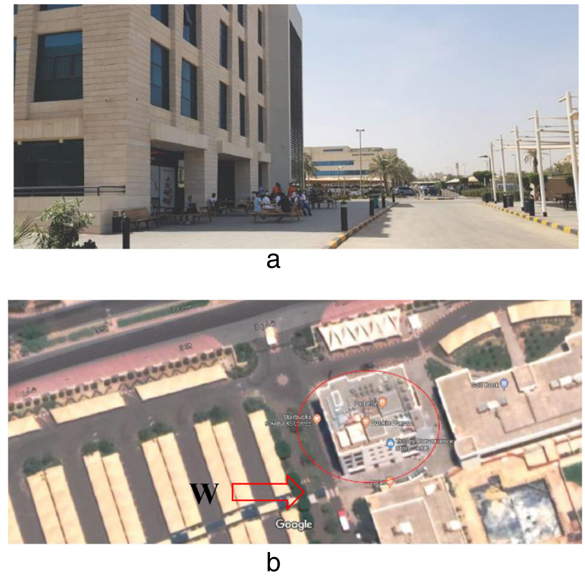


Fig. 1 **a** Northside photo of the building in ACK. **b** Google map of the building (window films installed on the second floor, west side of the building)

used double-glazed windows and the window films mounted in the interior side of the windows. All these offices were equipped with thermal and solar measuring devices to record thermal-solar properties for 3 months of summer in Kuwait, i.e., June, July, and August 2019.

Experimental setup

Window films

Solar control films are generally made by metallizing a thin layer of aluminum metal on polymeric film substrates, usually polyester (PET), and laminating it with a second-colored PET film. Solar control film product is designed to fulfill the needs of solar energy control permitting required visible light transmittance. The acceptable limits of visible light transmittance and reflectance in desired colors are achieved by combination of colored films and aluminum metallized films. Commercially available films are with visible light transmittance ranging from 3 to 70%. The window film laminate consists of optically clear, distortion-free PET film with thickness of 23 to 300 μm coated with acrylic base pressure sensitive adhesive and protected with a release liner (Garware, Adsul 2011).

In the first part, a number of markets with readily available window films designed for buildings were

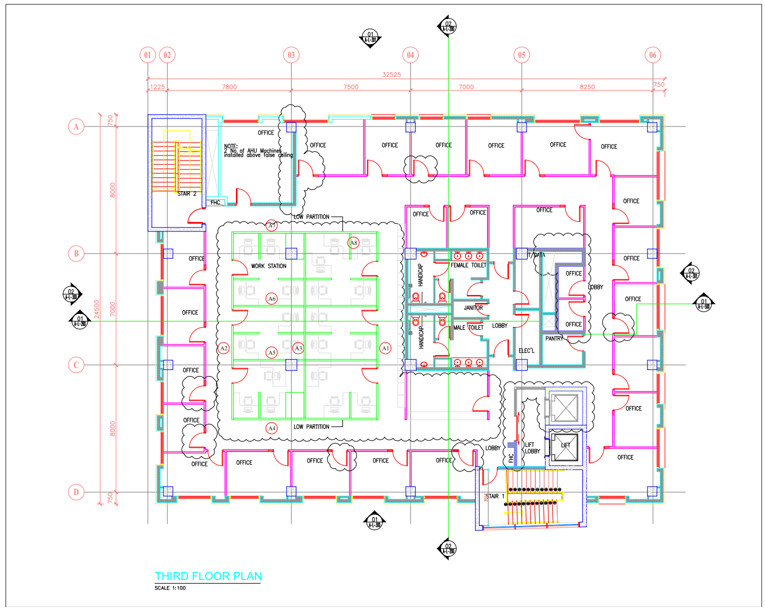


Fig. 2 2D plan view of the third floor in the ACK building

investigated. Three major companies were identified and their products are listed in Tables 1, 2, and 3 for the Reflective, the 3M, and the LLumar companies, respectively. The 3M Co. (2019) has a branch in Kuwait; therefore, it is decided to select two types of 3M window films; i.e., Neutral 20 and Neutral 70.

The 3M Co. manufactures various ceramic fibers by using the sol–gel technique. These fibers are made of alumina, silica, and boria with oval cross-sections. 3M Co. have produced multilayer films for applications such as solar window films with reflective optical properties to control UV, IR, and so on to reduce heat in cars and houses (Berger and Bunsell, 2000). 3M window films are usually 2-mm thick films and are produced from at least 220 nanolayers of polyester of SAN25/THV 95 nm thick reflective layers (Berger and Bunsell 2000) that are optically clear. One side of the film has adhesive which is pressure sensitive and the other side is reinforced by a resistant coating from acrylic abrasion (3M Co. 2019).

Table 1 Window film products of the Reflective Co. (Reflective Co. 2019)

Film type	Visible light Transmitted (%)	Total solar energy rejected (%)	Total solar energy reflection (%)	UV light transmission (%)
SOL 101	16	78	55	5
SOL 102	16	78	65	1
SOL 148	58	77	28	10
SOL 150	47	80	27	3

The window films that were purchased from 3M Co. were installed by the skilled workers in two offices in the second floor of the ACK building (see Fig. 3). The process includes cleansing the windows to remove any dust or particles, applying the glues on films, sticking to the windows, and cutting edges. The window films were allowed to dry stick for 72 h untouched and the installation was quality checked after this time. The installation of sensors was conducted after 2 weeks to ensure that the window films firmly dried stick to the windows.

Sensors and microprocessors

The temperature and humidity sensors, solar radiation sensors (LUX meter), and UV (UVM 30A model) sensors were installed to the interior surface of the offices, the window glasses, and outside of the offices to open ambient to measure thermal and solar properties. These sensors were connected to two types of microprocessors, ESP8266 and D1-WEMOS Arduino microprocessors, both equipped with WiFi network (Random Nerd Tutorials 2019; LOSANT 2019; Arduino IOT 2019; Arduino Project Hub 2019). Each processor can handle 6 to 8 sensors readily; therefore, two of ESP8266 microprocessors were mounted on a single breadboard for each of two larger offices for reading 14 sensor output.

Table 2 Window film products of the 3M Co. (3M Co. 2019)

Film type	Visible light Transmitted (%)	Total solar energy rejected (%)	Solar heat gain coefficient (G value)	U value (W/m^2.K)	UV light rejected (%)
Neutral 20	15	62	0.38	5.6	99
Neutral 35	36	56	0.44	5.6	99
Neutral 50	52	44	0.56	5.8	98
Neutral 70	69	32	0.68	5.8	98

Figure 4 shows the schematic of the first half of the board with 3 DHT22 temperature-humidity sensor and a LUX sensor (LDR model).

Figure 5 shows the schematic of the second half of the board with 3 DHT22 temperature-humidity sensor and a UV (UVM 30A model) sensor. The full board connects through an adaptor to the AC power supply and collects data in 3 min interval from 6 temperature-humidity sensors, one LUX, and one UV sensor, and transfers the data through WiFi Internet to the iCloud website of ThingSpeak (ThingSpeak for IoT projects 2019).

Each of D1-WEMOS Arduino microprocessors were good enough to collect data from 3 temperature-humidity sensors, one LUX (BH1750 model), and one UV (UVM 30A model) sensor to deliver 8 readings (as shown in Fig. 6).

In general, D1-WEMOS Arduino microprocessors used here are faster processors and less fragile compare with smaller ESP8266 microprocessors. Few of ESP8266 microprocessor break down during USB connection for uploading the codes, although these tiny processors are more robust and stable when compiling and executing Arduino codes.

The selected microprocessors and sensors were assembled and tested to ensure all sensors and connections were correct and working error free (see Fig. 7).

Data collection

Four boards as shown in Fig. 7 were assembled and programmed to transfer readings from the sensors to the iCloud website ThingSpeak (ThingSpeak for IoT projects 2019) (see Fig. 8). Three Arduino codes were prepared and tested for recording and transferring sensor readings to the website through WiFi system. A large number of tutorials and open access codes such as those in (Random Nerd Tutorials 2019; LOSANT 2019; Arduino IOT 2019; Arduino Project Hub 2019) were utilized to prepare the Arduino codes in this work. Once the Arduino codes are uploaded to the boards, it is ensured that the data is recorded and transferred to ThingSpeak website (ThingSpeak for IoT projects 2019) (see Fig. 8).

The iCloud website ThingSpeak (ThingSpeak for IoT projects 2019) allows four links for each user and each link can handle a maximum of 10 data series. Therefore, two user accounts were created and 6 links were created to receive and record data from all sensors.

After testing the boards, the four offices were installed with the boards (Fig. 9). The sensors were attached to the designated surfaces using black glue tapes. The board was connected to an AC plug through an adaptor. The black glue tapes were not efficient and fall off due to the heat; therefore, they have been replaced with normal colorless glue tapes later.

Table 3 Window film products of the LLumar Inc. (LLumar Inc. 2019)

Film type	Visible light Transmitted (%)	Total solar energy rejected (%)	U value (W/m^2.K)	UV light rejected
R15B SR CDF (Bronze)	8	78	0.89	99
R15BL SR PS (Blue)	9	78	0.93	99
R15G SR CDF (Gray)	6	77	0.92	99
R15GO SR PS (Gold)	13	80	0.92	99

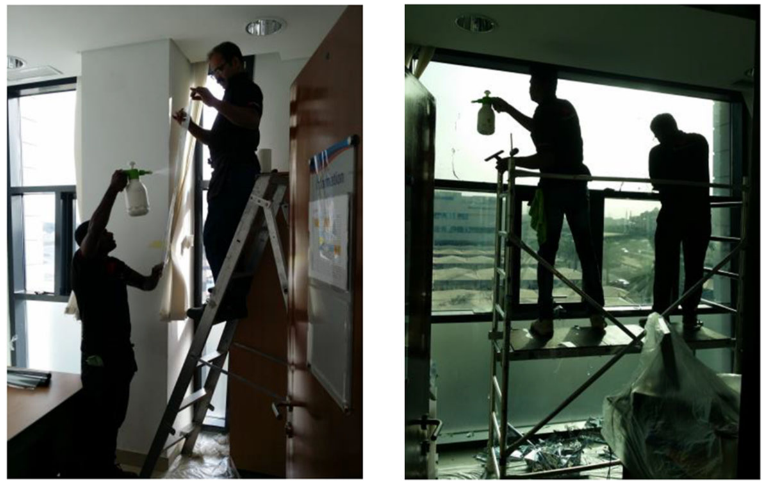


Fig. 3 Installation of 3M window films by the skilled company workers. Smaller office with 3M Neutral 70 (left). Larger office with 3M Neutral 20 window films (right)

The temperature, humidity, Lux, and UV readings were recorded in 3 min interval for the full months of June, July, and August 2019. Nearly, 50,000 data were recorded for each sensor over this period and a data bank of nearly 2 million data was created. All the four offices are located on the west side of the building which are most affected by solar irradiation.

Results and discussions

The weather condition in Kuwait is among the top extreme weather condition in the world. The global environment crisis such as global warming necessitates to closely study the weather conditions in Kuwait. A data bank of heat and radiation along with the technologies and plans, such as window films in this work, to remedy and withstand undesirable effects of the extreme weather condition seems inevitable. This will help to closely monitor the weather condition and prepare for the future.

Some selective experimental results are presented and discussed in this section to compare offices with and without window films and also to compare the two selected window films, i.e., 3M Neutral 20 and 3M Neutral 70. The UV measurements only qualitatively showed that the UV index of the offices with window films possess the lowest values, but the readings throughout days and nights remain almost constant. Therefore, the results of UV sensors are not presented here.

3M Neutral 20 window films

The results from the measuring thermal-solar devices in two offices in the ACK building with and without 3M Neutral 20 window films were recorded and summarized in a form of daily graphs of temperature, humidity, and lux for the months of June, July, and August 2019. Here, we examine the results for 15 June, 15 July, and 15 August 2019.

Results for 15 June 2019

Figure 10 compares the experimental results for two offices with and without 3M Neutral 20 window films

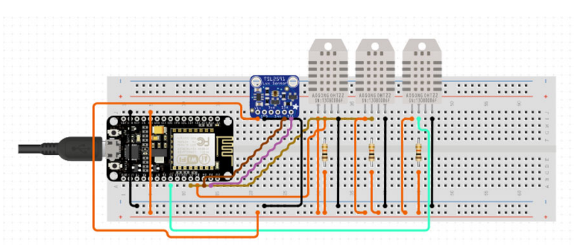


Fig. 4 First half the board with 3 DHT22 temperature-humidity sensors and a LUX sensor

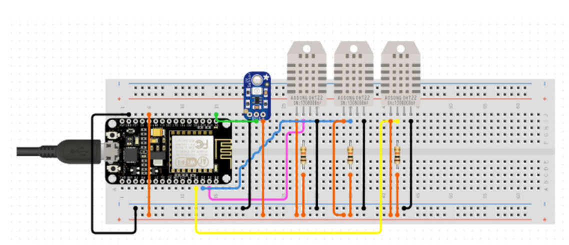


Fig. 5 Second half the board with 3 DHT22 temperature-humidity sensors and a UV sensor

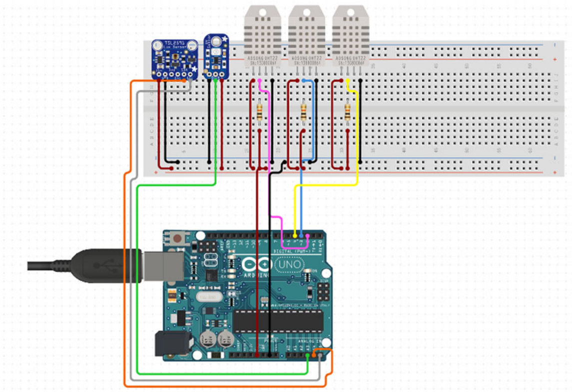


Fig. 6 The D1-WEMOS Arduino board with 3 DHT22 temperature-humidity sensor, 1 UV sensor, and 1 LUX sensor

on 15 June 2019. For lux measurements in these offices, the LDR sensor was used. Figure 10 a clearly shows the solar luminous in the office with window films have been substantially reduced.

However, window glasses with window films, temperature increased slightly in order of 2 to 3 °C in peak hot hours of the day, i.e., at 5:00 pm (see Fig. 10b). Humidity sensors on windows in Fig. 10c show that the offices with window films conserve humidity within 1 to 5% compare with the office without window films.

All offices utilized double-glazed windows; hence, window films were installed on double-glazed windows. Some studies suggested that window films perform worst on double-glazed windows (Huang et al. 2014). However, all windows in the studied ACK building are double glazed.

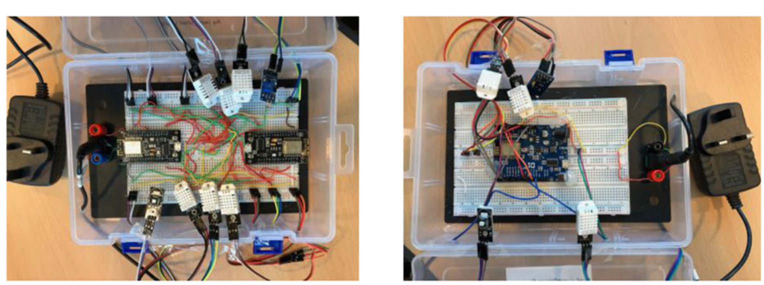
Figure 10d shows that the interior temperature for one of the sensors in the office with window films was lower up to 5 °C in peak hot hours of the day. But, the second sensor merely shows the same temperature as of the office without window films. As shown in Fig. 10e, the interior humidity was higher in the office with window films within 3 to 5%. Exterior temperature variation for both floors 2 and 3 of the building shows same trends with a maximum temperature of 53 °C at 5:00 pm in Fig. 10f, although level 2 shows higher humidity of about 5%. Figure 10 shows that temperature and humidity measurements can be dependent on local positions of the installed sensors, but in overall, the 3M Neutral 20 window films improved noticeably luminous and humidity of the offices yet temperatures in peak hot hours.

Results for 15 July 2019

Figure 11 shows the results for the offices with and without window film type 3M Neutral 20 in 15 July 2019. Lux measurements by LDR sensors show substantial reduction of luminous in the office with window films (Fig. 11a). Temperatures on windows of both offices are very close except one of the sensors reported lower temperatures by 10 °C (Fig. 11b). One of the undesirable effects of window films reported to be higher window temperatures, although the present results do not show significant temperature rise of windows. The humidity variations from the sensors installed on windows do not show noticeable changes between two offices.

As shown in Fig. 11c, there is slightly higher humidity values for the office with window films. Two interior temperature sensors show slightly higher temperature of 2 to 3 °C during early morning and late night, but the office with window films was colder by 5 °C during peak hot hours of the day, i.e., 12:00 to 16:00, see Fig. 11d. Figure 11e shows that the humidity of the office with window film was 5% higher than the office without window films in most hours of the day. Exterior temperature and humidity on level 2 and level 3 are compared in Fig. 11f. Both levels show same temperature trends although slightly higher humidity is observed in level 2.

Fig. 7 Assembly of the boards for connection of ESP8266 and D1-WEMOS Arduino microprocessors with DHT22, LUX, and UV sensors



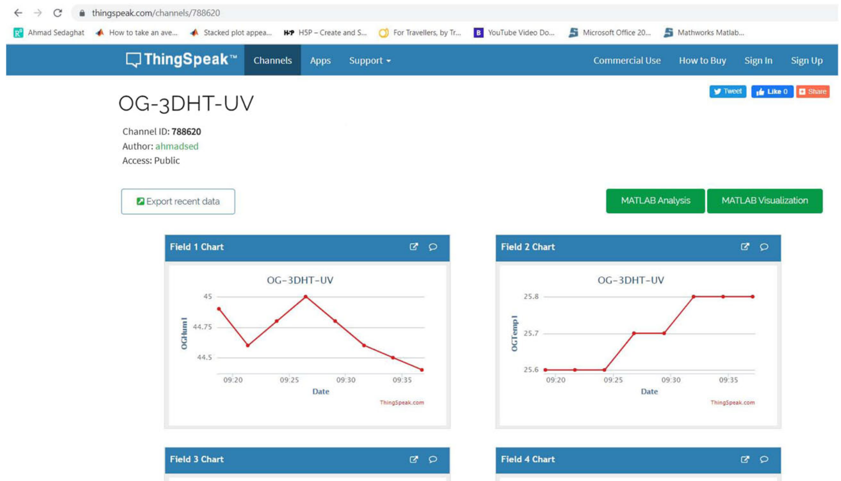


Fig. 8 Data upload to the iCloud website ThingSpeak (ThingSpeak for IoT projects 2019)

Results for 15 August 2019

Figure 12 summarizes the thermal and solar measurements for two offices with and without 3M Neutral 20 window films during 15 August 2019. Lux measurements in all days were consistently reported lower luminous radiation for the office with window films (see Fig. 12a).

Window temperatures with window films are surprisingly lower than double-glazed windows as shown in Fig. 12b from 9:00 am to 7:00 pm but was higher by 2 °C in other times of the day. However, the room with window film possesses higher humidity in all hours of the day as seen in Fig. 12c. For the room interior temperature and humidity as shown in Fig. 12d and e, respectively, the room with window film is warmer by 2 to 3 °C compared with the room without window film. Results on 15 August 2019 using 3M Neutral 20 show that the selected window film cannot be efficient in all days and months of the year. This can be correlated to the cumulative effects of preserving temperature in the room with window films that prevented heat loss from the office during early morning and night hours. The level of heat preservation can also be related to high humidity levels observed in Fig. 12f at early morning hours. Additional factors can be related to the fact that the offices with and without window films were not identical in terms of available furniture, equipment, and also occupant habits. Each floor AC system operated separately which can marginally affect the outcome of this research.

Fig. 9 Assembly of the Arduino boards and sensors in offices

Results for 3M Neutral 70 window films

The results from the measuring thermal-solar devices in two offices in the ACK building with and without 3M Neutral 70 window films were recorded and summarized in the form of daily graphs of temperature, humidity, and lux for the months of June, July, and August 2019. Here, we examine the results for 15 June, 15 July, and 15 August 2019. All offices utilized double-glazed windows; hence, window films were installed on double-glazed windows. Some studies suggested that window films perform worst on double-glazed windows (Huang et al. 2014).

Results for 15 June 2019

Figure 13 compares the experimental results for two offices with and without 3M Neutral 70 window films on 15 June 2019. For lux measurements in these offices,

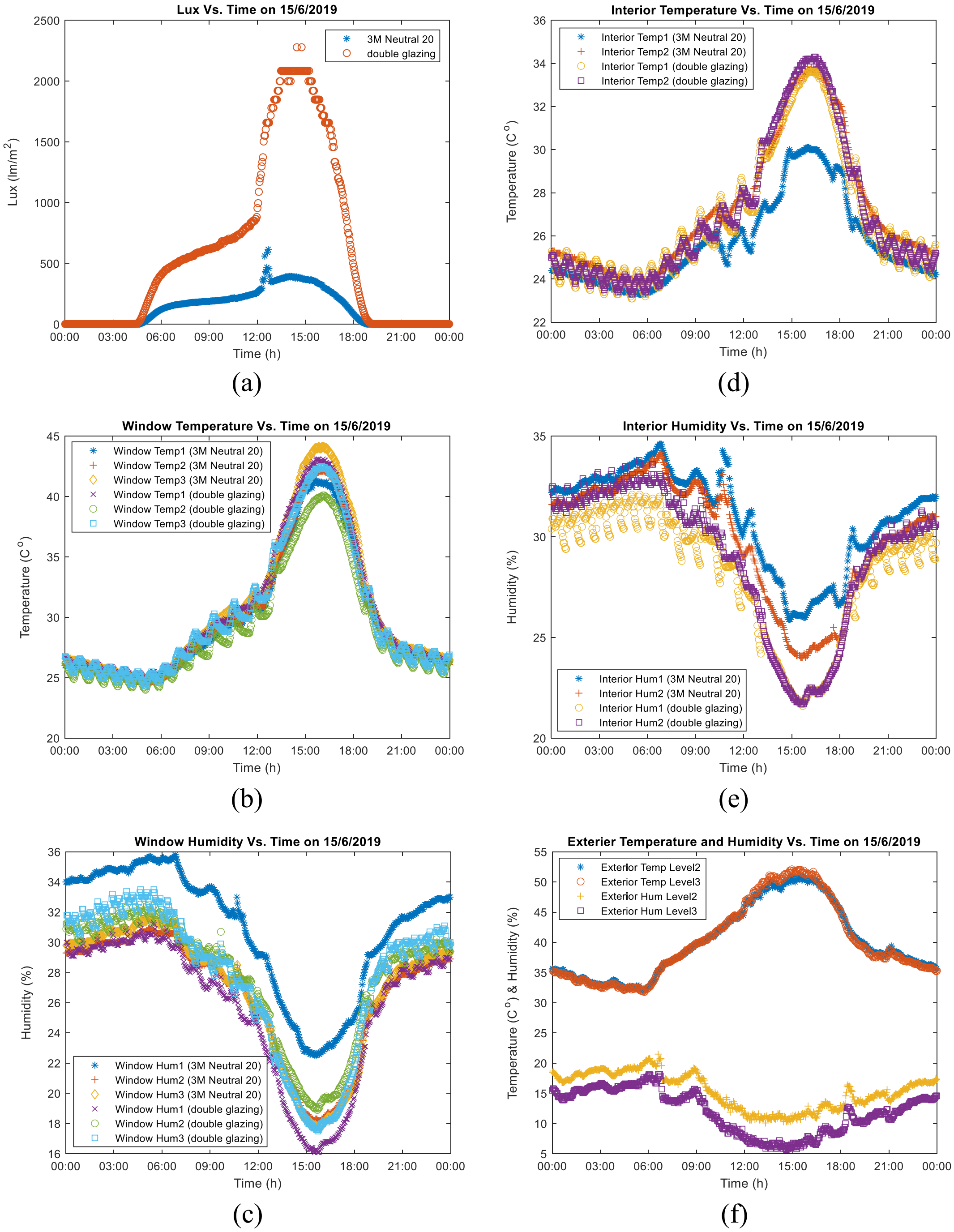


Fig. 10 Thermal-solar properties of two offices with and without window films 3M Neutral 20 on 15 June 2019

the BH1750 model sensor was used. This sensor shows more sensitivity particularly during high radiation of the day. Figure 13a shows that window film 3M Neutral 70 has marginally restricted the solar luminous in the hot hours of the day. Figure 13b and c show that interior temperature/humidity in the office with the window films was lower/higher by 2 °C and 2% throughout the day, respectively.

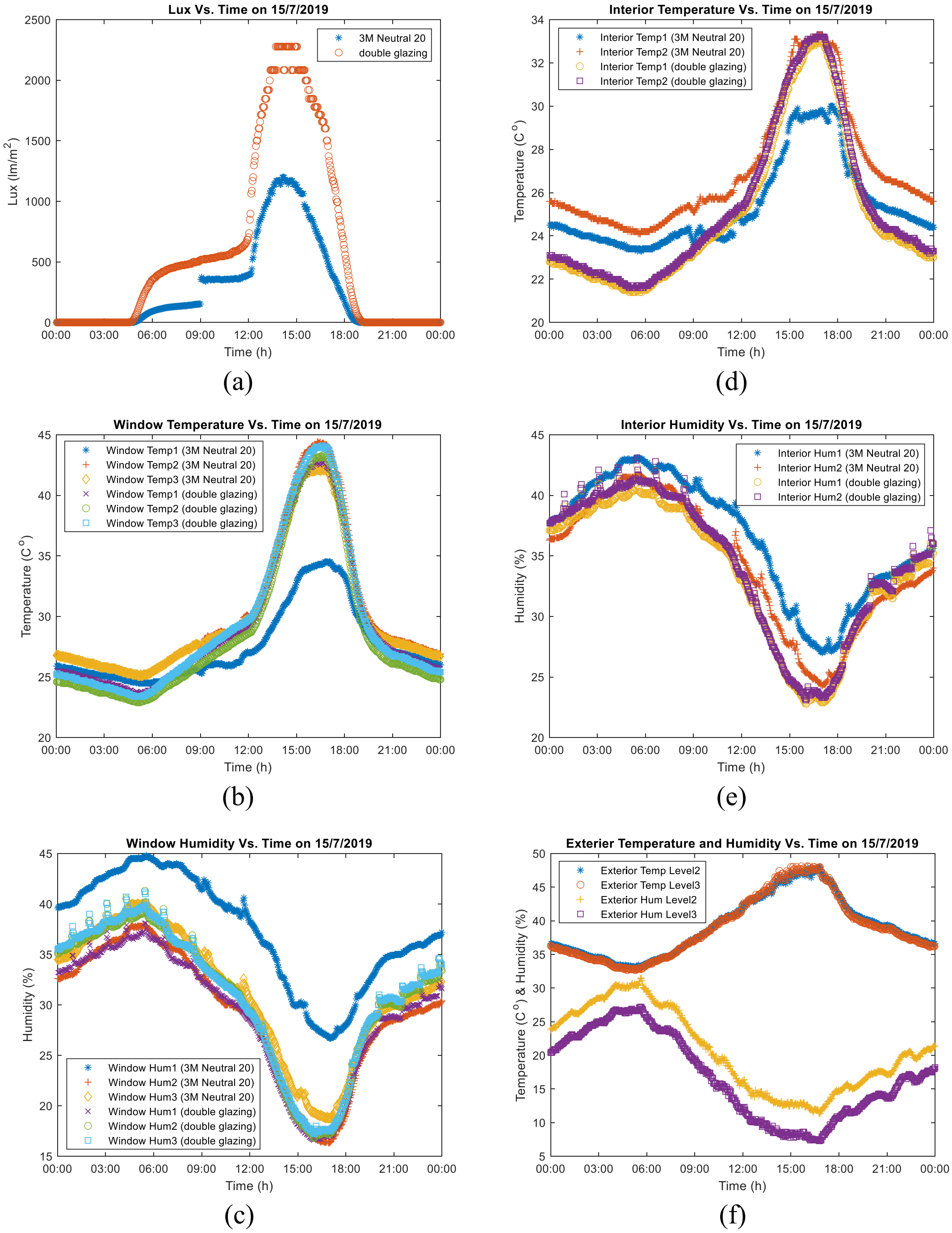


Fig. 11 Thermal-solar properties of two offices with and without window films 3M Neutral 20 on 15 July 2019

Figure 13d shows that the window temperature was higher in the office with window film by maximum 4 °C in peak hot hours of the day, although humidity levels remain similar magnitudes for both offices (see Fig. 13e). As shown in Fig. 13f, the exterior temperature variation for both offices show similar trends with a maximum temperature of 53 °C at 5:00 pm, although level 2 shows higher humidity of about 5%.

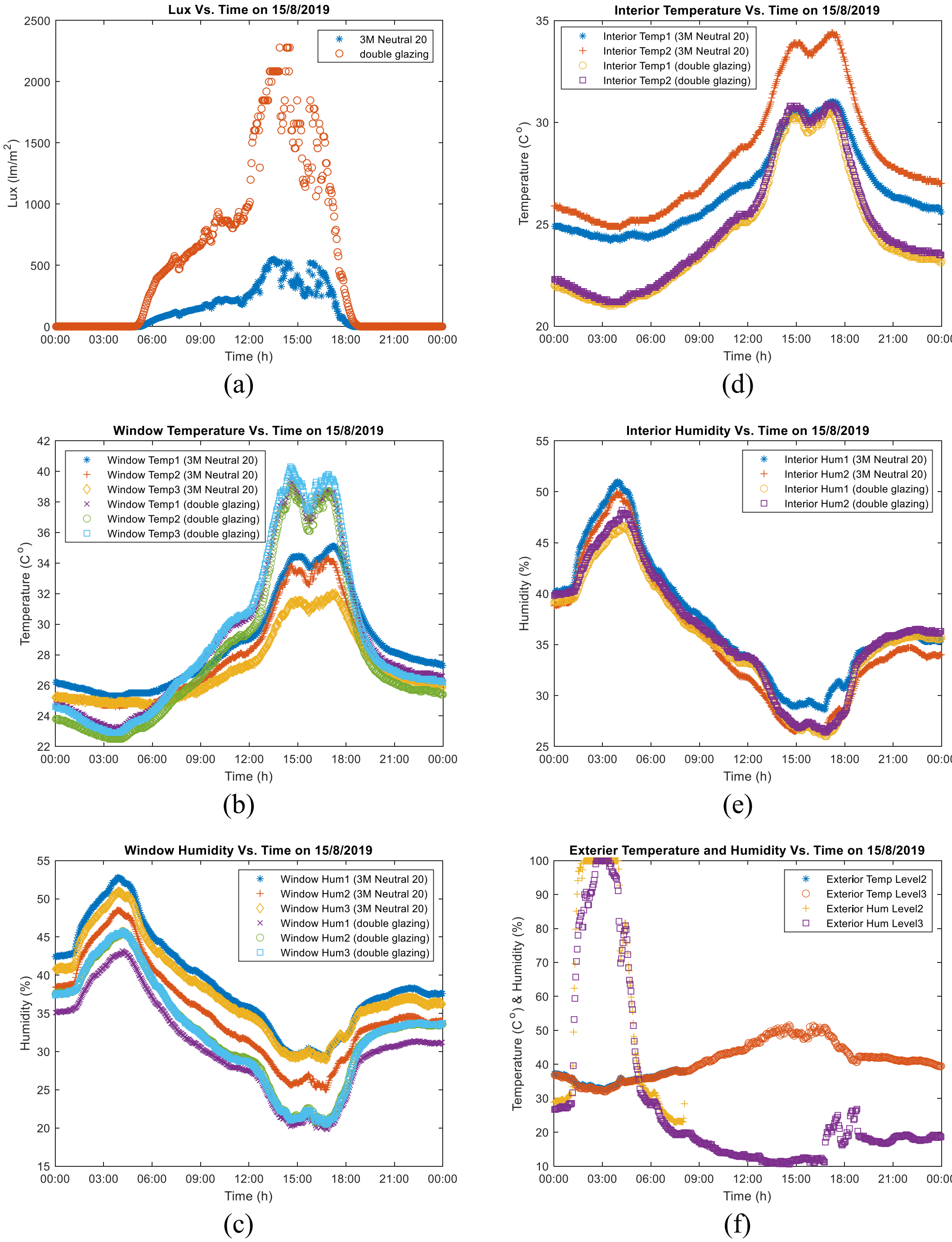


Fig. 12 Thermal-solar properties of two offices with and without window films 3M Neutral 20 on 15 August 2019

In 15 June 2019, the results in Fig. 13 show that temperature and humidity measurements can be dependent on local positions of the installed sensors, but in overall, the 3M Neutral 70 window films improved marginally luminous in peak hot hours of the day, but temperature and humidity of the office with window film shows improvements, i.e., minimum 2 °C cooler and 2% more humid in all hours of the day.

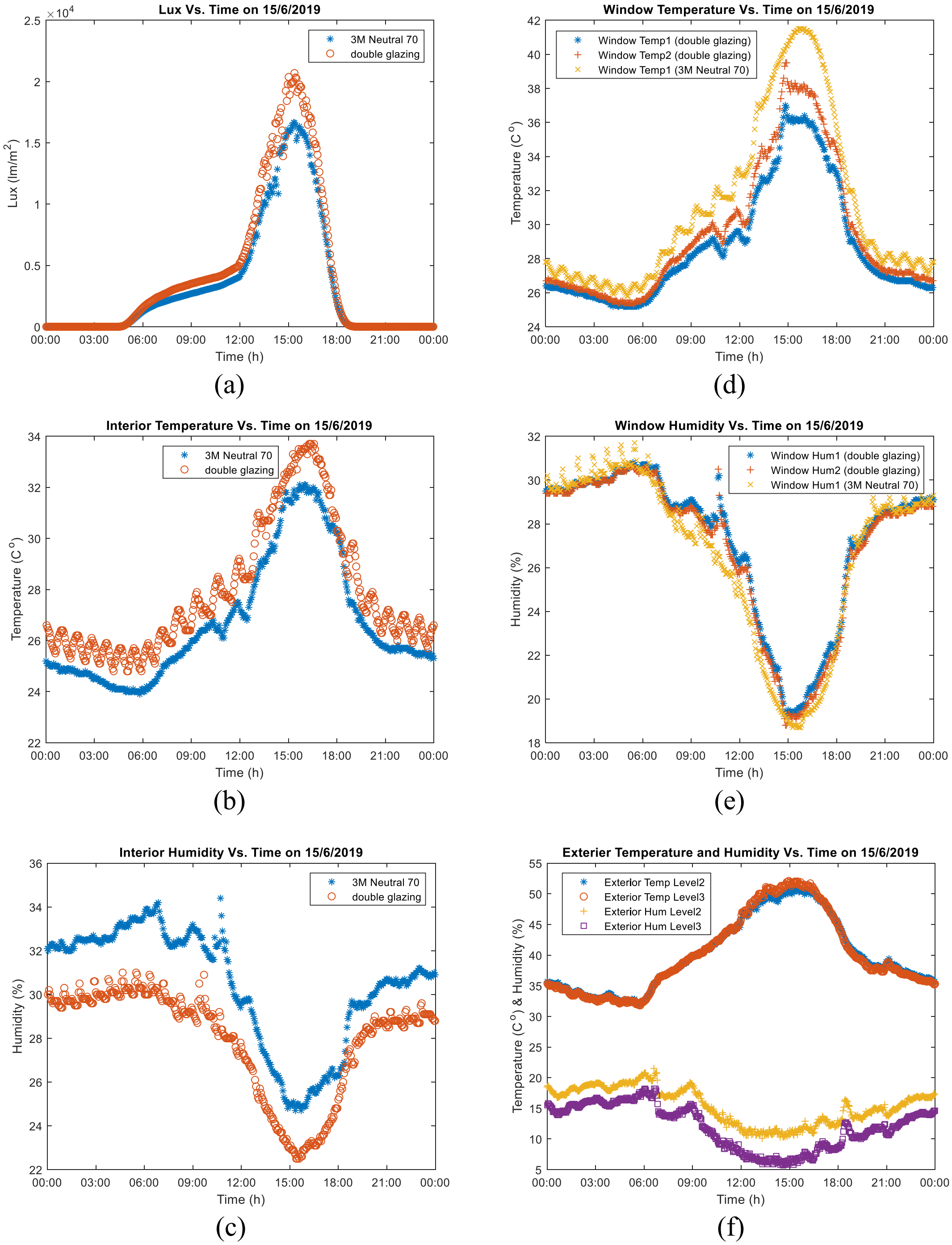


Fig. 13 Thermal-solar properties of two offices with and without window films 3M Neutral 70 on 15 June 2019

Results for 15 July 2019

Figure 14 shows the results for the offices with and without window film type 3M Neutral 70 in 15 July 2019. Lux measurements by BH1750 sensors show marginal reduction of luminous in the office with window films (Fig. 14a). Figure 14b shows that the interior temperature in the office with window film is warmer from 00:00 to 10:00 am and 19:00 to 00:00 pm by a maximum of 2 °C, while the room

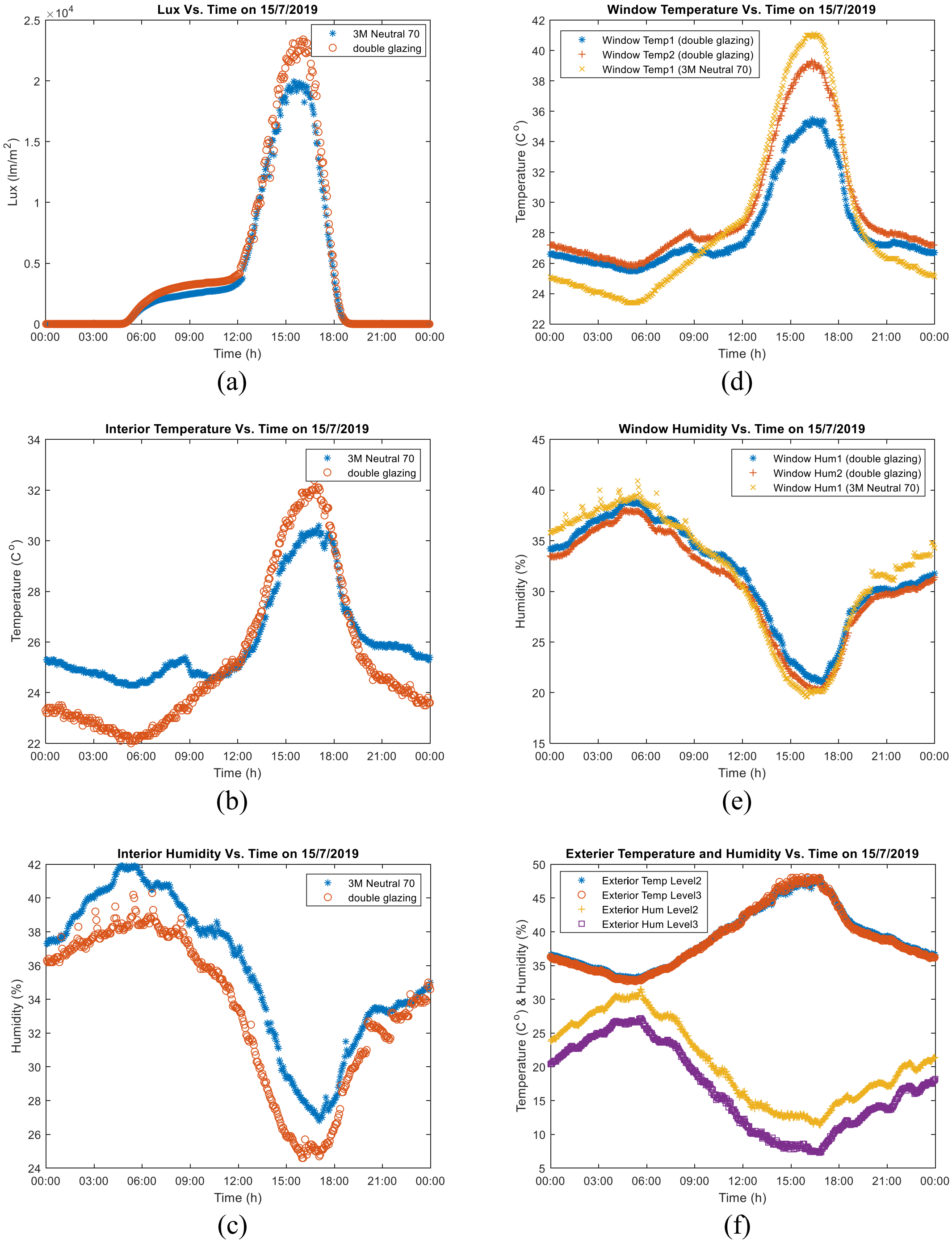


Fig. 14 Thermal-solar properties of two offices with and without window films 3M Neutral 70 on 15 July 2019

have the same temperature or lower temperature of 2 °C in the peak hot hours from 3:00 to 6:00 pm. The humidity level in the office with window film remains higher by 2% in all hours of the day (see Fig. 14c). Window temperatures of the office with window film are marginally lower in off-peak hot hours of the day and slightly higher in peak hot hours (see Fig. 14d). No noticeable changes can be observed in humidity levels of two offices (see Fig. 14e). Exterior temperature and humidity on level

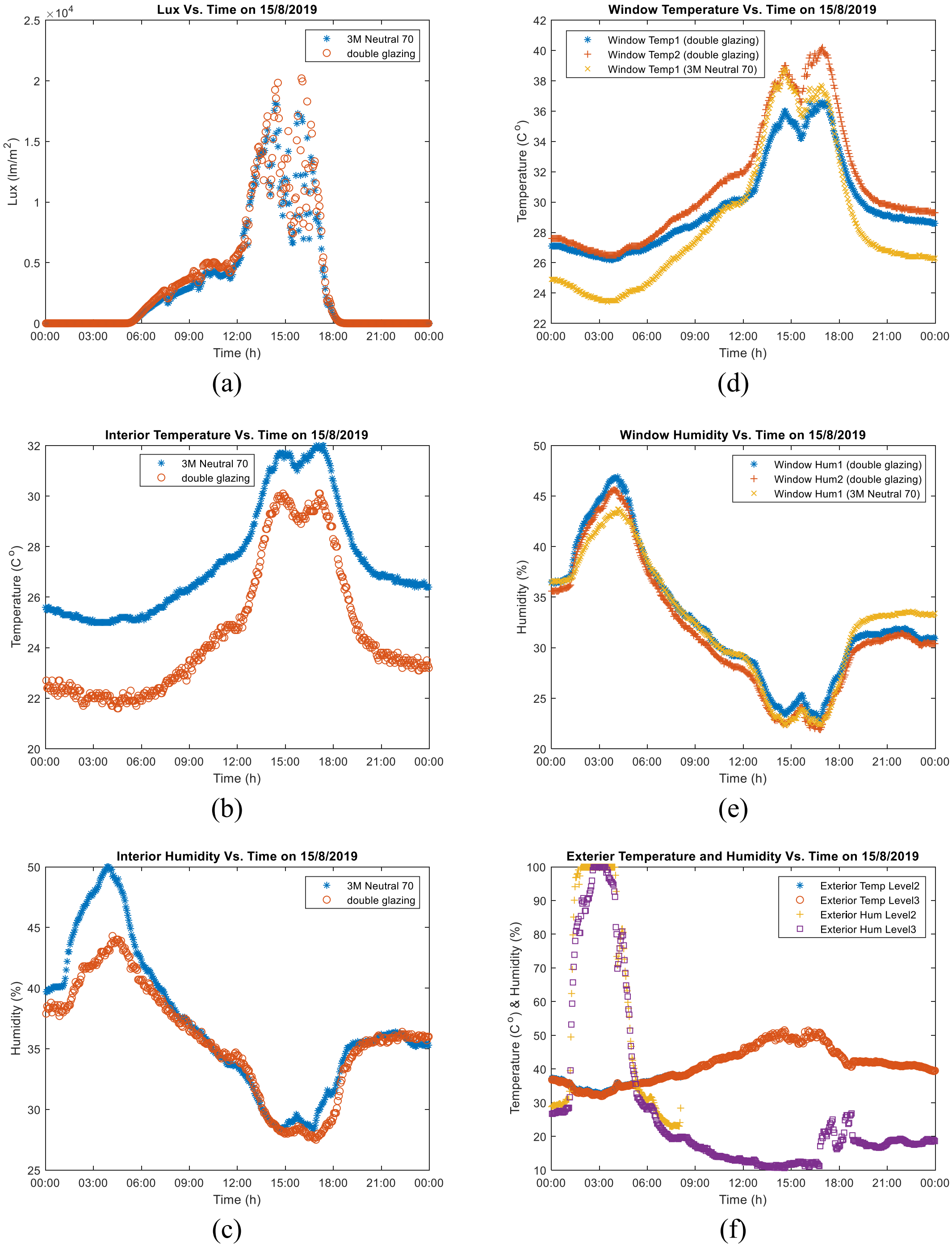


Fig. 15 Thermal-solar properties of two offices with and without window films 3M Neutral 70 on 15 August 2019

2 and level 3 are compared in Fig. 14f. Both levels show identical temperature trends although slightly higher humidity is observed in level 2.

Results for 15 August 2019

Figure 15 summarizes the thermal and solar measurements for two offices with and without 3M Neutral 70 window films during 15 August 2019. Lux measurements were scattered during the day although slightly lower for the office with window films (see Fig. 15a).

As shown in Fig. 15b, the interior temperature was higher between 2 and 3 °C in the office with window films throughout the day compared with office without window films. Although the humidity only increased in the early hours of the morning (see Fig. 15c). Surprisingly, the window temperature in the office with window film was colder for most of off-peak hot hours by 3 °C as shown in Fig. 15d. The variation of humidity from sensors on window does not show noticeable changes (see Fig. 15e). The exterior temperature and humidity of both offices were nearly identical as shown in Fig. 15f.

Results on 15 August 2019 using 3M Neutral 70 show that the selected window film cannot be efficient in all days and months of the year even with lowest heat rejection using this class type of window film. This can be related to the cumulative effects of preserving temperature in the room with window films that prevented heat loss from the office during early morning and night hours. Additional factors can be related to the fact that the offices with and without window films were not identical in terms of available furniture, equipment, and also occupant habits. Each floor AC system operated independently which can marginally affect the outcome of this research.

Concluding remarks and future works

The electricity demand for AC systems accounts for about 70% on peak load and over 45% of the annual electricity production in Kuwait (KEO 2019). Global warming is a critical international issue that can be addressed by energy saving and reducing in CO_2 footprints in residential buildings. Therefore, it is absolutely necessary to examine all possible methods to improve energy efficiency of buildings and to protect the environment. Window films can obstruct over 76% of solar rays with 99% of UV waves which can improve energy efficiency of buildings by reducing light luminous penetration and hence heat rejection in hot months. Moreover, window films may increase thermal comfort for residents of buildings prohibit harmful UV rays to support human health in Kuwait. Lowering glare and providing fade protect interior furniture from being deteriorated. In this research, the energy saving potential of two types of window films are investigated for office building in ACK (Australian College of Kuwait) in Kuwait through experiments.

Experimental measurements had been successfully carried out on 4 offices in the ACK building with two types of 3M Neutral 20 and 3M Neutral 70 window films. The results are presented for the months of June, July, and August in summer of 2019 in Kuwait. Conclusions of this study can be drawn as follow:

- The offices with window films usually possess 5 to 10% higher humidity compared with offices without window films.
- The offices with window films usually possess lower temperatures within 2 to 5 °C compared with offices without window films.
- The cumulative effects of preserving temperature in the offices with the window films may have opposite effect of preventing heat loss in the evenings.
- The lux intensity was reduced applying window films particularly on peak solar radiation of the day.

Research continues by calibrating and validating a simulation software to investigate the annual performance of the studied window films in terms of energy saving and CO_2 footprint reduction.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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