Thermal Loss Reduction Using a Ventilated Double-Glazed Window for Commercial Buildings in Average-Climate Environments

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Abstract— **The power consumption of buildings is exacerbated in modern societies. The most effective load in buildings is heating and cooling systems. Numerous studies have been done on energy saving for buildings recently. Windows are one of the most thermal loads that cause the loss of heat from inside to outside a room during winter. This paper demonstrates an alternative insight into the use of double glazed windows in average climate environments. The proposed system uses an air inject system to impact the heat transfer properties of the window considering the trade-off between the heating load energy saving and air injection power consumption. The theoretical analysis showed a reduction of 52 % in the thermal loss of the window, in addition to a declination in the heat transfer coefficient of the window from 3.5 to 1.8 W/m^{2}K. Consequently, an energy saving of 19 % in the heating capacity has been achieved.**

Keywords—ventilated window, energy saving, double-glazed window, thermal loss reduction, smart building

I. Introduction

With the increase of energy consumption in buildings, numerous studies have been focused recently on energy saving in buildings. In modern cities, the energy consumption of buildings becomes higher than transportation and industry sections. In China, the energy demand of buildings is 28.6% of the total energy consumption [1]. In addition, the International Energy Agency (IEA) stated that the buildings that are used for accommodation purposes required 20% of the overall energy consumption in Japan, China, Russia, India, and the United States [2]. In 2013, a study revealed that 40% of energy consumption in Taiwan goes to commercial and residential buildings [3]. The energy department in the United States stated that the energy consumption of buildings in industrial countries can reach 40% [4], [5].

The energy consumption of a building is influenced by different parameters. A study shows the impact of opting of the glazing type on the power consumption of a modelized energy model, 40% of energy consumption was reduced, in addition, the emission of carbon dioxide was 30% degraded [6], however, for previously constructed buildings, it is costly to replace the glazing. One more research emphasized that glazing type, the orientation of the windows, and the dimension of the glazing should be considered altogether in the design of the glazing to achieve an optimum power performance [7], but once the construction is finished, it will be impossible to change the orientation of the building.

Energy consumption is also related to the window-to-wall ratio (WWR) of the glazing, based on some researches, the capacity of the heating and cooling systems required for a building is directly proportional to the WWR ratio [8], [9]. Another study considered the impact of various WWR in four directions in Lebanon. The outcome showed a considerable influence of WWR on the annual energy consumption [10]. Similar to building orientation, WWR ratio should be considered at the earlier stage of the construction, else, it will be difficult and costly to modify after construction.

The techniques used to shade the buildings also have a big impact in determining the power consumption as stated in [11], [12]. Window shading causes a reduction in the amount of daylight inside the building, as a result, more artificial light is required. A study revealed that since the geographical location of the building determines the amount of solar radiation and climate temperature, therefore, the location also contributes to the energy consumption [13], however, it is not possible always to rely on the location to reflect a positive impact on the consumption as it is a non-selectable feature.

Some studies have been focused recently on the influence of using semi-transparent photovoltaic (STPV) systems on energy saving [14]–[17]. For example, 43% energy saving has been realized in Brazil by Leite and Wanger after integrating the semi-transparent PV panels with a model building [18]. Another study by Ng et al., 16.7 – 41.3 % energy saving has been accomplished in Singapore by utilizing STPV panels as a window with a window-to-wall ratio of 70 – 100 % [19]. Another study investigated the advantage of integrating the STPV panels to lighting up the public tunnels. An annual energy saving in lighting loads of 60% has been achieved, in addition to a 7% reduction in overall consumption [20]. In general, STPV panels have a shading effect due to the low transparency, consequently, artificial light should be used to compensate for the reduction in the daylight access to the buildings.

Another recently developed technique is suspended particle device (SPD) opaque/transparent thin film, the transparency of this film can be changed by applying alternating power. Aritra Ghosh et al. concluded that attaching an SPD layer to a double-glazed window could decrease the overall heat transfer coefficient to 1.99 W/m^{2}K [21]. In contrast, SPD films lessen the transmission of windows, also requires additional excitation power.

A validated novel design has been introduced by Behrouz Nourozi et al. to minimize the thermal conductivity of the window. The new model has an Argon-filled double-glazed window, in addition, it is sandwiched by another two coated glazing panes. A heat exchanger is employed to provide warmed air to the window. Also, the wasted warm air of the building is fed to the heat exchanger, this increases the efficiency of the system. The simulation showed that if the air temperature supplied by the heat exchanger is more than the room temperature, the U-value of the window could be less than 0.65 W/m^2.C [22]. However, the additional components in the new design add more complexity to the structure, which will inflate the installation cost. On the other hand, the author emphasized that the system should be injected by the wasted heated air of the building, but, if the warm air is restored from a humid or a fumy area, the kitchens, for instance, will be necessary to add a dehydration unit and a special filter to absorb the humidity and to purify the air before injecting it into the heat exchanger. Also, this requires additional infrastructure like pipes and fans to be equipped for the building.

A study introduced a phase change material ventilated window, the window has been suggested for pre-heating/pre-cooling use. The study concluded that when the window works in heating mode, the temperature of the inlet air is raised by 2C° along 12 hours in the daytime, in addition, when it works in cooling mode, the temperature of the inlet air temperature decreased by 1.4C° along 7 hours in daytime [23]. Other researchers utilize the fresh air or warmed exhausted air to be injected into the double-glazed window (between the panes), this modification helps in reducing the heat transfer coefficient of the window. Lago et al. [24] and Zeyninejad et al. [25] used a solar reflective film with a double-glazed window. The thermal performance of the proposed system has been evaluated. Lago et al. concluded that a spacing of 25 mm between the panes is the best fit to achieve the lowest heat loss during summer. A comparison has been made by Zhang et al. [26] to show the contrast in the performance of a normal triple-glazed and triple-glazed exhaust window. The latter window works in heating/cooling modes and uses the exhaust air from the room to be injected into the window. The study reveals that compared to the conventional window, the exhaust window has the potential to reduce the heating and cooling consumption to 50.1% and 25.3% respectively. Michaux et al. [27] investigated the thermal performance of a triple-glazed airflow window and then compared it with conventional double-glazed and triple-glazed windows. The result showed declination in the heating loads of 5% during night and 90% during daytime. Fifteen windows with different types have been placed in an area by Liu et al. [28]. They evaluated the energy performance of the windows and the thermal comfort in the space. The study concluded that using ventilated windows can enhance thermal comfort and reduce the consumption of heating and cooling loads. Another design suggested by Lollini et al. [29], a dynamic glazing system that responds to the outdoor environmental loads. The factors that have an effective influence on the performance of the window like U-value, g-value, spacing airflow thickness, and airflow rate to achieve optimum performance in various weather conditions.

The previously recalled papers used different sources to inject the air into the gap of the window, some of them preheat the fresh air from the external environment before directing it to the room, while other studies exhaust the air of the room to outdoor environment through the gap to heat the panes during winter or cooling them during summer. In some regions, flowing of air from outdoor environment to inside a room through the gap of the window has a negative impact. For instance, in tropical regions where the humidity is high most days of the year, the humidity can reduce the comfort vision through the window, also, adding more maintenance requirement, furthermore, additional power will be needed to restore the desired level of humidity. Moreover, the cities that are influenced by a dusty atmosphere due to being close to a desert, additional filtration devices should be added to eliminate the impact of the dust on the window and the internal environment. Therefore, it is necessary to take the purity of the air utilized in ventilated windows into consideration, to avoid more complexity and cost in the systems.

This paper proposed an improved low-cost double-glazed window system to minimize the thermal loss and then the total energy consumption for heating in a Façade building. An experimental investigation has been carried out on a small-scale room with a double-glazed window and air inject arrangement. The ventilated indoor air has been recycled to circulate the warmed conditioned air of the room within the window panes in a controlled manner to achieve different U-value and heat transfer. The purpose of this modification is to raise the temperature of the internal pane, to minimize the heat loss due to the conduction and convection through the window during winter. The proposed system provides a less complexity/cost ventilated window for the average climate countries, as it does not require a complex ventilation system. In addition to earlier research on active dynamic windows [30], the present solution transforms the window to an energized part in the envelope of buildings instead of the conventional inactive windows, as a result, achieving minimal consumption of heating loads and enhance the thermal comfort in the internal environment.

II. Materials and Methods

A. The proposed system

Fig. 1 demonstrates the proposed system to reduce the heat loss in the double-glazed window. The warmed air in the room will be recycled and circulated between the glazing layers. An air pump is employed to draw the warmed air from the room and inject it in the bottom of the window via a check-valve. As a result, the air drifts toward another check valve fixed at the top of the window and returns to the room. The system operates in three modes: (1) when the air between the panes is kept without circulation, the window acts as a conventional double-glazed window, (2) when the air between the panes is exchanged with the warmed room air at different times or (3) continuously, in case 2 and 3, the window will be converted to the forced ventilation mode. The three modes are discussed and demonstrated in detail during the implemented

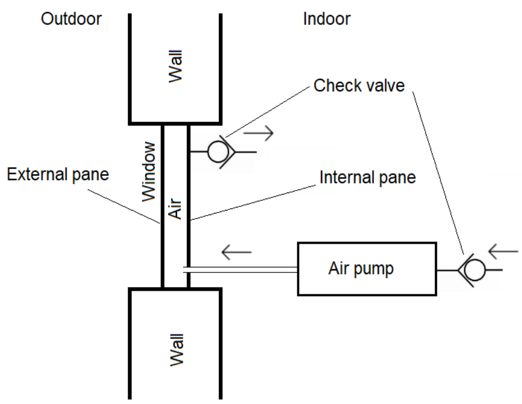

Fig. 1. The proposed integrated double-glazed window

experiments in the next sections, in addition to how different cases affect the thermal performance of the window.

B. Methodology

Fig. 2 shows the research method, which is used to process the work, validate the experimental model, and evaluate the experimental outcome. Before conducting the experimental investigations for the case under consideration, a proof of concept exercise was carried out. The experimental test room, using the traditional double-glazed window, has been modelled by the commercial DesignBuilder software. The validation of the established model and the experimental setup will provide a proper reference setup for testing the proposed system and also will validate the energy results of the experimental setup when the proposed system is deployed. It is worth mentioning here that the software does not have the options to model the proposed system. The initial conditions and other input parameters are obtained from the field and the lab measurement. Furthermore, the mathematical model of the heat source used in the experimental test room should be created. Finally, the experimental result will be employed to fulfil energy and heat transfer (U-Value) calculations, as well as to evaluate the performance of the system.

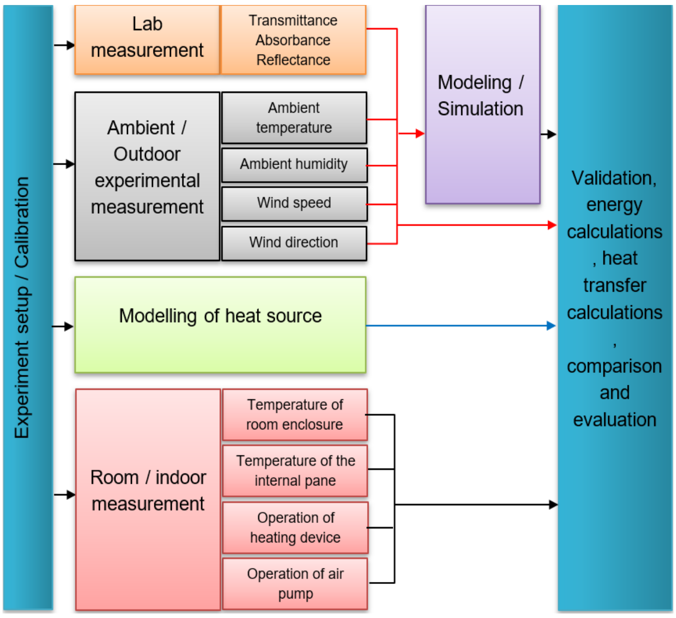

Fig. 2. Research method

C. The test room

In Fig. 3 a test room is placed inside a bigger box, the space between the room and the outer box represents the atmosphere. Thus, the experiment can be done in a controlled environment. The temperature of the atmosphere will be controlled by an external cooling system. Fig. 3 B shows a cross-sectional area for the experimental setup, an external cooling system was used to inject the cooled air into the outer box, the air spreads in the atmosphere space and then is exhausted from small holes to the outside environment keeping it at a specific temperature. The advantage of the outer box is to provide a dark environment for the test room, this helps to investigate the thermal loss through the window without the effect of solar radiation [31].

In Fig. 4, where the experimental setup is shown, the test room, and the outer box have been made from an insulated board. The board consists of a thick layer of polystyrene with thermal conductivity of 0.046 W/m.K, the polystyrene is sandwiched by two thin layers of steel. A 7-inches hose is attached between the front side of the outer box and the external cooling device.

The heat source used in the experiments is a conventional tungsten-based heater. It utilizes a tungsten wire with an electrical resistivity of 168 Ω (at room temperature 25 C°) placed inside a pottery base with a mass of (0.53 Kg) and heat capacity of (0.85 kJ/kgC°).

Table 1 provides details about the test room structure, double-glazed window, and the outer box, as well as the materials used to build them. A spectrometer was used to provide the optical characteristics of the window glazing.

D. Simulation and validation

An experiment has been conducted to validate the test room; the profile of the atmosphere temperature shown in Fig. 5 has been applied to the test room, the heat source was OFF. Simultaneously, the heat sensor recorded the room temperature, while the weather station gathered the atmospheric conditions: atmosphere temperature, humidity, pressure, and wind speed.

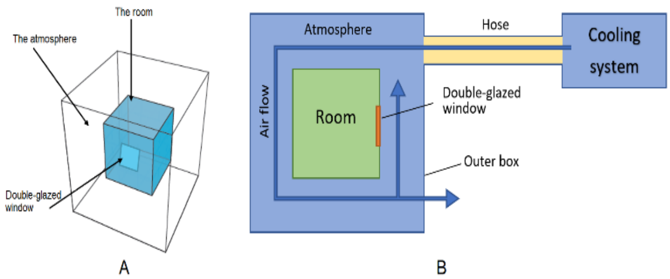

Fig. 3. (A) The test room with the outer box (B) Cross-section area for the test room with the cooling system

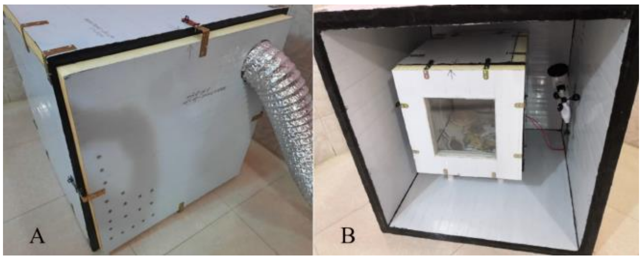

Fig. 4. The experimental setup (A) The outer box (B) The test room inside the outer box

TABLE 1. SPECIFICATIONS OF THE TEST ROOM AND THE OUTER BOX

Item	Part	Details
Board	***Polystyrene thickness***	4.9 cm
	Steel thickness	0.05 cm
Wall dimension of the room		55x55 cm^2
Wall dimension of the outer box		100x100 cm^2
Double glazed window	***area***	30x30 cm^2
	WWR	44%
	Glazing type	Clear
	Glazing thickness	0.4 cm
	Thermal conductivity for the glazing	0.9 W/m.K
	Glazing transmittance	0.83
	Glazing reflectance	0.12
	Glazing absorbance	0.039
	Depth of the air layer	2 cm
	Outside reveal depth	0 cm
Room dimension		45x45x45 cm^3
Outer box dimension		90x90x90 cm^3
Heat source	***AC input voltage***	225 V
	Tungsten wire resistance at 25 C°	168 Ω
	Mass of the pottery	0.53 kg
	Heat capacity of the pottery	0.85 kJ/kgC°

On the other hand, the DesignBuilder EnergyPlus software has been employed to model the test room based on the parameters mentioned in Table 1. Also, the weather data file (required for the simulation) has been prepared to match the experimental conditions; this includes the data measured by the weather station. For the solar and illuminance data, they are set to zero as the experiment has been executed in a dark space (inside the outer box).

The room temperature has been obtained by the simulation and experimentally as depicted in Fig. 5. The result shows that the simulated and experimental curves are responding according to the variation of the atmosphere condition. Furthermore, the average difference between the simulated and the experimental room temperature is 0.2 C°. Therefore, it is possible to assume that the experimental test room is a valid reference for further consideration when the proposed system is deployed.

E. Experiment scenarios

The experiment has four scenarios to be executed by the test room, a logging and a control system were created. The execution time is 10 hours per scenario, and the data has been taken with a time step of ten seconds. The key point for each experiment is the reference temperature used by the controller to turn the air pump on, with a flow rate of 2000 cc/min. The target is to exchange the air between the panes of the window with that of the room. This should be done by the air pump every time the inner pane temperature raises to a reference temperature. Based on the given specification of the double-glazed window, the volume between the two panes is 1800 cc.

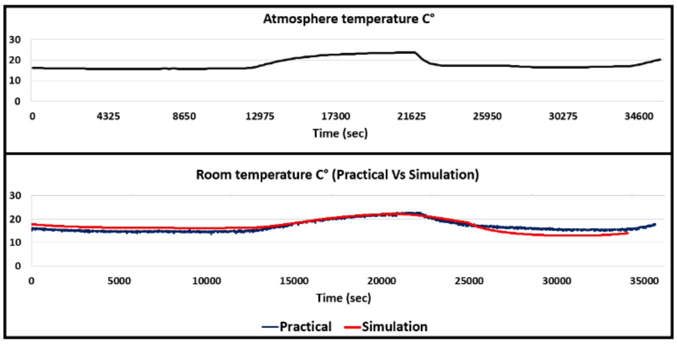

Fig. 5. The validation of the experimental room

TABLE 2. EXPERIMENT SCENARIOS

Experiment	Reference (inner pane) temperature C°	Operation mode of the window	Target range of room temperature C°	Execution duration (hours)
1st	---	Conventional double-glazed (reference window)		
2nd	19.5 C	Forced ventilation	22-27	10
3rd	21 C	Forced ventilation		
4th	22.5	Forced ventilation		

Therefore, the operation time required by the pump each time is 0.9 min or 54 sec. On the other hand, the operation of the heat source is controlled to maintain the room temperature with a range of 22 to 27 C°. The experiment scenarios are shown in Table 2. The window works as a conventional double-glazed window in the first experiment, as the air pump is off, this case will be considered as the reference in energy and heat transfer calculations, while it works in forced ventilation mode in experiments 2, 3, and 4.

Regarding the values of the reference (inner pane) temperature, they have been chosen experimentally, to make the pump works from OFF to ON along the experiment. For instance, while the reference temperature raises, the internal pane requires longer time to heat up to the setpoint, therefore the operation duration of the pump becomes longer accordingly. This will help to investigate the minimum operation period for the pump that leads to the maximum possible energy saving.

F. Heat transfer model

The experimental test room has a heating source to warm the room. The generated heat should be transferred to the available different parts of the room, which act as thermal loads. For instance, a part of the generated heat warms the internal environment and the pottery, while the residual heat is dissipated by the walls and the glazing of the window. However, the equations introduced in this part are as suggested by Ghosh et al. [21], have been modified to include the heat absorbed by the pottery according to the given heat system as shown below.

$$Q_{Tungsten} = Q_{pot} + Q_g + Q_{room} + Q_w \qquad (1)$$

Where:
$Q_{Tungsten}$ is the heat generated by the tungsten wire (W), Q_{pot} is the heat stored in the pottery (W), Q_g is the heat transfer through the glazing (W), Q_{room} is the heat stored inside the room (W), and Q_w is the heat transfer through inside and outside air convection and conduction through the insulation board. After solving (1) to find the value of Q_g, then the U-value of the glazing U_g is given in (2):

$$U_g = \frac{Q_g}{A(T_{in} - T_0)} \qquad (2)$$

Where: A is the glazing area (m^2), T_{in} and T_o are the room and outdoor ambient temperature respectively in (C°).

III. RESULTS

The four scenarios in Table 2 have been executed, Fig. 6 to 9 show the results of experiments 1 to 4 respectively,

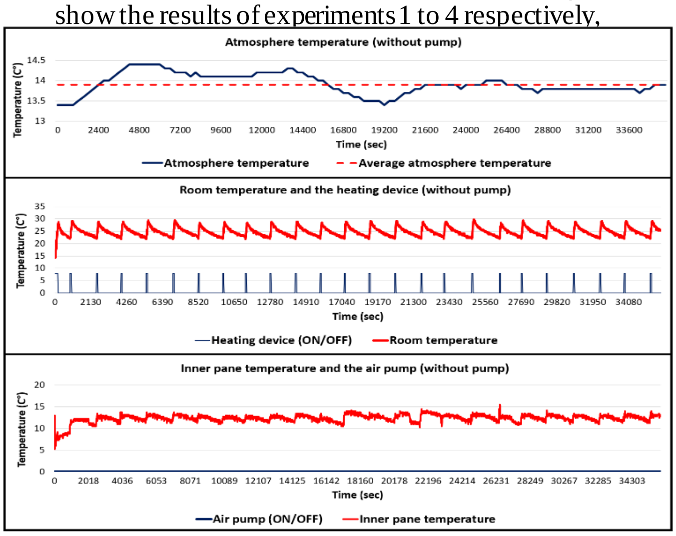

Fig. 6. The result of experiment No.1 (the pump is OFF)

including the atmosphere temperature, room temperature, inner pane temperature, and the operation of the heat source and the air pump. In Fig. 6, the pump is off over the experiment time as for scenario 1, and the average atmosphere temperature applied to the test room is 13.9 C°. The heating element needed to run 25 times in the 10 hours, with an accumulated operation period of 1830 sec. The room temperature fluctuated within the set range (22-27 C°), with an average of 24.77 C°. The rising intervals represent the heating time (while the heat source is on), while the falling intervals represent the cooling time (while the heat source is off). Thus, the result shows that the average heating time is 70 sec, while the average cooling time is 1337 sec. Finally, the temperature of the internal pane is varied with the room temperature accordingly, with an average value of 12.4 C°.

In Fig. 7, results of scenario 2, the average atmosphere temperature applied to the test room is 13.9 C°. The heat source requires to operate 26 times, with an accumulated operation period of 1710 sec. The room temperature fluctuated within the set range (22-27 C°), with an average of 24.43 C°. The result shows that the average heating time is 65.8 sec, while the average cooling time is 1242 sec. The accumulated operation period of the air pump is 7128 sec.

The temperature of the internal pane is varied with the room temperature accordingly, with an average value of 19.47 C°.

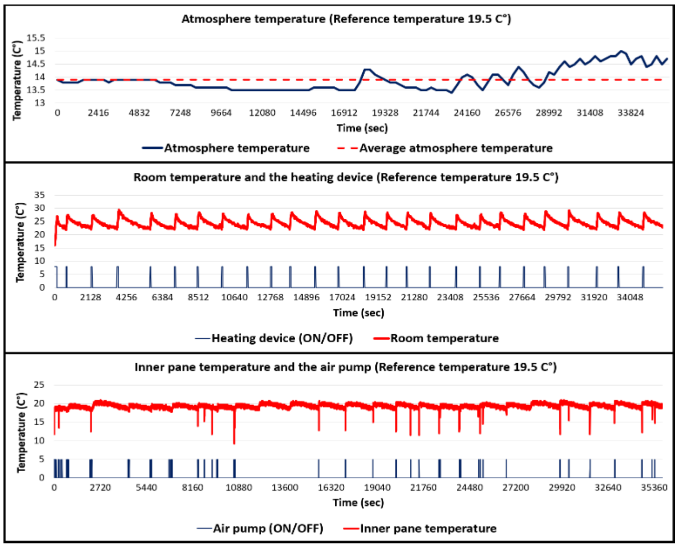

Fig. 7. The result of experiment No.2 (reference temperature 19.5 C°)

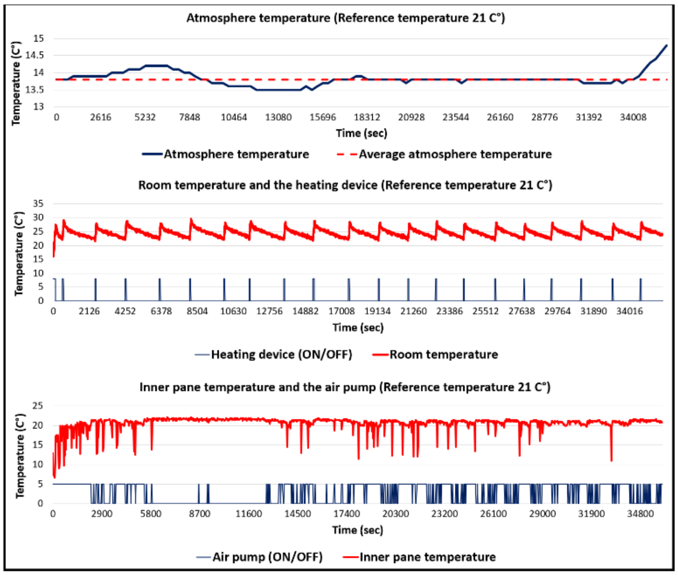

Fig. 8. The result of experiment No.3 (reference temperature 21 C°)

In Fig. 8, results of scenario 3, the average atmosphere temperature applied to the test room is 13.8 C°. The heat source requires to operate 21 times, with an accumulated operation period of 1350 sec. The room temperature fluctuated within the set range (22-27 C°), with an average of 24.5 C°. The result shows that the average heating time is 64.3 sec, while the average cooling time is 1564 sec. The accumulated operation period of the air pump is 29668 sec. The temperature of the internal pane is varied with the room temperature accordingly, with an average value of 20.65 C°.

In Fig. 9, results of scenario 4, the average atmosphere temperature applied to the test room is 13.9 C°. The heat source requires to operate 20 times, with an accumulated operation period of 1310 sec. the room temperature fluctuated within the set range (22-27 C°), with an average of 24.53 C°. The result shows that the average heating time is 60 sec, while the average cooling time is 1714 sec. The air pump operates all the time. The temperature of the internal pane is varied with the room temperature accordingly, with an average value of 22.33 C°.

Now, returning to (1) and (2) to estimate the average heat waste in the window Q_g and the heat transfer coefficient U_g

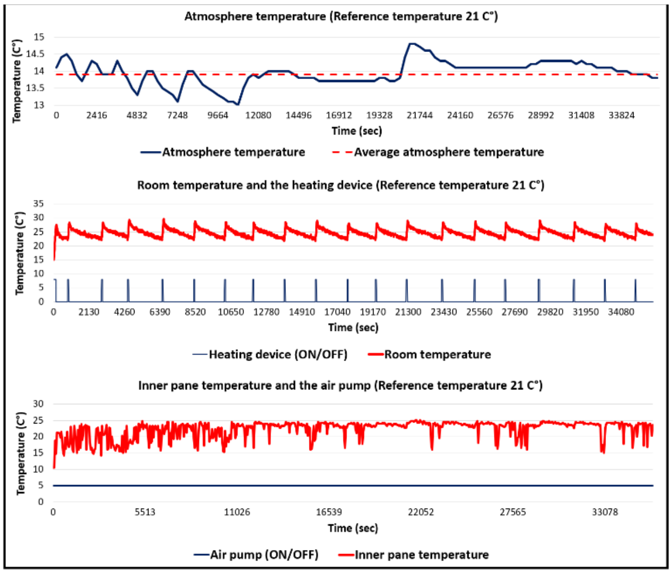

Fig. 9. The result of experiment No.4 (reference temperature 22.5 C°)

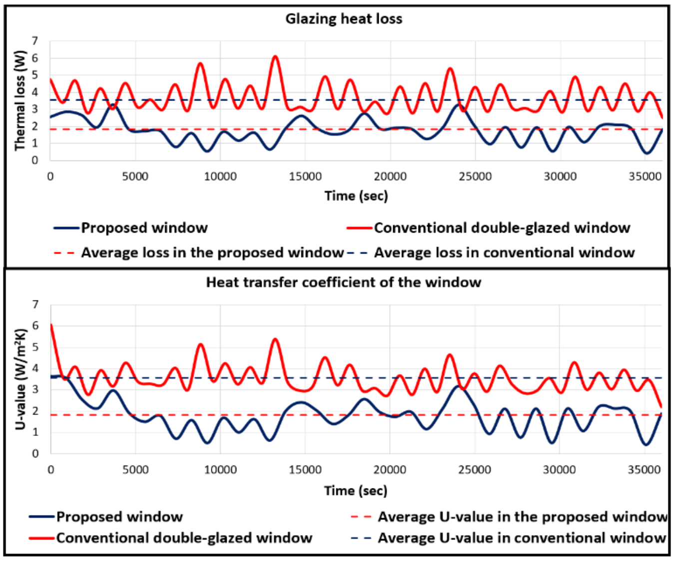

Fig. 10. Heat loss and heat transfer coefficient of the window

as depicted in Fig. 10.

When the pump is OFF, the average value of heat loss in the window is 3.7 W and the average value of the heat transfer coefficient is 3.56 W/m^{2}K. On the other hand, with a reference temperature of 22.5 C° the average value of glazing loss is 1.77 W and the average value of heat transfer coefficient is 1.82 W/m^{2}K.

IV. Discussion

In this study, the heat transfer due to conduction and convection in a ventilated double-glazed window has been analysed. A forced ventilation air system was used to warm the window by injecting the conditioned room air into the cavity of the window.

More statistics can be extracted from the experimental result to analyse the performance of the system. Table 3 lists the reference temperature and the average atmospheric temperature of the conducted experiments. Besides, the operation time for the heating device and the air pump is recorded.

For energy calculations, the electrical power consumed by the heating device (301 Watt) and the air pump (1.5 watt) is multiplied by the running period of the corresponding device.

TABLE 3. ENERGY CALCULATIONS OF THE FOUR EXPERIMENTS

Inner pane reference temperature C°	Average atmosphere temperature C°	Operation time for the heating device (sec)	Energy consumed by the heating device (Wh)	Operation time for the air pump (sec)	Energy consumed by the Air pump (Wh)	Total consumption (Wh)	Energy saving %
No pump	13.9	1830	153	0	0	153	-----
19.5 C	13.9	1710	143	7128	2.97	145.97	4.6
21 C	13.8	1350	113	29668	12.36	125.36	18
22.5	13.9	1310	109	35262	14.69	123.69	19

The total energy in each experiment has been determined in Wh, as well as the energy-saving with respect to the first reference case (the case of the conventional double-glazed window). The calculations refer to that the highest energy saving took place in the last experiment of (19%), with a reference temperature of 22.5C°. The result shows that while the reference temperature is raised, the running duration of the air pump was getting longer while it becomes shorter for the heating device, however, the effective power consumption is in the heat source, hence, the overall consumption becomes less. The extension of the operation time of the pump maintained a higher temperature in the cavity of the window, as a result, the difference between room temperature and inner pane temperature was decreased from 12.37 C° (in the conventional window) to 2.2 C° for the ventilated window. Simultaneously, since the room temperature is controlled within a specific range, the heat loss of the glazing to the outside of the room was declined. Under this condition, the thermal conductance of the window is decreased, as a result, the room becomes able to maintain the desired temperature range for a longer period.

Table 4 and Fig. 11 demonstrate a comparison between the thermal performance of the conventional window in experiment 1 and the ventilated window in experiment 4. The result shows that the test room required less average heating time when it is equipped with the ventilated window, in addition, the span of cooling duration was longer. Furthermore, the calculations demonstrated that the glazing loss is minimized by 52%, as a result, the average value of the heat transfer coefficient was reduced correspondingly from 3.56 to 1.82 W/m^{2}K as shown in Fig. 11. Moreover, an annual energy saving of 0.25 MWh can be achieved in the heating load of the small-scaled test room. In the same manner, if a real-dimension room such as 6x5 m^2 and a height of 3 m is equipped with the proposed ventilated window, an annual consumption of 247 MWh will be saved, furthermore, for a building of 30 rooms, the annual energy saving will be 7.4 GWh.

The major change that led to enhance the thermal performance is increasing the velocity and the temperature of the air inside the cavity by the forced ventilation, this modification affects the rate of convective heat transfer in the gap of the window [22].

The proposed system showed that the heat transfer coefficient of the window is adapted to the set temperature of the inner pane, this is conditioned to the constancy of other factors related to the thermal performance. However, the present paper studied only the effect of heat transfer due to conduction and convection. For instance, solar radiation has an effective impact on the thermal performance of the window, the increase in outdoor temperature can reduce the temperature difference across the window, hence the overall heat glazing loss can be dropped.

TABLE 4. SUMMARY OF HEAT TRANSFER CALCULATIONS

Experiment	Conventional system	Proposed system
Average heating time (sec)	70	60
Average input power to the test room during the heating time (W)	14.69	13.1
Average cooling time (sec)	1337	1714
Average input power to the test room during the cooling time (W)	6.17	5.7

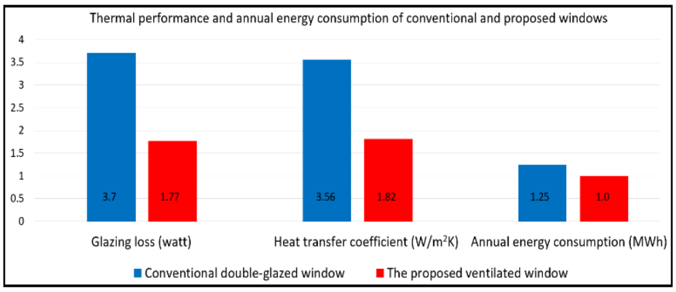

Fig. 11. Thermal performance and annual consumption for conventional and proposed windows

During the calculation of heat transfer coefficient according to (2), the average temperature values of the room and the outdoor within heating/cooling intervals have been considered, therefore, the values of heat transfer coefficient in Fig. 10 were a function of the glazing loss. However, the study did not examine other factors that affect the heat transfer through the window such as the flowrate/velocity of airflow.

V. CONCLUSIONS

The study introduced an alternative insight into the use of double-glazed windows in average climate environments. The warmed air inside the test room has been circulated between the window glazing panes. This produces adaptive heat transfer properties to the glazing and is responsive to the building room's temperature serving as an active smart component in buildings. The proposed system has been modelled and tested experimentally. The major outcomes are:

- The circulating of warm air between the room and the window continuously led to a reduction in the average difference between the room and inner pane temperatures.
- The thermal currents from the room to the outside environment through the window have been minimized.
- When the air pump runs continuously, the running time of the heating device falls by 28.4 %, keeping the same range of room temperature 22 C° to 27 C°.
- A maximum energy saving of 19% has been achieved in the heating consumption.
- The theoretical analysis of the heat transfer model showed a reduction of 52% in the thermal loss of the window, and declination in the U-value of the window from 3.5 to 1.8 W/m^2K.

REFERENCES

[1] H. W. S.G. Li, "Summarization of present building energy consumption and corresponding strategies in China," *Environ. Sci. Manag. 33(2)*, pp. 6–9, 2008.

[2] International Energy Agency, "Statistics and Data," 2018. https://www.iea.org/.

[3] J. Zemitis and A. Borodinecs, "Energy saving potential of ventilation systems with exhaust air heat recovery," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 660, no. 1, 2019, doi: 10.1088/1757-899X/660/1/012019.

[4] N. Lu, T. Taylor, W. Jiang, J. Correia, L. R. Leung, and P. C. Wong, "The temperature sensitivity of the residential load and commercial building load," *2009 IEEE Power Energy Soc. Gen. Meet. PES '09*, 2009, doi: 10.1109/PES.2009.5275654.

[5] Z. Jiang and H. Rahimi-Eichi, "Design, modeling and simulation of a green building energy system," *2009 IEEE Power Energy Soc. Gen. Meet. PES '09*, pp. 1–7, 2009, doi: 10.1109/PES.2009.5275755.

[6] A. Eljojo, "Effect of Windows Size, Position and Orientation on the Amount of Energy Needed for Winter Heating and Summer Cooling," *J. Eng. Res. Technol.*, vol. 1, no. 1, pp. 0–8, 2017, doi: 10.13140/RG.2.2.32424.47361.

[7] A. S. Muhaisen and H. R. Dabboor, "Studying the Impact of Orientation, Size, and Glass Material of Windows on Heating and Cooling Energy Demand of the Gaza Strip Buildings," *J. Archit. Plan.*, vol. 27, no. 1, pp. 1–15, 2015.

[8] A. M. A. Youssef, Z. J. Zhai, and R. M. Reffat, "Design of optimal building envelopes with integrated photovoltaics," *Build. Simul.*, vol. 8, no. 3, pp. 353–366, 2015, doi: 10.1007/s12273-015-0214-y.

[9] A. Cannavale, U. Ayr, and F. Martellotta, "Energetic and visual comfort implications of using perovskite-based building-integrated photovoltaic glazings," *Energy Procedia*, vol. 126, pp. 636–643, 2017, doi: 10.1016/j.egypro.2017.08.256.

[10] S. Saridar and H. Elkadi, "The impact of applying recent façade technology on daylighting performance in buildings in eastern Mediterranean," *Build. Environ.*, vol. 37, no. 11, pp. 1205–1212, 2002, doi: 10.1016/S0360-1323(01)00095-6.

[11] A. A. M. Ali and M. F. Ahmed, "Evaluating the impact of shading devices on the indoor thermal comfort of residential buildings in Egypt," *Proc. fifth Int. Conf. IBPSA-USA*, pp. 603–612, 2012.

[12] K. J. Chua and S. K. Chou, "Evaluating the performance of shading devices and glazing types to promote energy efficiency of residential buildings," *Build. Simul.*, vol. 3, no. 3, pp. 181–194, 2010, doi: 10.1007/s12273-010-0007-2.

[13] O. Aydin, "Conjugate heat transfer analysis of double pane windows," *Build. Environ.*, vol. 41, no. 2, pp. 109–116, 2006, doi: 10.1016/j.buildenv.2005.01.011.

[14] H. Alrashidi, A. Ghosh, W. Issa, N. Sellami, T. K. Mallick, and S. Sundaram, "Evaluation of solar factor using spectral analysis for CdTe photovoltaic glazing," *Mater. Lett.*, vol. 237, pp. 332–335, 2019, doi: 10.1016/j.matlet.2018.11.128.

[15] H. Alrashidi, A. Ghosh, W. Issa, N. Sellami, T. K. Mallick, and S. Sundaram, "Thermal performance of semitransparent CdTe BIPV window at temperate climate," *Sol. Energy*, vol. 195, no. November 2019, pp. 536–543, 2020, doi: 10.1016/j.solener.2019.11.084.

[16] H. Alrashidi, W. Issa, N. Sellami, A. Ghosh, T. K. Mallick, and S. Sundaram, "Performance assessment of cadmium telluride-based semi-transparent glazing for power saving in façade buildings," *Energy Build.*, vol. 215, p. 109585, 2020, doi: 10.1016/j.enbuild.2019.109585.

[17] R. Khalifeeh, H. Alrashidi, N. Sellami, T. Mallick, and W. Issa, "State-of-the-Art Review on the Energy Performance of Semi-Transparent Building Integrated Photovoltaic across a Range of Different Climatic and Environmental Conditions," *Energies*, vol. 14, no. 12, p. 3412, 2021, doi: 10.3390/en14123412.

[18] E. Leite Didoné and A. Wagner, "Semi-transparent PV windows: A study for office buildings in Brazil," *Energy Build.*, vol. 67, pp. 136–142, 2013, doi: 10.1016/j.enbuild.2013.08.002.

[19] P. K. Ng, N. Mithraratne, and H. W. Kua, "Energy analysis of semi-transparent BIPV in Singapore buildings," *Energy Build.*, vol. 66, pp. 274–281, 2013, doi: 10.1016/j.enbuild.2013.07.029.

[20] D. Sun, A. Athienitis, and K. D'Avignon, "Application of semitransparent photovoltaics in transportation infrastructure for energy savings and solar electricity production: Toward novel net-zero energy tunnel design," *Prog. Photovoltaics Res. Appl.*, vol. 27, no. 11, pp. 1034–1044, 2019, doi: 10.1002/pip.3182.

[21] A. Ghosh, B. Norton, and A. Duffy, "Measured overall heat transfer coefficient of a suspended particle device switchable glazing," *Appl. Energy*, vol. 159, pp. 362–369, 2015, doi: 10.1016/j.apenergy.2015.09.019.

[22] B. Nourozi, A. Ploskić, Y. Chen, J. Ning-Wei Chiu, and Q. Wang, "Heat transfer model for energy-active windows – An evaluation of efficient reuse of waste heat in buildings," *Renew. Energy*, vol. 162, pp. 2318–2329, 2020, doi: 10.1016/j.renene.2020.10.043.

[23] Y. Hu, P. K. Heiselberg, and R. Guo, "Ventilation cooling/heating performance of a PCM enhanced ventilated window - an experimental study," *Energy Build.*, vol. 214, p. 109903, 2020, doi: 10.1016/j.enbuild.2020.109903.

[24] T. G. S. Lago, K. A. R. Ismail, and F. A. M. Lino, "Ventilated double glass window with reflective film: Modeling and assessment of performance," *Sol. Energy*, vol. 185, no. April, pp. 72–88, 2019, doi: 10.1016/j.solener.2019.04.047.

[25] S. Zeyninejad Movassag and K. Zamzamian, "Numerical investigation on the thermal performance of double glazing air flow window with integrated blinds," *Renew. Energy*, vol. 148, pp. 852–863, 2020, doi: 10.1016/j.renene.2019.10.170.

[26] C. Zhang, W. Gang, J. Wang, X. Xu, and Q. Du, "Numerical and experimental study on the thermal performance improvement of a triple glazed window by utilizing low-grade exhaust air," *Energy*, vol. 167, pp. 1132–1143, 2019, doi: 10.1016/j.energy.2018.11.076.

[27] G. Michaux, R. Greffet, P. Salagnac, and J. B. Ridoret, “Modelling of an airflow window and numerical investigation of its thermal performances by comparison to conventional double and triple-glazed windows,” *Appl. Energy*, vol. 242, no. March, pp. 27–45, 2019, doi: 10.1016/j.apenergy.2019.03.029.

[28] M. Liu, P. K. Heiselberg, O. K. Larsen, L. Mortensen, and J. Rose, “Investigation of Different Configurations of a Ventilated Window to Optimize Both Energy Efficiency and Thermal Comfort,” *Energy Procedia*, vol. 132, pp. 478–483, 2017, doi: 10.1016/j.egypro.2017.09.660.

[29] R. Lollini, L. Danza, and I. Meroni, “Energy efficiency of a dynamic glazing system,” *Sol. Energy*, vol. 84, no. 4, pp. 526–537, 2010, doi: 10.1016/j.solener.2009.12.006.

[30] M. Casini, “Active dynamic windows for buildings: A review,” *Renew. Energy*, vol. 119, pp. 923–934, 2018, doi: 10.1016/j.renene.2017.12.049.

[31] T. Y. Y. Fung and H. Yang, “Study on thermal performance of semi-transparent building-integrated photovoltaic glazings,” *Energy Build.*, vol. 40, no. 3, pp. 341–350, 2008, doi: 10.1016/j.enbuild.2007.03.002.