Design, fabrication, and characterization of thermal and optical properties of nano-composite self-cleaning smart window

Mehdi Jafari Vardanjani1 · Mehdi Karevan2

Received: 10 February 2021 / Accepted: 11 September 2021 / Published online: 11 October 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
Polymer-based smart windows have recently received attention due to their capabilities in energy consumption reduction. A smart window provides desired optical properties when heated/cooled by using solar energy when the ambient temperature requires regulation. Thus the main axis of the current paper is the design and fabrication of such a smart element which operates according to temperature and energy efficiency requirements. The window in the proposed design operates the way that the percentage of light transmission depends on the presence of nanofluid between the two walls and refractive index conformity between the fluid and the polymeric walls; Therefore the percentage of light transmission will be at its minimum value (45%) in the absence of fluid and it will be at the maximum value (80%) at the presence of fluid. The fundamental steps of the present design includes design, fabrication, and characterization of the materials. In this regard experiments to determine the mechanical, physical, structural, optical, and thermal properties of components have been performed after considering, designing, and manufacturing various samples. The results show that the proposed smart window offers acceptable performance with a fast switching rate and even more than other similar smart glasses due to the usage of discharge/injection mechanism. In overall, the product can be used as a smart transparent element in various structures such as buildings and even vehicles to regulate energy consumption and/or block the view for security purposes.

Keywords  Smart window · Nanofluid · Nanocomposite · Light transmission · Self-cleaning

1 Introduction
Buildings now account for 40% of energy consumption and consequently 36% of carbon dioxide emissions according to previous research (Allen et al. 2017). This indicates the major importance of the study of the buildings in terms of environment and energy
consumption. Currently, standard windows typically waste a third of all energy used for heating and ventilation. Thus efforts have been focused solely on windows and the use of appropriate technology to reduce this energy loss (Donaldson 2018). A switchable glass (transparent/opaque) is a logical solution to transmit/reflex solar light based on requirements. These devices are designed to reduce air conditioning costs via sunlight blocking in summer and improve light harvesting during winter. Their fundamental mechanism is based on the tunable optical transmittance of incorporated switchable devices, generally stimulated as a response of an applied energy or changes in environmental conditions (Sala et al., 2018). The main issue of such devices is to utilize newer technologies and solutions to improve thermal and optical properties of them to compromise fabrication and production costs. Polymer-based smart windows are one of the reasonable elements that can be used in buildings to have the required features in this regard. The economical design and manufacturing capabilities, flexibility, optical/thermal features, and nanotechnological compatibilities of polymeric products, are the main reasons of the focus of this study on polymer-based smart windows. These types of smart-windows are of the most controllable products in terms of design, fabrication, and application. Polymer-based smart windows can be comfortably embedded in buildings and vehicles to improve energy consumption, automation, and even safety in terms of blocking the sight while required.

Previous studies about smart windows design and application are found to be in different categories ranging from energy consumption management purposes to advanced fabrication methods from which the more important cases are described here in a classified manner.

1.1 Energy consumption optimization

Hoffmann et al. (Hoffmann et al. 2014) investigated the effects of temperature change on thermochromic smart windows in a hot–cold climate and a warm and humid region of the United States. It was found that compared to the new standard low-transmission windows, a low-temperature switching thermochromic window consumes less energy by 10–17% in the south and west. These results have been verified only in the specific geographical regions which have been examined, however Warwick et al. (Warwick et al. 2014) have analyzed this type of windows under a broader range of conditions and have proven a 50% reduction in energy consumption compared to standard windows.

Thermochromic performance of copolymerized micro-hydrogel particles has also been investigated by adjusting the particle size and the structure (Li et al. 2019) to increase the energy consumption reduction in these type of windows however subtle improvement is obtained and fabrication process of such window is also complicated. Regardless of production cost, thermochromic smart windows must be investigated deeper due to their potential application for building automation purposes (Piccolo and Simone 2015).

Allen et al. (Allen et al. 2017) gained more control over the absorption of solar energy by considering the variable nature of smart windows between clear and opaque modes, compared to the fixed behavior of the low emission (LE) window. For example, hydroxypropyl cellulose smart window transmits 74% of the sun’s radiation in the transparent state and only 11% in the opaque state. This value for the LE window is a fixed value of 53%. Therefore during the cold periods of the year, the low percentage of passing through the LE window loses useful solar energy and causes the additional energy required for heating to increase. In contrast, smart windows reduce the amount
of energy required by high solar energy (74%) during the cold season. Although this advantage seems reasonable and practical due to inherent properties of the materials used in smart windows, the exact extent of its superiority over LE windows must be tested in a broader manner.

1.2 Electrochromic smart windows

Electrochromic switchable devices (SW) are usually composed of multi-layers of components in which switching process is obtained by oxidation/reduction processes and diffusion of externally activated ions (Baetens et al. 2010). Then some features as rapid switching by external voltage (Wu et al. 2015) and reflection control can be achieved for these devices. Although this type of device can be valuable, it requires several steps for materials development and layers construction, which might consequently lead to reduced transmittance (Chen et al. 2014). Additionally, since they change their optical properties by switching between oxidized and reduced form (Baetens et al. 2010), these electrochemical reactions can have a reduced performance overtime due to unwanted side reactions between the electrolyte and active materials (Wang et al. 2014a, b) such as decomposition of electrolytes and efficiency reduction of charge transfer reaction between the electrolyte and active materials (Hu et al. 2016).

1.3 Other smart windows (photochromic, gasochromic, etc.)

The efforts on manufacturing photochromic and gasochromic windows are almost considerable as photochromism has already been utilized in fabrication of smart glasses for years and gasochromism has appeared to be a more reasonable approach than electrochromism (Sala et al. 2018). In this regard, Wu et al. (2017) have used transparent photochromic films for smart window applications by embedding organic photochromic dyes in a sol–gel-based matrix. The degree of connection of the coating matrix and the types of organic groups have had effects on the transmission of visible light and the rate of bleaching (opaqueness). By changing the amount of color concentration in the coating, as well as the thickness of the coating, the amount of light transmission reduction has been adjusted between 30 and 60%. According to the author this product will significantly reduce the passage of energy in the tropics. It should be noted that the high time of state change, lack of high percentage of transparency, and complexity of the structure are among the disadvantages of this design.

In another study conducted by Feng et al. (2016) intelligent gasochromic windows were tested for energy efficiency in terms of optical and thermal properties. This was done in more depth by simulating energy consumption in a building. This study showed that the best areas to use this type of window are areas with cold winters and hot summers. The use of these areas reduces energy consumption in terms of ventilation, cooling, and heating. Nevertheless, the limitation in geographical location and relatively complex equipment required to produce gas should not be overlooked in this plan.
1.4 Simulations

Numerical simulation of the performance of smart windows have not been very common among the researchers yet, however there have been some attempts to perform this task. A numerical study on the performance of a multilayer smart window embedded in water-cooled third-generation solar cells has been conducted by Sabri et al. (2014). System optimization parameters such as light concentration ratio and cooling flow of water are required to prevent system performance loss due to thermal stresses and high cell temperatures. In this study detailed modeling of thermal properties of window system was performed using fluid analysis software; Finally by considering the conductive, convective, and radiative heat transfer mechanisms in the proposed smart window numerical solution results have been presented.

In another study, the effect of passive ventilation system and smart windows has been studied by Khalesi et al. (Javad and Navid 2019) in a building adaptable to climatic conditions. The distribution of temperature and air conditions have been investigated for two heat sources, smart windows, and two types of ventilation systems in fluid analysis software. Thermal comfort criteria have also been set by the validated model for smart windows. The results of the analysis show that smart windows are superior in terms of fulfillment of comfort criteria. It was also shown that the temperature difference between floor and ceiling can be reduced by up to 50% with the help of electrochromic windows.

1.5 Overview

Some of the limitations existing in previous studies and products can be summarized as follows:

- Time (seasonal) and spatial (geographical) constraints in achieving useful product efficiency
- High cost of construction
- Structural complexities of used materials
- Complexity of manufacturing the required product and equipment
- Major dependence of state change on thermal energy
- Lack of high transparency
- Long switching duration
- Restriction of the window installation position due to sight blocking when the temperature rises

Here an innovative design of smart windows is provided by harnessing light refraction index conformity and taking the advantage of simple draining/injection system. Thereby the optical transmittance of the smart windows can be changed between extreme values at any time without the need to reach a switching threshold in response to intense solar heating. The window in the proposed design operates in such a way that the percentage of light passing through the window depends on the presence or absence of fluid (nanofluid) inside the polymeric plate together with the refractive index conformity between these components according to the percentage of nanoparticles in the fluid. Therefore the percentage of light transmission will be at its minimum value (45%) in the absence of fluid and it will be at the maximum value (80%) at the presence of fluid. Characterizing experiments,
fabrifications steps, and obtained results are explained and discussed in the following sections in detail.

2 Materials and methods

2.1 Materials

Transparent polymers usually exhibit various optical properties such as tailored emission/absorption properties and/or low/high refractive index. These facts about such polymers attract great interest because of the potential optoelectronic applications (Demir et al. 2007). Hence the polymer used here has been PMMA. Another reason for choosing this polymer has been its availability. PMMA as a transparent polymeric material offers excellent transparency in the visible and near-infrared range (Zettl et al. 2017). It is often used as an alternative to glass. PMMA has a transmission of more light and it is much lighter than silica glass. In addition, it is almost easy to find a fluid with a similar light refractive index \((n)\) which can be modified with the desired coating. Nevertheless, PMMA transmits UV light; thus manufacturers usually apply UV coatings on PMMA to overcome this deficiency (Hammani et al. 2018).

The nanocomposite coating for this purpose was ZnO-PMMA. ZnO nanoparticle is a well-known multifunctional inorganic filler that has outstanding properties such as high refractive index, high thermal conductivity, self-cleaning behavior as well as photo-catalytic, antibacterial, and UV-protection properties (Sun et al. 2007).

In overall the polymeric component (PMMA) contributes to good processability, transparency, and flexibility, while the nanoparticles (ZnO) provide the desired thermal, and optical properties (Dai Prè et al. 2015).

The target fluid is methyl salicylate, which turns to nanofluid after the addition of zinc oxide nanoparticles. Among the important properties of the desired fluid can be mentioned as the following:

- The refractive index close to the PMMA
- Medium and low viscosity, which is suitable for the state change mechanism
- High transparency
- Large boiling point and ignition which makes it stable in the desired temperature range
- Environmental adaptation (skin contact)

2.2 Fabrication

The experimental steps including fabrication process and characterization tests (Fig. 1) are explained in this section.

Assembled sample is demonstrated in Fig. 2. The sample is prepared by injecting fluid inside polymeric box while external surfaces are covered by nanocomposite film.

2.2.1 Polymeric plates

After analyzing different geometries, rotated cube appeared to be a better choice. In this pattern the rotated cubes are considered as cavities inside the plate. Figure 3 shows the details of this design. Using this design causes the light to refract successively when the
fluid is not inside the window. Consequently the percentage of transmission is significantly reduced. In contrast, the presence of fluid increases the transparency considerably due to refraction index conformity between fluid and polymer when the nanofluid is injected.

Polymeric prototypes were firstly 3D-printed by Polyethylene (PE) (Fig. 4). Then resin mold was produced using polymeric prototype (Fig. 5). Finally PMMA plates were fabricated by injecting polymer inside the strengthened resin mold.

### 2.2.2 Nanocomposite film

The desired values of the percentage of nanoparticles are as follows: NCS$_1$: 1% ZnO, NCS$_2$: 2% ZnO, and NCS$_3$: 5% ZnO. It should be noted that according to research, the maximum achievable concentration of nanoparticles in the polymer matrix is about 10 wt%, which is due to the high surface energy and low solubility of nanoparticles. Therefore values lower than 10 wt% were considered here for the production of nanocomposites.
To mix and dissolve the polymer in the solvent a magnetic stirrer-heater with a maximum temperature of 120°C was used (Fig. 6). PMMA-fluid solution \( \frac{1 \text{ gr (PMMA)}}{50 \text{ ml (Fluid)}} \) was obtained as a relatively thick white liquid. Since zinc oxide powder was purchased in the form of nanoparticles there was no need for initial synthesis to prepare the oxide powder; therefore the powder was used directly. Then different amounts of zinc oxide nanoparticle powder were added to the solution. In the next step the sample was mixed for 60min at a temperature range of 60–65 °C and a semi-white product was obtained. At next step the gel state product was placed on a glass plate to prepare the film. Finally the produced film was placed at 80°C for 11min to remove the solvent from the sample.
Fig. 4 3D printed polymeric prototype of plate

Fig. 5 Resin mold preparation. a Before curing. b After curing

Fig. 6 Dissolving polymer in propanone (acetone)
The sample thickness was measured in different spots and the desired thickness was considered to be 30\(\mu\)m.

**2.2.3 Nanofluid**

To prepare the desired nanofluid, zinc oxide nanoparticles were added and mixed with concentrations of 0.1 (NFS\(_1\)), 0.5 (NFS\(_2\)), and 1 wt% (NFS\(_3\)) according to the mass of the desired fluid. The mixture was then placed on a magnetic stirrer before performing the ultrasonic process to ensure re-dispersion of nanoparticles in the base fluid.

**2.2.4 Assembled product**

In order to simplify the production and assembly process of the sample, the dimensions of the sample were considered to be 0.1 \(\times\) 0.1 m\(^2\). The final assembly was obtained by attaching the plates and installing holes required for fluid injection/drain (Fig. 7).

**2.3 Tests**

Characterization tests have been performed in the field of physical, mechanical, thermal, structural and optical properties on product components.

**2.3.1 Physical properties**

**2.3.1.1 Contact angle test**  Contact angle test was performed based on ASTM D7490 with the aim of achieving compatibility between fluid and solid materials used in the sample. To perform this test, the method of measuring the contact angle and surface tension with the help of droplets in the CA-ES10 device was used. Contact angle testing was performed for polymer sheets and nanocomposite films versus water, fluid, and nanofluid with two repli-
cates. The important technical characteristics of this device was as $3 - 72 \, \text{mN}$ available range and $5^\circ - 179^\circ$ as available contact angle range. The polymeric sample is shown in Fig. 8.

2.3.2 Mechanical properties

2.3.2.1 Tensile test Tensile test was performed for polymeric plate with two replicates on the samples (Fig. 9). The Tinus-Olsen ST-100 was used to perform this test.

2.3.2.2 Impact test Impact test was performed for polymeric plate with two replicates. PIT-501A device was used for this test.

2.3.2.3 Flexure test Flexure test for polymeric plates was performed twice with a strain rate of $2 \, \text{mm} \, \text{min}^{-1}$ on the samples (Fig. 10). The Tinus-Olsen ST-100 was used to perform this test.

2.3.3 Thermal properties

2.3.3.1 DSC test Since PMMA is a thermoplastic polymer it was important to determine the glass transition temperature range ($T_g$), melting temperature ($T_m$) (process temperature
range), and crystallization temperature using the DSC test to perform the fabrication process. This test has been done for polymer and nanocomposite. To perform DSC test, SA059 device with important technical specifications of \(-150 - 700\) °C as temperature range, ±0.2 K as temperature accuracy, ±0.02 K as temperature precision, 0.02–300 K/min as heating rate, and 0.02–50 K/min as cooling rate has been used.

2.3.3.2 Heat conductivity test Heat conductivity coefficient of polymer and nanocomposite film has been measured to recognize the heat transfer rate of external and internal surfaces of the product. SDK TCC 001 (Fig. 11) with the important technical specifications of 20 °C – 100 °C as temperature range, ±1 °C as temperature accuracy, and 0.02.0.50 K/min as cooling rate has been used.

2.3.4 Optical properties

2.3.4.1 UV–VIS-NIR Spectroscopy Spectrophotometric test was used to evaluate the light absorption and transmission of window elements using JASCO-V670 device with 190 – 2700nm spectral range. This test was performed for different subsets of components including simple polymeric plates with nanocomposite films and nanofluid with two replications.

2.3.5 Structural characteristics

2.3.5.1 Light and electron microscopy The nanocomposite and fluid structural characterizations were each performed separately to determine the existing structure. This was done for nanoparticles with two replications by X-ray diffraction based on ASTM D5357 by Bruker D8-Advance with the important technical specifications of 500 mm and 560 mm as default measuring diameter, \(-110^\circ < 2\theta \leq 168^\circ\) as maximum measurable range, 0.0001° as Angular resolution, and \(\theta / \theta\) or \(\theta / 2\theta\) as available configurations. To perform this test ZnO nanoparticles were subjected to X-ray scattering test with specifications of 40kV and 20mA. The crystal dimensions of nanoparticles were obtained using Equation Eq. (1) (Gopi et al. 2016):

Fig. 11 SDK TCC 001 Heat transfer conductivity measuring device used in experiments (Fabricated by author)
where $d$ is the crystal dimension, $K$ is the dimensionless shape factor with a value close to the unit value, $\lambda$ is the beam wavelength, $\theta$ is the radiation angle, and $\beta$ is the width of the half of the maximum value at the peak of the scatter.

For nanocomposite film, the structural test was performed by scanning electron microscope (SEM) based on ASTM E2015 using Philips XL30 with 2.0 nm resolution in two replications. Thus the morphology and chemical composition of nanocomposite films were examined with a 10kV SEM with low suction.

For nanofluid, dynamic light scattering (DLS) method was performed based on ASTM E2490 using NanoPartica SZ-100V2 device with $\pm 2\% \times 100$nm measurement accuracy. Nano particle size analysis was performed in the desired solution with a laser beam. The wavelength has been chosen based on the requirements of the test with regard to the nanoparticle size and Eq. (2) (Nimesh, 2013) while technical specifications of the test device has been respected.

$$I = I_0 \cdot \frac{1 + \cos^2 \beta}{2R^2} \left( \frac{2\pi}{\lambda} \right)^4 \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 r^6$$

where $I$ is the intensity, $\lambda$ is the wavelength of the un-polarized incident light, $R$ is the distance to the particle, $\beta$ is scattering angle, $n$ is the refractive index of the particle and $r$ is the radius of the particle, and $I_0$ is the un-polarized intensity incident light.

![Fig. 12 Polymeric sample tensile test results](image-url)
3 Results and discussion

3.1 Mechanical tests

3.1.1 Polymeric plates

3.1.1.1 Tensile test  Tensile test results performed on polymer plates is demonstrated in Fig. 12. The average value obtained for different parameters is as follows:

\begin{align*}
S_y &= 17.6 \text{MPa} \\
E &= 8.5 \text{GPa} \\
e_f &= 0.21\%
\end{align*}

where $S_y$, $E$, and $e_f$ are tensile strength, tensile elasticity modulus, and elongation of the sample respectively.

The tensile test results have been normal and acceptable according to the results obtained in Fig. 12.

3.1.1.2 Impact test  The impact test results performed on the polymer plates were measured. According to the obtained results the average measured toughness value has been $15 \text{J/m}^2$. The results has been normal and acceptable.

3.1.1.3 Flexural test  The results of the flexure test performed on the polymer plates is mentioned in Fig. 13. The average value obtained for different parameters is as follows:

\begin{align*}
S_{yb} &= -0.82 \text{MPa} \\
E_b &= -0.019 \text{GPa}
\end{align*}

Fig. 13  Polymeric sample flexural test results
where $S_{fb}$, $E_{fb}$, and $e_{fb}$ are flexural strength, flexural elasticity modulus, and flexural elongation of the sample respectively.

According to the results obtained in Fig. 13 the results have been normal and acceptable.

### 3.2 Physical test

#### 3.2.1 Contact angle

The results of contact angle test between fluid and solid (polymer) are presented in Table 1. An example of the image presented in this test is depicted in Fig. 14.

According to the results obtained in Table 1, the results related to polymeric plates and water has been normal according to other studies (Ma et al. 2007). The value has increased in the case of polymer and fluid. This is even more for plates and nanofluid which indicates higher fluid phobicity of the PMMA and nanofluids.

As the results show the contact angle for nanocomposite film and fluid has increased in all three cases indicating that the film is more fluid-phobic. The maximum value is

\[ e_{fb} = -4.28\% \]  

**Table 1** Contact angle test results

| Sample                  | Contact angle (average value) (°) |
|-------------------------|-----------------------------------|
| Polymeric plate—water   | 74                                |
| Polymeric plate—fluid   | 76                                |
| Polymeric plate—nanofluid | 78                            |
| Nanocomposite film—water | 76                              |
| Nanocomposite film—fluid | 79                               |
| Nanocomposite film—nanofluid | 81                          |

**Fig. 14** Photograph of a contact angle test between polymeric sample and water
obtained for nanocomposite film and nanofluid. Although fluid phobicity alone does not reflect the property of self-cleaning, the point here is that this property will be less effective if the surface is not exposed to environmental pollution. Because when the film is exposed to contamination, there is a possibility of non-fluid particles adhering which will require surface washing due to its subtle fluid-philicity property. Therefore, the fluid-phobicity of the inner surfaces of the window will cause self-cleaning inside the window.
3.3 Structural test

3.3.1 Nanoparticles

3.3.1.1 XRD test  XRD test results on nanoparticles in Fig. 15 mentioned.

3.3.1.2 SEM test  A section of SEM test result on the nanocomposite is demonstrated in Fig. 16. The result shows the common granularity of zinc oxide nanoparticles in nanocomposite.

According to the results obtained in Fig. 15, zinc oxide particles size have been acceptable and it is within the standard range for nanocomposites and nanofluids. In addition as seen in Fig. 16 the surface obtained from the nanocomposite film is in appropriate condition according to the results of similar study (Hammani et al. 2018).

3.3.2 Nanofluid

3.3.2.1 DLS test  The results of DLS test on nanofluid in the range of 0 – 100 nm shows the acceptable dispersion of nanoparticles in the fluid. The results show that the particle dimensions have been between 3.5 nm and 12 nm.
3.4 Thermal test

3.4.1 DSC test

The DSC test result is shown in Fig. 17 on pure polymer. The rest of thermal PMMA results with different zinc oxide percentages are shown in Table 2.

As data show $T_g$ in nanocomposite films are higher than pure polymer. This value has increased with increasing the percentage of ZnO nanoparticles.

According to the results obtained in Fig. 17 and Table 2 the range of vitrification and melting of the polymer is suitable for its manufacture. An important point to be seen in these results is that $T_g$ has increased with increasing the percentage of ZnO which could be due to the lack of complete solubility of the polymer in the solvent and reduction in molecular weight distribution. This is due to the direct relationship of $T_g$ value with the mobility of the polymer chain (Kim et al. 2012). Although $T_g$ does not necessarily affect the performance of the window, knowing its thermal characteristics can ensure a safe temperature range for its working conditions.

Table 3 Light transmission test results (Average value obtained for the sample in a certain comparable range of tested wavelength)

| Sample                                         | Transmission percentage (average) |
|------------------------------------------------|------------------------------------|
| Simple polymeric plates                        | 87                                 |
| Patterned polymeric plates                     | 45                                 |
| Simple polymeric plates with nanocomposite film (NCS$_3$) | 82                                 |
| Simple polymeric plates with nanofluid (NFS$_3$) | 85                                 |
| Assembled window (NCS$_3$ and NFS$_3$)         | 80                                 |

Fig. 18 UV–Vis transmission curve obtained for simple polymeric plates
3.4.2 Thermal conductivity test

The results of the thermal conductivity coefficient test are listed in Table 2. The thermal conductivity coefficient has increased slightly with increasing the percentage of zinc oxide according to the results obtained in Table 2. Although this parameter does not have considerable influence on the desired performance of the window, it will be considered in terms of heat loss or the input of unwanted heat from outside. In general it can be said that the plate of the window play a more insulating role than conductive.

3.5 Optical test

Figure 18 and Table 3 show the results of the UV–Vis test for polymers, nanocomposites, and nanofluids in visible and ultraviolet range in the room temperature. The utilized method here is similar in results and usage with ellipsometry as it provides optical properties of the sample by measuring the change of the optical properties and thickness of the materials during adsorption and desorption of a volatile species at atmospheric pressure or under reduced pressure depending on the application. The method has also been compared with similar studies using ellipsometry method in terms of reliability (Jonas et al. 2016; Reben et al. 2010). The results including plain and patterned polymeric plates, as well as windows containing fluid with different percentages of ZnO nanoparticles are shown in Table 3. According to the results the variation in light transmittance for the opaque and transparent state is between 45 and 80%. The opaque state occurs when the windows does not include the fluid and the transparent state occurs when complete set is used.

3.6 Smart window performance evaluation

3.6.1 Overview of smart windows mechanisms

A brief comparison is made between the existing instances of the conventional smart windows and the proposed smart window in terms of mechanism and capabilities. Table 4 lists the materials and mechanisms used for state change. According to Table 4 the major disadvantages of the existing smart windows are the high cost of components materials together with the complex mechanism, regardless of the small range of solar heat gain coefficient (SHGC) in both opaque and transparent modes. In the proposed window, PMMA is readily available as the main transparent plate of the window while the switching mechanism is facilitated by a simple injection/drain mechanism and refractive index conformity between plate and nanofluid. The use of nanocomposite material has been considered optional as it helps with improving self-cleaning properties as well as photocatlysis process.

3.6.2 Ratio of light transitivity ($R_p$)

Proposed window performance has been compared with other smart windows in terms of light transitivity percentages by defining ratio of light transmission percentage ($R_p$):

$$R_p = \frac{P_H}{P_L}$$  \hspace{1cm} (9)
### Table 4  Brief comparison of materials and mechanisms of current smart windows and proposed type

| Smart window type   | Components                                        | Mechanism                                                                 |
|---------------------|---------------------------------------------------|---------------------------------------------------------------------------|
| Electrochromic       | Multi-layer glass                                 | Direct correlation of the applied voltage with the level of turbidity (opaqueness) caused by ion transfer |
| Photochromic         | Glass or polycarbonate or other specific polymers | A reversible ionic chemical reaction between some elements in the glass such as chlorine and silver to make turbidity (opaqueness) |
| Gasochromic          | Polymer with tungsten oxide and hydrogen gas       | Reversible chemical reaction of gas and polymer causing turbidity (opaqueness) |
| Other types          | Hydrogen, low emission glass, …                   | Modern chemical, electrical, and other types of mechanism to make turbidity (opaqueness) |
| Proposed smart window| Polymer, nanofluid, nanocomposite (optional)      | Nonconformity of refractive index between fluid and polymer to cause turbidity (opaqueness) |
where $P_H$ and $P_L$ are the percentage of light transitivity in transparent and opaque state respectively. Values of $R_P$ have been compared for different types of smart windows in Table 5 and Fig. 19.

### 3.6.3 Ratio of temperature difference ($R_\Delta$)

A dimensionless parameter has been presumed as ratio of temperature difference for evaluating the performance of smart windows for both cool and warm weather conditions:

$$R_\Delta = \frac{|\Delta T|}{T_E} = \frac{|T_E - T_I|}{T_E}$$

(10)

### Table 5

$R_P$ for different types of smart windows (Cao et al. 2019; Hoffmann et al. 2014; Piccolo and Simone 2015; Sala et al. 2018)

| Smart window       | $P_L$ | $P_H$ | $R_P$ |
|--------------------|-------|-------|-------|
| Glass (W1)         | 0.9   | 0.9   | 1     |
| Gasochromic (W2)   | 0.6   | 0.8   | 1.17  |
| Electrochromic (W3)| 0.6   | 0.74  | 1.23  |
| Photochromic (W4)  | 0.56  | 0.7   | 1.25  |
| Proposed window (W5)| 0.3  | 0.85  | 2.83  |

### Table 6

Experimental and predicted value of $R_\Delta$ during 12:00–13:00 for proposed smart window

| Weather condition | Window state | Predicted results | Experimental results |
|-------------------|--------------|-------------------|----------------------|
| Warm              | HT*          | 35 32 0.09        | 35 33 0.06           |
| Warm              | LT**         | 35 27 0.23        | 35 26 0.26           |
| Cool              | HT           | 20 18 0.1         | 20 19 0.05           |
| Cool              | LT           | 20 15 0.25        | 20 14 0.3            |

*HT High transparency mode, **LT Low transparency mode (Opaque)
where $T_E$ and $T_I$ are external and internal temperatures of the room under test, respectively. This parameter demonstrates the ratio of sun light transmission in cool weather, while it states the ratio of opaqueness for warm weather conditions. A test room (chamber) has been prepared to check the temperature variations during a certain time in daylong, for further evaluation of the smart window performance by the use of $R_\Delta$. In order to achieve temperature stability, this experiment has been done within one hour while the room has been controlled in terms of thermal aspects so that only sun light have been the most effective heat source influencing the temperature variations. Following results (Table 6) have been obtained for the proposed smart window experimentally and numerically for a certain duration in daylong. Energy Plus software has been utilized as simulation tool for obtaining numerical results. Adequate optical and thermal properties measured in previous sections have been defined in the software to calculate the results. Acceptable range of discrepancies are observed between experimental and numerical results in Table 6 which indicates the reliability of the simulation results.

It should be noted that larger values of $R_\Delta$ in warm weather means the higher performance of smart window (values close to 1), while smaller value of $R_\Delta$ indicates the

| Smart window type | Warm weather (LT*) | Cool weather (HT**) |
|-------------------|--------------------|--------------------|
| Glass (W₁)        | 0.09               | 0.08               |
| Gasochromic (W₂)  | 0.18               | 0.14               |
| Electrochromic (W₃) | 0.19             | 0.13               |
| Photochromic (W₄) | 0.21               | 0.11               |
| Proposed window (W₅) | 0.26            | 0.05               |

*LT Low transparency mode (Opaque), **HT High transparency mode

*Fig. 20* Comparison of predicted $R_\Delta$ for different smart windows in a warm weather (low transparency), and b cool weather conditions (high transparency)
better performance of the window in cool weather conditions. Thus the weather condition must be considered initially before comparison of $R_\Delta$ for different smart windows.

Predicted values of $R_\Delta$ have been calculated based on $P_H$, $P_L$ and other optical and thermal properties of each smart window, while it is compared with proposed smart window in Table 7 and Fig. 20. According to results in Table 7 and Fig. 20, higher $R_\Delta$ in warm weather and less $R_\Delta$ in cool weather has been obtained for the proposed window compared to the other smart window mechanisms, which shows the reliable performance of the proposed design in terms of energy efficiency.

In overall $R_P$ and $R_\Delta$ of the proposed design has been in influential in terms of energy consumption for temperature adjustment and air conditioning compared to the other types of smart windows. In addition the versatile and efficient proposed design of state switching has provided temperature independent system which is stimulated by small input power, requiring less energy consumption and just a drain/injection process to provide a reversible optical process compared to the other types.

### 3.6.4 Switching duration

It should be noted that one of the features of smart glass is the time required to switch between the states. According to the previous studies this period is relatively time consuming for thermochromic, electrochromic, and gasochromic glasses due to the chemical processes required to switch the state. This is also the case for other smart glasses. Glasses containing hydrogels for example take about 40 min to change state due to rising and falling temperatures (Gyenes et al. 2003). The more advanced version of this window (containing microgels) has just reduced this time to 4 min (M. Wang et al. 2014a, b). In glasses containing hydroxypropyl methyl cellulose, the time required to change state during the temperature reduction process is about 6 min (Kiruthika and Kulkarni 2017).

Although some efforts are seen in previous studies to reduce the switching time, most of them operate during a period longer than 1 or 2 min while this period has reduced to a duration as short as 1 min due to harnessing injection/drain mechanism in the proposed window. As mentioned previously, the mechanism operates in such a way that the presence or absence of fluid (nanofluid) inside the window and the matching of the refractive index between the fluid (nanofluid) and the plates, respectively, make the window transparent or opaque. However, it should be noted that the area of the window and the inlet–outlet flow of the fluid will also affect this period of time.

### 4 Conclusion

The main benefits of using smart windows are reducing energy consumption and improving the building automation. The use of this technology is more necessary in summer when energy consumption peaks for cooling systems as well as winter when these glasses play an effective role in reducing energy consumption by passing a high percentage of sunlight into the building since the sunlight is less intense due to the angles of the sunlight with the ground.

Although the technology of most smart glasses has had a positive impact on energy management, the significant cost of making these glasses have been still major obstacles. Current smart windows which are switched by changes in the intensity of sunlight are not only cost-effective to produce, but also do not they work well in the long run. In
addition toxic substances are usually used in the process of making these types of windows which can pose significant risks to nature and human health.

The proposed smart window offers a cheaper and more cost-effective idea for making these types of windows. In this window the mentioned problems have been considerably resolved to an acceptable extent by using nontoxic materials and simple switching mechanism while having a stable performance in the long run. In addition the time period for switching between the states is relatively short, while its fabrication cost is reasonable compared to similar types. The major advantages of this product can be summarized as follows:

- The selection of PMMA and proposed manufacturing method have both reduced the cost of materials and fabricating smart window as predicted.
- The simple switching mechanism in the proposed design has considerably reduced the complexity and requirements of the proposed smart window compared to the other types in which complicated chemical and electrical processes are mandatory for switching state.
- The proposed smart window has had a wider range of transparency variation according to the proposed parameter titled as the ratio of light transitivity \((R_p)\) compared to the existing types due to the matching properties of the polymer and the nanofluid together with the switching mechanism.
- The energy efficiency and the performance of the proposed window has been considerable compared to the existing types according to the calculated ratio of temperature difference \((R_{Δ})\) based on the optical properties and experiments. Thus a higher percentage of sunlight passing in cool weather and a lower percentage of sunlight passing in warm weather can cause to reduce heating and cooling costs compared to other smart windows.
- The switching time has reduced compared to the existing smart windows according to the other studies. This time has been shortened to less than 1 min (compared to 4 min as the minimum time required for state switching in other type) due to the simple injection/drain mechanism however the area of the window and the flow rate are two important controlling factors.

The research was funded by Iran National Science Foundation (INSF).

**Authors’ contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mehdi Jafari Vardanjani and Mehdi Karevan. The first draft of the manuscript was written by Mehdi Jafari Vardanjani and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Declarations**

**Conflict of interest** The authors declare no conflict of interests.

**Ethical approval** The research conducted in this work did not involve human participants or animals.

**Consent to participate** All authors have read and consented to the final version of the manuscript.

**Consent for publication** All authors have consented to the publishing of the manuscript.
References

Allen, K., Connelly, K., Rutherford, P., Wu, Y.: Smart windows—dynamic control of building energy performance. Energy Build. 139, 535–546 (2017). https://doi.org/10.1016/j.enbuild.2016.12.093

Baetens, R., Jelle, B.P., Gustavsen, A.: Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review. Sol. Energy Mater. Sol. Cells 94(2), 87–105 (2010). https://doi.org/10.1016/j.solmat.2009.08.021

Cao, S., Zhang, S., Zhang, T., Yao, Q., Lee, J.Y.: A visible light-near-infrared dual-band smart window with internal energy storage. Joule. (2019). https://doi.org/10.1016/j.joule.2018.12.010

Chen, Z., Cao, C., Chen, S., Luo, H., Gao, Y.: Crystallised mesoporous TiO2(A)–VO2(M/R) nanocomposite films with self-cleaning and excellent thermochromic properties. J. Mater. Chem. A 2(30), 11784–11884 (2014). https://doi.org/10.1039/C4TA01585A

Dai Prè, M., Martucci, A., Martin, D.J., Lavina, S., Di Noto, V.: Structural features, properties, and relaxations of PMMA-ZnO nanocomposite. J. Mater. Sci. 50(5), 2218–2228 (2015). https://doi.org/10.1007/s10853-014-8784-0

Demir, M.M., Koynov, K., Akbey, Ü., Bubeck, C., Park, I., Lieberwirth, I., Wegner, G.: Optical properties of composites of pmma and surface-modified zincite nanoparticles. Macromolecules 40(4), 1089–1100 (2007). https://doi.org/10.1021/ma062184t

Donaldson, L. (2018). Cheaper and easier smart windows. Materials Today, 21(6), 584. https://doi.org/10.1016/j.mattod.2018.06.017

Feng, W., Zou, L., Gao, G., Wu, G., Shen, J., Li, W.: Gasochromic smart window: optical and thermal properties, energy simulation and feasibility analysis. Sol. Energy Mater. Sol. Cells 144, 316–323 (2016). https://doi.org/10.1016/j.solmat.2015.09.029

Gopi, D., Kavitha, L., Ramya, S., Rajeswari, D.: Chapter 15 - Chemical and green routes for the synthesis of multifunctional pure and substituted nanohydroxyapatite for biomedical applications. In: Grumezescu, A.M. (ed.) Engineering of nanobiomaterials, pp. 485–521. William Andrew Publishing, Norwich (2016)

Gyenes, T., Szilágyi, A., Lohonyai, T., Zrínyi, M.: Electrically adjustable thermotropic windows based on polymer gels. Polym. Adv. Technol. 14(11–12), 757–762 (2003). https://doi.org/10.1002/pat.391

Hammani, S., Barhoum, A., Bechelany, M.: Fabrication of PMMA/ZnO nanocomposite: effect of high nanoparticles loading on the optical and thermal properties. J. Mater. Sci. 53(3), 1911–1921 (2018). https://doi.org/10.1007/s10853-017-1654-9

Hoffmann, S., Lee, E.S., Clavero, C.: Examination of the technical potential of near-infrared switching thermochromic windows for commercial building applications. Sol. Energy Mater. Sol. Cells 123, 65–80 (2014). https://doi.org/10.1016/j.solmat.2013.12.017

Hu, K., Blair, A.D., Piechota, E.J., Schauer, P.A., Sampao, R.N., Parlane, F.G.L., Berlinguette, C.P.: Kinetic pathway for interfacial electron transfer from a semiconductor to a molecule. Nat. Chem. 8(9), 853–859 (2016). https://doi.org/10.1038/nchem.2549

Javad, K., Navid, G.: Thermal comfort investigation of stratified indoor environment in displacement ventilation: Climate-adaptive building with smart windows. Sustain. Cities Soc. 46, 101–121 (2019). https://doi.org/10.1016/j.scs.2018.11.029.

Jonas, S., Januš, M., Jaglarz, J., Kyziol, K.: Formation of SixNy(H) and C:N:H layers by plasma-assisted chemical vapor deposition method. Thin Solid Films 600, 162–168 (2016). https://doi.org/10.1016/j.tsf.2016.01.016

Kim, D., Jeon, K., Lee, Y., Seo, J., Seo, K., Han, H., Khan, S.: Preparation and characterization of UV-cured polyurethane acrylate/ZnO nanocomposite films based on surface modified ZnO. Prog. Org. Coat. 74(3), 435–442 (2012). https://doi.org/10.1016/j.porgcoat.2012.01.007

Kiruthika, S., Kulkarni, G.U.: Energy efficient hydrogel based smart windows with low cost transparent conducting electrodes. Sol. Energy Mater. Sol. Cells 163, 231–236 (2017). https://doi.org/10.1016/j.solmat.2017.01.039

Li, X.-H., Liu, C., Feng, S.-P., Fang, N.X.: Broadband light management with thermochromic hydrogel microparticles for smart windows. Joule 3(1), 290–302 (2019). https://doi.org/10.1016/j.joule.2018.10.019

Ma, Y., Cao, X., Feng, S., Ma, Y., Zou, H.: Fabrication of super-hydrophobic film from PMMA with intrinsic water contact angle below 90°. Polymer 48(26), 7455–7460 (2007). https://doi.org/10.1016/j.polym er.2007.10.038

Nimesh, S.: 3 - Tools and techniques for physico-chemical characterization of nanoparticles. In: Nimesh, S. (ed.) Gene therapy, pp. 43–63. Woodhead Publishing (2013)

Piccolo, A., Simone, F.: Performance requirements for electrochromic smart window. J. Build. Eng. 3, 94–103 (2015). https://doi.org/10.1016/j.jobe.2015.07.002
Reben, M., Wasylak, J., Jaglarz, J.: Changes of refractive index of tellurite glass. Photon. Lett. Poland (2010). https://doi.org/10.4302/plp.2010.1.05
Sabry, M., Eames, P.C., Singh, H., Wu, Y.: Smart windows: thermal modelling and evaluation. Sol. Energy 103, 200–209 (2014). https://doi.org/10.1016/j.solener.2014.02.016
Sala, R.L., Gonçalves, R.H., Camargo, E.R., Leite, E.R.: Thermosensitive poly(N-vinylcaprolactam) as a transmission light regulator in smart windows. Sol. Energy Mater. Sol. Cells 186, 266–272 (2018). https://doi.org/10.1016/j.solmat.2018.06.037
Sun, D., Miyatake, N., Sue, H.-J.: Transparent PMMA/ZnO nanocomposite films based on colloidal ZnO quantum dots. Nanotechnology 18, 215–231 (2007). https://doi.org/10.1088/0957-4484/18/21/215606
Wang, J., Zhang, L., Yu, L., Jiao, Z., Xie, H., Lou, X.W.D., Sun, X.W.: A bi-functional device for self-powered electrochromic window and self-rechargeable transparent battery applications. Nat. Commun. 5(1), 1–7 (2014a)
Wang, M., Gao, Y., Cao, C., Chen, K., Wen, Y., Fang, D., Guo, X.: Binary solvent colloids of thermosensitive poly(n-isopropylacrylamide) microgel for smart windows. Ind. Eng. Chem. Res. 53(48), 18462–18472 (2014b). https://doi.org/10.1021/ie502828b
Warwick, M.E.A., Ridley, I., Binions, R.: The effect of transition gradient in thermochromic glazing systems. Energy Build. 77, 80–90 (2014). https://doi.org/10.1016/j.enbuild.2014.03.044
Wu, C.-C., Liou, J.-C., Diao, C.-C.: Self-powered smart window controlled by a high open-circuit voltage InGaN/GaN multiple quantum well solar cell. Chem. Commun. 51(63), 12625–12628 (2015). https://doi.org/10.1039/C5CC04031K
Wu, L.Y.L., Zhao, Q., Huang, H., Lim, R.J.: Sol-gel based photochromic coating for solar responsive smart window. Surf. Coat. Technol. 320, 601–607 (2017). https://doi.org/10.1016/j.surfcoat.2016.10.074
Zettl, M., Mayer, O., Klampaftis, E., Richards, B.S.: Investigation of host polymers for luminescent solar concentrators. Energ. Technol. 5(7), 1037–1044 (2017). https://doi.org/10.1002/ente.201600498

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.