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A novel concept of a responsive transparent façade module: optimization of energy performance through parametric design

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Abstract

A novel concept of a responsive transparent façade module was developed and analyzed in its energy performance. The module consists of three glazings: a low-E selective glass; a PCM filled double-pane glazing for solar control; an aerogel filled double-pane glazing for thermal insulation. These layers are dynamically combined in response to external conditions so as to minimize the energy consumption for lighting and HVAC systems. The module was applied to a sample room in Turin and the global energy demand was calculated through a parametric design, using DIVA-for-Rhino. Different room orientations and thicknesses of PCM and aerogel layers were analyzed.

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1. Introduction

Presently non-residential buildings rely more and more on highly transparent façades with enhanced performances and presenting a responsive behavior, i.e. able to dynamically respond and adapt to different boundary conditions. In order to reduce the global energy demand of a building, actively balancing its energy use for heating, cooling and lighting, new façades concepts need to be defined and integrated approaches addressing all main energy uses during the course of a whole year need to be adopted. In this regard, different typologies of Responsive Building Elements RBE have been developed with a function of shading or of modifying the window-to-wall ratio WWR of the façade so as to enhance the control of winter losses and of summer solar gains, but reducing to a remarkable extent the amount of daylight admitted into the indoor spaces [1-5].

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In this context, this paper presents a study for the definition of a novel concept of RBE: thanks to the use of translucent materials with high energy performances, this RBE is able to enhance both the insulating performance in winter and the energy storage capability in summer, without compromising the transparency of the façade so as to admit into indoor spaces an appropriate amount of daylight and to reduce the need for electric lights.

The study was aimed at: 1) assessing the annual global energy performances (for cooling, heating and lighting) for a sample room located in Turin with different configurations of the RBE and 2) optimizing such performance through a comparison with the performance of a 'static' transparent envelope with a Low-E selective double pane glazing.

2. Concept of the novel transparent RBE

The module consists of three different glazings (Fig. 1): a) a low-E selective glazing; b) a double-pane glazing filled with PCM to enhance the performance in terms of solar control; c) a double-pane glazing filled with aerogel to enhance the performance in terms of thermal insulation. The façade module is conceived as a smart element: a mechanical system keeps the low-E glass in a fixed position ('passive' layer) and allows the other two glazings to be moved automatically ('active' layers) in front of it or behind it, thus creating an optimized configuration to reduce the energy consumption for any boundary condition. The responsive behavior of the global system is entrusted to internal and external sensors based on which an automated handling system moves the different glazings.



Fig. 1. Visualization of the concept of the RBE, with the two active layers sliding in front or back a static Low-E selective glazing.

3. Method

The RBE module was applied to a sample cellular peripheral office room office room, located in Turin (45°N, 7.7°E, northern-western Italy). The annual energy demand was then calculated for different configurations of the room, so as to optimize the energy performance concerned with the use of the RBE.

3.1. Definition of the case-study

The sample room measured 3.5 m in width, 5 m in depth and 3 m in height (net sizes), with one transparent wall. These sizes were assumed to represent a peripheral cellular office room typically designed in the layout of modular office buildings. All the non-transparent room surfaces were supposed to be adiabatic so as analyze the mere fluxes incident onto the glazed wall. Design temperatures for winter and for summer were set equal to 20°C and to 26°C, respectively, while light reflectance values for ceiling, walls and floor were set to 80%, 60% and 30%, respectively. The room was considered occupied Monday through Friday, from 8:00 until 18:00, with a lunch break from noon 'till 13:00, accounting for the daylight saving time. A value of 0.06 people/m² was assumed to quantify the occupancy. For HVAC and lighting systems, the following values were assumed: efficiency of the heating and cooling systems = 0.9 and 4, respectively; set-point temperatures for summer and winter = 26°C and 21°C, respectively; average efficiency of the national Italian electric system: 0.46; lighting power density = 12 W/m². Internal gains from appliances were set to 8.6 W/m².

3.2. Configurations analyzed for the room equipped with the RBE

Two variables were changed to analyze their impact on the annual energy performance of the RBE:

- *orientation*, to analyze the energy performance of the active layers for different irradiance conditions hitting the façade. In this regard, all cardinal orientations were considered as variables (north, south, east, west)
- *thickness* (s) of the ‘active’ layers of the RBE module, to analyze the impact on the annual energy use of the sample room: the typical thicknesses (60 mm for the aerogel, 27 mm for the PCM) were compared to reduced thicknesses (15 mm for both layers). The expected advantage for this latter case is the reduced weight and size of the RBE and consequently in the global installation cost as well as in the energy used by the handling system.

3.3. Workflow and simulation tools

The room global energy demand was analyzed through a three-step procedure, using a parametric design through DIVA-for-Rhino and Grasshopper to use in synergy two dynamic simulation tools, Energy Plus and Daysim:

- 1) in step one, a 3D model of the room equipped with the RBE was built in Rhino (modeling the different orientation and the different thicknesses of the ‘active’ layers). Then, using the interface, each material was modeled in the analysis packages Energy Plus and Daysim. The RBE was designed using real materials existing in the market. Their performances were therefore taken from technical datasheet or measured on material samples available at the laboratories of the Dept. of Energy DENERG of Politecnico di Torino:

- low-E selective glazing, with commercial performances: U -value= $1.0 \text{ W/m}^2\text{K}$, τ_{vis} =60%, g -value=37%
- double-pane glazing filled with PCM. This was modeled based on measurements taken on samples installed in a facility called ‘Twin Cells’ [6]. For the PCM with standard thickness (27 mm), the performances measured were: U -value= $1.0 \text{ W/m}^2\text{K}$, τ_{vis} =46% and g -value=37% when in solid state; τ_{vis} =75% and g -value=65% when in liquid state. For the case of reduced thickness (15 mm), the performances were taken based on previous measurements carried out in the Twin Cell facility [7]: (U -value= $1.0 \text{ W/m}^2\text{K}$, τ_{vis} =55% and g -value=46% when in solid state, τ_{vis} =85% and g -value=75% when in liquid state)
- double-pane glazing filled with aerogel, with commercial performances: U -value= $0.3 \text{ W/m}^2\text{K}$, τ_{vis} =45%, g -value=54% for the $s = 60 \text{ mm}$; U -value= $1 \text{ W/m}^2\text{K}$, τ_{vis} =55%, g -value=46% for $s = 15 \text{ mm}$.

A special attention was paid to modeling the transparent PCM. Due to the lack of a tool to simulate its dynamic behavior, this was modeled through a detailed approximation procedure: for each time step of an annual simulation, the actual activation curve of the PCM was replaced with a function with a constant value for the considered time step. A subdivision of the course of a year in time-steps of 1 hour was adopted so as to increase the accuracy of the replacing function. As a result, for each time-step, three functions were determined, for solid, intermediate and liquid state, respectively. These were then matched with the weather file of Turin and, based on the annual profile of the external temperatures, the most appropriate function was used to simulate the dynamic behavior of the PCM. The reliability of this approximation was tested by comparing the energy demand for summer cooling and for winter heating obtained from Energy Plus simulations with data measured in the ‘Twin Cell’ facility for some representative days. Figure 2 shows an example of this comparison which allowed simulations to be validated. The average relative difference between simulated and measured data was found to be 17% in summer and 23% in a winter.

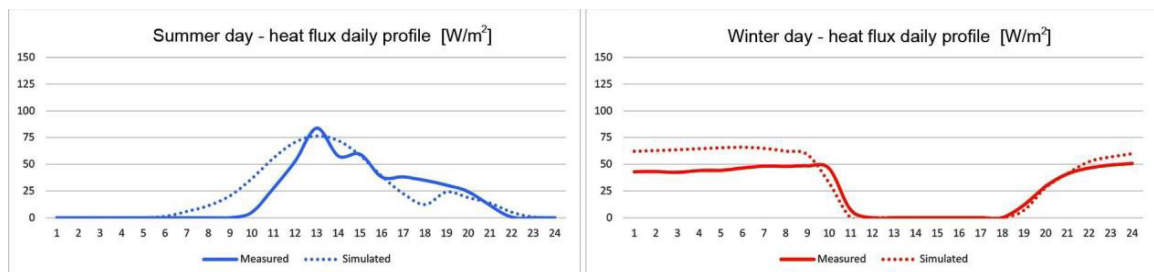


Fig. 2. Example of comparison between simulated and measured data for a summer day and a winter day.

- As final output of this phase, the annual energy performances for cooling, heating (using Energy Plus) and for lighting (using Daysim) were calculated for the three configurations separately: the Low-E selective glazing; the low-E selective glass coupled with the aerogel module; the low-E selective glass coupled with the PCM module;
- 2) in step two, results of phase 1 were imported into an Excel file and a ‘cut and paste’ algorithm was built: for each time-step of the annual simulation, the algorithm reads the global energy consumed (for cooling, heating and lighting) corresponding to each ‘stand-alone’ configuration and then identifies the configuration yielding the least global energy demand and the sequence of movements of the system was defined. As a result, a new annual profile is built, which represents the dynamic behavior of the smart façade module (‘activation profile’ of the module) through the combination of the two active layers with the passive layer;
 - 3) in step three, the energy consumption of an automated handling system EP_{motion} was calculated to assess its impact on the global energy demand. Two values of electric power were assumed, equal to 2 kW and 1 kW, for the two sets of thicknesses assumed in the parametric study. A period of 30 seconds was assumed for the motion of layers to get to the desired configuration. A purpose-algorithm was developed to control the activation of the handling system on an hourly basis, so as to avoid a too frenetic motion of the active layers which could annoy the occupants. Starting from the activation profile which was determined in step 2, the EP_{motion} was calculated for each time-step and summed to the other consumptions. The configuration yielding the best annual performance, in terms of energy savings with regard to the use of the low-E selective glazing alone, was eventually identified.

4. Results

4.1. Parametric analysis

The following criterion was adopted to analyze and compare the energy consumption results obtained from the parametric study: one configuration was selected to act as ‘reference case’, that is the case to which all other cases are compared. The ‘reference case’ was a sample room with the RBE façade module facing south and equipped with ‘standard’ thicknesses of active layers ($s=60$ mm for the aerogel and $=27$ mm for the PCM). The comparative analysis was then performed through two phases: a) comparison of the energy demand results for the ‘reference case’ with data for other orientations, keeping constancy of the active layers’ thicknesses; b) comparison of the results for the ‘reference case’ with cases with reduced thicknesses ($s=15$ mm), for all orientations.

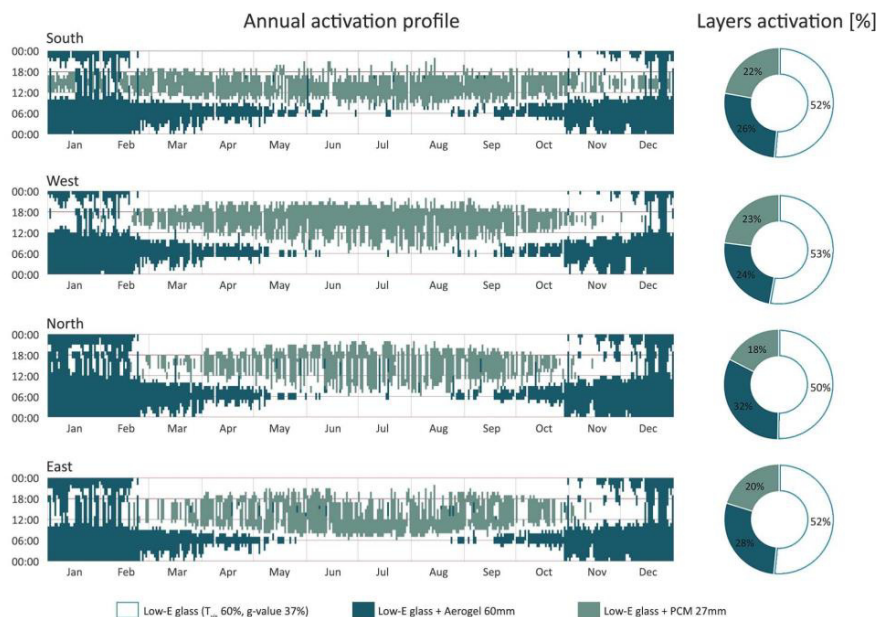


Fig. 3. Activation profile of PCM and aerogel for all orientations. The Low-E layer is ‘passive’ (i.e. in a fixed position)

With regard to the analysis phase a), Fig. 3 shows the annual frequency of activation of each layer (active and passive) which were found for different orientations, with regard to ‘standard’ thicknesses. It can be observed that aerogel and PCM are activated in different periods throughout a year (for instance, the aerogel use is prevailing during the heating season, especially for north and east orientations, when higher insulation properties are required), but in frequency terms they are both activated for about 50% of a year. It appears that, for configurations with standard thicknesses, the annual global energy demand in the presence of the RBE is lower than that observed in the presence of the Low-E selective glazing alone (on average: -44%).

With regard to phase b), Fig. 4 shows the energy savings, with respect to the reference case, which were obtained thanks to the RBE, for both thicknesses of the active layers. It is worth observing that the use of layers of reduced thickness (s=15 mm) allows saving similar to the ones of standard thicknesses to be obtained. The highest difference between standard and reduced thicknesses were calculated for west-facing configurations, while for south and east orientations the savings are practically the same, in spite of a quite different activation profile for the active layers.

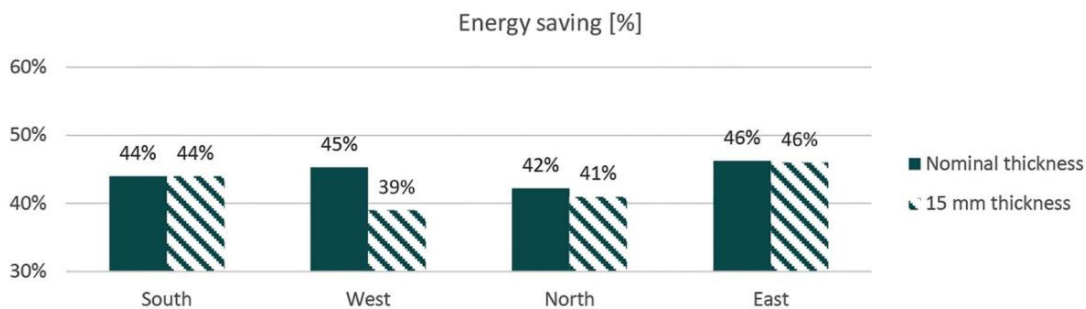


Fig.4. Energy savings due to the RBE compared to a Low-E glazing alone.

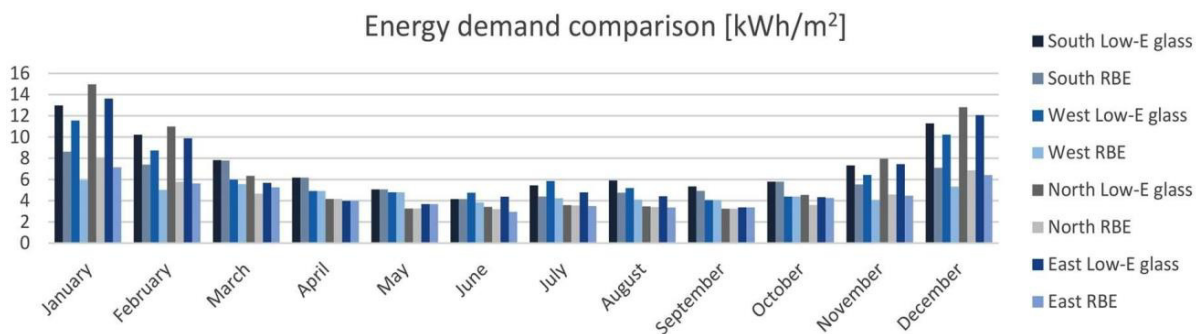


Fig. 5. Comparison of energy consumptions of the RBE and of the Low-E glazing alone for all orientations (standard thicknesses).

To analyze the different behavior of the RBE compared to a static Low-E glazing in more detail, Fig. 5 shows the energy consumption of each system on a monthly basis: the energy performance of the RBE is constantly better (i.e. the consumption is lower). The difference particularly increased in mid-seasons, during which both PCM and aerogel layers become ‘active’ every day. This is probably due to the difference between day and night conditions: during the day, temperature is high enough to get the PCM activated and during the night cold enough to activate aerogel. Data displayed in Fig. 5 include the energy consumption of the handling system was found to be in the range 4% - 6.5% of the global energy consumption of the sample room, for the different configurations analyzed.

4.2. Optimization of the RBE: identification of the best performance

The energy analysis shown in previous sections does not allow clearly identifying a unique configuration which provided the best performance for all conditions in terms of orientation and thickness of the RBE’s active layers. As a consequence, the definition of which configuration to use for the orientation of the project under examination can

be also based on other reason, such as the cost to achieve, install and handle the active layers of the RBE. In this regard, for south and east orientations, a RBE with reduced thicknesses of 15 mm for both the aerogel and the PCM is preferable, as it allows the same performance of a static Low-E glazing but implying lower costs. On the contrary, configurations with standard thicknesses provided better performances for north-facing façades.

5. Discussion and conclusions

A novel concept of a RBE was developed in this study. It consists of a static Low-E selective glazing coupled with two active layers (with an automated motion), one with an aerogel to increase the insulation in winter and one with a PCM to increase the solar control in summer. The system was designed for a sample office room located in Turin (Italy). The annual energy consumption (for cooling, heating and lighting) was assessed for different configurations, changing the orientation of the sample room and the thicknesses of the 2 active layers of the RBE.

The results showed that the RBE allowed annual primary energy performances significantly lower compared to a traditional transparent façade with a double panel Low-E glazing. The activation profile of the 2 active layers throughout a year revealed that they are used with a frequency comparable, even though to a different extent in different periods. It was also observed that the PCM and the aerogel modules do not become active only in summer or in winter, respectively, but they continuously work during the course of a year. A reduction in the ED_{gl} in the range -39% to -46% for the RBE developed in the study, with respect to the single Low-E glazing, was observed. The advantage of using the RBE was particularly evident for south, west and east orientation, as the active layers compensate for the performance weakness of a static Low-E glazing alone, whilst the RBE is less performing for the north orientation, mainly due to the scarce activation of the PCM in summer.

As for the thickness of the active layers, the reduced $s=15$ mm performed as good as the standard $s=60$ mm (aerogel) and $s=27$ mm (PCM) in terms of combined lighting, cooling and heating performance, for both south, north and east-facing rooms. On the contrary, the standard thickness performed better for west-facing rooms.

The simulation of a RBE is a complex process, due to difficulty in reproducing in analysis software the dynamic behavior of active elements or of changing properties materials. For this reason, a particular attention was paid in the study to the approximation of such dynamic behavior through a reliable combination of different ‘static’ analyses (one for a Low-E glazing, one for a Low-E glazing with aerogel and one for a Low-E glazing with PCM) on an hourly basis. Nevertheless, the development of a more accurate model for PCM and of simulation tools able to reproduce the adaptive behavior of RBE through a ‘run-time’ approach will make results more reliable in the future.

As a potential limit, it is worth stressing that the quality of the view outside may get reduced for the occupants when either one of the two ‘active’ layers of the RBE is used. To overcome this problem, an optimized configuration was also defined: the façade module is subdivided in three vertical stripes, so as to identify a central window to treat as ‘view window’ and to apply the RBE to side stripes. The room energy consumption is therefore calculated as trade-off between the best energy performance and comfort conditions for users.

The work is still on-going, with two main aims: on the one hand, increasing the number of variables of the parametric analysis, so as to include locations other than Turin and representative of different climate conditions; on the other hand, running a thermal analysis for a whole sample office building rather than for a single office.

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