Laboratory Testing of Small-Scale Active Solar Façade Module

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Abstract – Buildings are linked to a significant untapped energy saving potential, accounting for 40 % of European Union's (EU) final energy and 36 % of CO₂ emissions. Energy efficient building envelopes plays the key role to achieve decarbonization of the EU's building stock by 2050. Active building envelopes are emerging and novel trend offering the paradigm shift in perception of building enclosures. Paper presents study of active solar façade containing phase change material for energy storage. Study seeks for optimisation of solar façade module by introducing dynamic component and varying in the composition of module itself to ensure faster energy harvesting and minimise the heat losses at discharging phase. Comparative tests were carried out in laboratory, in controlled heating and cooling conditions to evaluate impact of dynamic component. The dynamic component has reflective inner coating that focuses solar radiation on the element in heating phase and aerogel insulation filling in the blades that decreases heat loss in the cooling phase. Varying components in the design were used– thickness of aerogel insulation, Fresnel lens and width of concentrating cone diameter. Wide range of phase change material average temperature was observed 24 °C in setups with full aerogel filling to 50 °C in setup Fresnel lens. Average temperature in phase change material was reached higher in all setups with dynamic component compared to identical setups without dynamic component. Temperature differences were in the range from 1 °C in aerogel filled setups till 6 °C in setups with Fresnel lens.

Keywords – Building envelope; energy efficiency; policy for buildings; renewable technology; solar energy; thermal storage

1. INTRODUCTION

Many Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, United Nations Framework Convention on Climate Change (UNFCCC) papers, protocols, and international agreements highlight energy saving and energy demand reduction as primary mitigation options [1]. Buildings are linked to a significant untapped energy saving potential, accounting for 40 % of EU final energy and 36 % of CO₂ emissions [2]. EU Energy Performance of Buildings Directive sets the goal of building decarbonization by 2050. Following the traditional path of energy efficiency strategies, it will be difficult to achieve ambitious goal. There is an urge for innovative technologies for building energy efficiency. Due to the demographic growth and changes in human lifestyles brought on by technological advancements and urbanization, it is expected that the energy consumption can increase by 53 % in the next decade, potentially increasing GHG pollution from this field [3]. A lot of the energy presently used in buildings is wasted due to out-of-date construction practices. There is a high demand of innovative technological solutions for the significant reduction of heating

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and cooling in buildings. Most of the building technologies today are based on static principle and conventional building insulation materials. To provide the necessary comfort for the inhabitants living inside the building and at the same time ensure high energy efficiency performance, building envelopes has to adapt to environmental conditions. New design trends of active building envelopes as dynamic and kinetic façades have appeared that are responding to surrounding environmental conditions such as sound, light, wind, heat and humidity [4].

1.1. Active building envelopes (ABEs)

Thanks to a growing demand to satisfy more progressive environmental, social and economic performance requirements, successful building style is changing into a more and more advanced task. The appliance of climate adaptive building envelopes has lately been suggested as a hopeful option among this try for increased rate of sustainability within the designed setting. Compared to traditional façades, ABEs provide possibilities that can occur for energy economy in addition improvement of indoor climate conditions [5]. These envelopes should be ready to adapt to the current condition and even return to their normal state if necessary in order to produce the intended outcome [6]. ABEs fulfil a number of requirements that are either incompatible or contradictory, such as finding a balance between sunlight and shadow, fresh air and draft, airflow and moisture, shutters and reflectors, heat gains and overheating [7]. There are various ways to achieve the dynamism of the envelope for example the moving components can be introduced by airflows or a chemical change of the material, but make it sufficient, adaptive features must be integrated into a whole system [8]. They can be categorized by several independent characteristics such as climatic factors (heat, light, air, water or other types of energy), the time frame scale, the scale of change [9], the control type (intrinsic or extrinsic regulators), the spatial scale (size of a system), the inspirational scale (biomimetic adaptive building skins), the development stage, the number of functions and the performance task [10]. ABEs are building element systems that:

- effectively manages the cooling and heating capacity of itself, reducing the load on central heating, ventilation, and air conditioning (HVAC) systems and often replacing their work by mechanical, electrical, or chemical actions;
- performs as energy converter by transforming renewable energy (solar, wind) into mechanical or chemical energy to improve the performance of the building [11].

Solar responsive systems work by converting solar energy into various forms. More detailed review on these systems can be found in studies [12]–[14]. They are usually based on 5 types of solar control devices: external, integrated, internal, double skin and ventilated cavity [6]. Heat too is a form of solar energy. Solar heat systems are designed and work to gain the maximum heat during wintertime and minimize it during the summer months. The solar barrel wall, rooftop water tanks, dynamic adaptable insulation, and colour-changing (thermos-chromic) materials on walls or windows are some examples of this technology [8].

Light is another form of solar energy that can be controlled by indoor illuminance levels, distributions, window views, and glare in systems that use this energy source. Classic mechanical systems such as venetian blinds, advanced mechanical systems that can rotate, slide and self-adjust, and smart glass or transparent thermos-chromic or photo-chromic materials are the three major approaches to achieve these functions. Systems used in windows, usually adapt their optical characteristics such as lighting angle and direction, visual aspects, and already mentioned thermo-chromic properties. Electrical façade glazing for buildings, for example, has evolved to be able to work in market condition and is by far the likely choice for smart building materials.

Luo *et al.* have highlighted in the review of active building envelopes that the studies in this field is insufficient [11]. There are available in decent amount of studies on photovoltaic systems and building integrated PV systems are even recognised by Fraunhofer institute as the only mass-produced system [15]. More attention have been paid to passive strategies and there is a lack of studies devoted to active systems. Study on presented in paper solar façade module will enrich the knowledge base in the field of active building envelopes, solar thermal façades and building components containing phase change materials.

1.2. Phase change materials (PCMs)

Through temperature differences in controlled conditions, phase change materials (PCM) allow energy to be stored and released according to heating and cooling demands [16]. A wide range of phase change materials are available depending on the temperature range needed. Solid-liquid PCMs are the most common to use in the building sector and they are divided into three main categories: organic, inorganic, and eutectics [17]. The most commonly used organic PCMs are based on paraffin, fatty acid and sugar alcohols with the temperature range of 0 °C to 150 °C. Paraffin is usually used because of its low temperature performance from -10 °C to 100 °C [18]. Hydrated salts are the mainly used inorganic PCMs due to their medium-low temperature heat storage properties. These materials are available and inexpensive, however they suffer from such problems as sub-cooling and phase separation [19]. Eutectics are mixtures of multiple solids in different ratios to reach the lowest melting temperature. The density of their storage volume is slightly higher than in organic compounds [20]. They can be divided in three main groups: organic-organic, inorganic-inorganic and inorganic-organic.

PCMs are used for wide range of applications in the latest decades such as thermal storage materials, air-conditioning systems, electronics, medicine and building envelopes [18]. In most cases temperature range for the building applications varies from -10 °C to +70 °C. PCMs such as salt hydrates, sugar alcohols, fatty acids, polyethylene glycols and paraffins are suitable for applications in building sector due to their melting point properties. Three fundamental considerations influence the choice of PCMs in any application: melting temperature, latent heat of fusion, and PCM thermo-physical concerns. Two key conditions in the selection method are a high heat of fusion and a specific melting/solidification temperature [21].

PCMs can be applied in passive storage systems such as walls, windows, ceilings, floor and roof where no mechanical interference is used to initiate charge and discharge cycles whereas in the active systems energy is added to make the storage system operate as necessary [22].

Research has been launched to develop an innovative dynamic façade system with solar energy storage and to evaluate the energy performance of the proposed technology. The technology is based on several previous studies of the solar façade module containing phase change material as energy storage media, silica aerogel as insulation layer and Fresnel lens for concentration of solar energy. Vanaga *et al.* [23] described comparative study – façade system containing phase change material was compared to the performance of traditional wall containing thermal insulation layer in small scale PASLINK type test cell that imitates building thermal envelope. In one cell solar façade module was built, in another test cell traditional lightweight wall construction was imitated. It was measured in 24h outdoor testing that in autumn façade system containing phase change material ensured higher indoor temperature than traditional wall. Širmelis *et al.* [25] performed laboratory testing seeking for optimisation of solar façade module. Six alternative module compositions were developed – with air gap, full aerogel filling, cone shaped insulation layer and these three were

multiplied in two variations: with and without the Fresnel lens. Results were compared with reference wall results. Small scale PASLINK test cell was used for indoor testing in climate chamber that ensured defined ‘outdoor’ temperatures and solar radiation simulation. Under these conditions laboratory testing results highlighted that 1) all modules containing phase change material ensured higher indoor temperature, thus demonstrating the advantages of energy storage thermal envelope and 2) all modules containing Fresnel lens ensured higher indoor temperature. In extended 48h testing period Mols *et al.* [24] revealed in detail charging and discharging processes in proposed façade modules. Gained results showed that despite wide range of peak temperatures at charging phase (22 °C to 35 °C) after 24h temperature in both indoor space in phase change material are close in all setups. In second 24h period devoted for discharging, less insulated modules lagged behind temperature wise. It was concluded that the combination between faster charging and slower discharging would provide better performance.

2. METHODOLOGY

Study presented in this paper seeks for optimisation of solar façade module developed in previous studies by introducing dynamic component and varying in the composition of module itself to ensure faster energy harvesting and minimise the heat losses at discharging phase. Basic structure is similar to the one in previous studies – it consists of phase change material that stores collected thermal energy and insulation layer. Introducing dynamic component in the next research steps will provide solar tracking function to absorb solar energy, respond to changing outdoor conditions (temperature and solar radiation) and diminish heat losses to the outdoor in discharging phase.

Launched research within upcoming years will follow the route reflected in Fig. 1. It consists of 4 stages – starts with conceptual design, followed by indoor and outdoor testing and ends with large scale testing where knowledge gained in first stages will be aggregated. The scope of this paper lies in first two stages of research – developing concept and indoor testing.

Fig. 1. Methodology of the research and the scope of the paper.

It is suggested to advance solar façade module by introducing dynamic element at the outer surface. Element consists of rotatable blades that opens and closes depending on the availability of solar radiation. Blades are covered with reflective coating and performs solar

tracking, thus harvesting more solar energy. When solar energy is available at a necessary intensity, blades opens and concentrates energy in the centre of the solar façade module where it is accumulated in phase change material. When solar radiation is at low intensity or at night rotating blades are closed to diminish the heat loss to surrounding environment thus allowing energy accumulated in phase change material to dissipate at a slower rate. The structure of the element is described in next chapters. The experiments in second stage are performed in controlled laboratory conditions as described later in the paper. Aim of indoor testing is to evaluate the impact of dynamic element on performance of solar façade composition variations.

2.1. Setups of solar façade module for the test

The design of the system with solar energy storage was based on the previous study [24], using the components and materials that showed the best performance results. The components included in the design is listed in Table 1.

TABLE 1. COMPONENTS OF THE WALL FAÇADE MODULE

Component	Characteristics
Phase-change material (PCM)	RUBITHERM RT21HC Melting area: 20–23 °C Congealing area: 21–19 °C
PCM glass container	Dimensions: 127×127×60 mm
Plastic box	Material: Polyethylene terephthalate glycol (PETG)
Cone	Material: Acrylonitrile styrene acrylate (ASA) white
Glass	Dimensions: 129×129×4 mm
Poly (methyl methacrylate) (PMMA) glass	Dimensions: 127×127×2 mm
Fresnel lens	Dimensions: 127×127×1.5 mm Focal length: 71.12 mm
Aerogel 1	LUMIRA translucent aerogel LA1000
Aerogel 2	ENERSENS Kwark GS
Aerogel 3	Thermal Wrap 8 mm blanket

RUBITHERM RT21HC is paraffin wax PCM with high thermal energy storage capacity of 190 kJ/kg. It is chemically inert and has no super-cooling effect. It is described by manufacturers as a long-life product, with stable performance through the phase change cycles. For the better solar energy concentration on the PCM, Edmund Optics Fresnel lens was used. It has a series of concentric grooves etched into plastic. The processing of solar light, which is nearly parallel, is one of the most popular uses for a Fresnel lens.

Fig. 2. Drawings of module in different setups.

Three kinds of aerogel were used for insulation. Aerogel 1 is LUMIRA Translucent Aerogel LA1000. It is a high-performance thermal insulator made from a modified, synthetic amorphous silica gel. The particle size ranges from 0.7 to 4 mm and the light transmission is more than 90 % per cm. Aerogel 2 is ENERSENS KwarK GS. This aerogel was chosen because of its high thermal conductivity performance ($0.018\text{--}0.022\text{ W m}^{-1}\text{K}^{-1}$) and its small particle size (10 to 1250 micrometres). Thermal Wrap 8 mm blanket or Aerogel 3 was used as filling for the blades due to its flexibility. The main difference comparing to the previous study is the implementation of dynamic component – rotating blades. This component has two main functions – concentrating light to the element to gain solar energy intensity and aerogel inner filling to protect module from heat loss. To determine the best combination of elements and materials in module, tests were performed in several setups. All setups had PCM, PCM glass container, glass and plastic box components unchanged during the whole first phase. Depending on the results of each setup some corrections and upgrades were made to reach better performance of the solar façade module such as change in the volume of aerogel filling and cone diameter. The components of all the setups are listed in the Table 2 and the drawings of different setups are illustrated in Fig. 2. The aerogel filament for setups 1 and 2 was chosen accordingly to the focal length in setups 3 to 6, but in setup 7 and 8 it was equated to the volume of filament in setups 3 and 4. Cone diameter from 1.5 to 2.4 cm in setups 5 and 6 was changed to improve the heat transmission to PCM.

Fig. 3. Cross-section of a solar façade module with dynamic component.

Fig. 3 represents the cross-section of the solar façade module with dynamic component. Module consists of 3 main elements – dynamic component (blades with hinges), heat transmission element (Fresnel lens, cone and plastic box) and energy storage (PCM). Plastic component for measurements is necessary to determine the temperature in different spots of PCM during the test. Glass container was made out of 5 sheets of 4 mm glass glued together with silicon paste. The glass component seals the aerogel in heat transmission element so that it can be easily moved between setups. Plastic box, hinges and the blades were printed out using 3D printer. Settings for the printer was chosen accordingly to printing filament. For the hinges and plastic boxes, the printing material was chosen PETG which is durable and tough with high impact strength with maximum service temperature from $51\text{ }^{\circ}\text{C}$ to $64\text{ }^{\circ}\text{C}$. As the

plastic box nor hinges gets to exposed to intensive solar radiation, the material is completely compatible for its purpose.

TABLE 2. COMPONENTS IN ALL OF THE SETUPS

Setup	1	2	3	4	5	6	7	8	9
Phase-change material (PCM)	+	+	+	+	+	+	+	+	+
PCM glass container	+	+	+	+	+	+	+	+	+
Glass	+	+	+	+	+	+	+	+	+
Plastic box	+	+	+	+	+	+	+	+	+
Hinges		+		+		+		+	+
Aerogel 1 (1006.69 cm ³)	+	+							
Aerogel 1 (768.47 cm ³)					+	+	+	+	
Aerogel 1 (763.62 cm ³)			+	+					
Aerogel 2 (683.80 cm ³)									+
Aerogel 3		+		+		+		+	+
Cone (diameter 1.5 cm)			+	+					
Cone (diameter 2.4 cm)					+	+			
Cone (diameter 4 cm)									+
Fresnel lens			+	+	+	+			+
Blades with reflector and aerogel filling		+		+		+		+	+

The blades and cones were printed out using ASA material because of its resistance in high temperatures (up to 105 °C). Cone, glass and lens were fixed together using transparent glue. The inner part of the blade has a shelf design so it can hold in the aerogel blanket from one side and provide the space for reflective component to lay down and seal from the other side. PMMA mirror was used as the reflective element of the blade.

This decision was made based on the characteristics of the component. PMMA is tough, durable and lightweight thermoplastic and its density is a half less than that of glass. It was cut into a triangle shape so that it can fit into the design of blade. Aerogel Thermal Wrap blanket was used as filling because of its superior thermal and insulation performance. Its operating temperature range is −200 °C up to 125 °C and thermal conductivity at room temperature is around 23 mWm^{−1}K^{−1}. To reduce the heat loss while the ambient temperature is lower than the temperature in PCM, rubber sealing was introduced to the air gaps of dynamic component.

2.2. Experiment planning

The main goal of the second stage laboratory test is to find out the most efficient and the most appropriate solar façade module for the outdoor testing, considering the temperature and heat flow performance of the PCM energy storage. Tests are carried out as a comparative study between different setups and taking place in a controlled indoor environment. The conditions including heating and cooling are provided equal for all of the setups. Conditions of experiment is summarised in Table 3.

TABLE 3. CONDITIONS OF THE EXPERIMENT

Condition	Value
Heating	7 hours
Cooling	17 hours
Irradiance	1000 W/m ²
Temperature of PCM	16 °C
Cooling temperature	2 °C
Cooling humidity	30 %

The length of the test is 24 hours. The heating phase of 7 hours is chosen based on spring and autumn weather conditions in temperate climate zone with an average daily solar irradiance of 1000 W/m². The temperature of PCM at the beginning of the test is set 16 °C to ensure the PCM is still in solid form as the melting starts from 20 °C. Cooling temperature is lowered to 2 °C to imitate the conditions in the night time. The necessary irradiance in the heating phase is provided by Litecraft PAR 64 light. The value of irradiance is set manually using the dimmer. In the cooling stage the test module is placed in environmental test chamber where the required temperature and humidity is set (see Fig. 4).

Fig. 4. PCM in solid state (left), heating phase (in the middle) and cooling phase (right).

PCM component is cooled to solid state (16 °C) before the insertion in the testing setup module. In the setups with dynamic component (setups 2, 4, 6, 8 and 9) the reflective blades have been set that they focus the light from the source to the centre of tested module in heating phase but during the cooling phase blades have been closed and fixed with the screws in hinges.

2.3. Selection of measuring equipment

During the test measurements are registered via Multipurpose data logger CR1000 Campbell Scientific combined with multiplexer AM16/32 Campbell Scientific. The period of data reading is one minute. Pyranometer CMP3, Kipp & Zonen is used to measure solar radiation and the usage for Type K thermocouples is to measure temperature in PCM. To capture heat flow and temperature measurements, Flux Tecq PHFS-01e sensors are used.

Temperatures inside the PCM is measured in 6 spots. Ambient room and outdoor temperature as well as temperature measures inside the cones in different setups has been taken. Heat flow and temperature measurements were taken by adding a heat flux sensor on the lens or PMMA (depending on the setup) in the cooling cycle.

3. RESULTS AND DISCUSSION

3.1. Laboratory testing results

Fig. 6 shows the graph of average temperature comparison between all setups. The first tests were done with Setups 1 and 2, where the thickness of aerogel filling was equalled to the length of the focal point of Fresnel lens. Temperature measurements in PCM showed that the phase change happens only in the upper layer of PCM. The lower layer does not reach the temperatures as high to completely melt. In the Setup 2 blades were added to concentrate more light on the test module. However, the temperature performance was similar to the Setup 1 and the phase change was not registered in all of the layers. In the comparison between average temperatures in PCM, Setup 2 reaches 1 °C higher at a peak. To provide faster energy transfer to PCM in the charging phase, the cone and Fresnel lens were added in the Setup 3 and Setup 4. Thermocouple sensor was added inside the cone to observe the temperature in the air gap between the lens and the PCM container. The temperature registered inside the cone was 75.6 °C in Setup 4 and the highest temperature inside the PCM was approximately 1.5 °C higher than in Setup 3. Based on temperatures in measurement points it is concluded that the phase change in all of the layers in PCM has happened in both of these setups (Setups 3 and 4). Due to higher temperatures inside the PCM reached in Setup 4, the time it takes to release heat is longer. Compared to first three setups, Setup 4 shows the best temperature performance in both, charging and discharging cycles of the PCM – temperatures are higher, and the solidification cycle takes longer time.

Fig. 6. Average temperature comparison in PCM between setups. Dotted lines for setups with blades.

Despite the fact that all the layers of PCM has reached the phase change in Setup 3 and 4, the maximum temperature in the lower layers does not exceed 28.5 °C. However, the temperatures in cone are high in both setups (69 °C and 75.6 °C) that points to a potential of using this heat to gain higher temperatures in PCM. For this reason, cone diameter (from 1.5 cm to 2.4 cm) at the PCM glass container was introduced in Setups 5 and 6. Temperature graphs shows that the phase change in lower layers has happened faster (approximately after 5:30 h) in Setup 6 compared to previous setups and the temperatures inside the PCM are higher as well, peaking at 40.6 °C and 46.4 °C in Setups 5 and 6 accordingly.

PCM in Setup 1 and 2 did not reach the phase change in lower layers possibly because of the thick aerogel coating. In Setups 7 and 8 the aerogel layer was reduced by the volume of cone in Setups 5 and 6. It is visible that the change of the aerogel coating layer dramatically effects the performance of the test module. Average PCM temperature peaks from 23.7 °C in Setup 1 to 49.5 °C in Setup 8. In Setup 8 phase change in the lower layers of PCM starts already at 4:40 h and the solidification period is the longest compared to all previous setups. These differences are significant between Setups 7 and 8 as well that highlights the positive effect of added blades. Comparing Setups 6 and 8, it is visible that the setup with cone (Setup 6) is lacking performance in average maximum temperature (42.57 °C in Setup 6 and 49.53 °C in Setup 8) and the length of the solidification of PCM (7 hours in Setup 6 and 8:30 hrs). Besides that, the high temperature inside the cone (the highest peak of 79 °C) indicates a possibility to transfer more heat energy to the PCM. Considering all of the factors mentioned above the test module for Setup 9 was designed. The cone diameter was increased from 2.4 cm to 4 cm and different kind of aerogel (Aerogel 3) with better thermal performance properties was introduced.

It is clearly seen that all of the setups with the dynamic component presents better thermal performance in heating and cooling cycles (see Fig. 8). In spite the slight lack of temperature performance in Setup 9 in solidification phase of the PCM comparing to Setup 8, it gathers significantly more heat in the charging phase. Due to the usage of cone and lens, heat energy is transferred to the PCM much faster. The aerogel used in Setups 1, 2, 7 and 8 is translucent and transfers solar radiation well, however, it takes some time and higher temperatures to deliver heat energy to the PCM. The solution in Setup 9 is more adaptive to changing environmental conditions and responds more dynamically by rising temperature in PCM and initiating melting and latent energy storing faster.

3.2. Further study

Setup 9 with cone diameter 4 cm and rotating blades demonstrated the highest performance – it had the fastest charging rate and due to the gained sensible heat, it entered solidification phase later in time compared to other setups – and is suggested for outdoor testing in the next steps of the research. Comparative testing is suggested for outdoor testing as well to evaluate the impact of dynamic component on overall performance of solar façade under real climatic conditions. Laboratory testing was performed in static circumstances – blades opened in optimal position in charging phase and closed in discharging phase. For outdoor testing, control mechanism will be applied to ensure the solar tracking function for blades and faster energy harvesting.

Results gained in laboratory and presented in paper are suitable for verification mathematical modelling. Mathematical modelling compared to laboratory testing allows exploring wider range of climatic conditions and dynamics. Verification of mathematical modelling results with laboratory testing raises the liability of modelling results. Verified model would allow to explore further optimisation strategies of solar façade model design to find optimal balance between charging and discharging of various climatic conditions.

4. CONCLUSION AND RECOMMENDATIONS

A new technology of dynamic façade with solar energy storage has been developed and tested in laboratory under controlled conditions. 9 designs of a small-scale façade modules were tested in laboratory with and without dynamic component – rotating blades that functions as solar energy concentrator during the availability of sun and as additional insulator

(blades with reflective surface and aerogel filling) when it is unavailable. Laboratory tests show the potential of dynamic component in proposed technology in both – thermal energy absorption in the PCM charging phase and storage in discharging phase. Wide range of phase change material average temperature was observed in laboratory testing under defined solar simulation and temperatures 24 °C in setups 1 and 2 with 7 cm aerogel filling to 50 °C in setup 9 with wider cone diameter (4 cm). Average temperature in phase change material was reached higher in all setups with dynamic component compared to identical setups without dynamic component. Temperature differences were in the range from 1 °C in aerogel filled (7 cm) setups 1 and 2 till 6 °C in setups 5 and 6.

Introduced Fresnel lens ensures more dynamic thermal behaviour of the module. Under real climatic loads it is crucial to enhance heat transfer when certain level of solar radiation is achieved especially in the conditions when sun shines periodically during the day.

Developed façade module demonstrates a potential to become on-site renewable energy storage media ensuring conversion of solar energy to thermal energy. Some further improvements are necessary to make for proposed façade module's dynamic component to increase the energy efficiency such as reflective component's performance should be controlled more dynamically according to changing environmental conditions and the air movements should be reduced by optimising air tightness.

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