Energy performance of a ventilated double skin facade with PCM under different climates

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Abstract

New policies are being promoted worldwide to reduce the energy consumption for space heating and cooling in the building sector. As a new technology to achieve this objective, phase change material (PCM) panels were installed in a new type of ventilated facade to reduce the consumption for space heating and cooling. During winter, the PCM increases the heat storage capacity of the system exposed to solar radiation, while during summer the system can be used as a cold storage unit or as a night free cooling device. The potential of the system to provide energy benefits in the heating period has been demonstrated experimentally under Mediterranean - continental climate conditions, on the other hand, limited benefits were found during the cooling season. The aim of this study is to determine the potential and suitability of this system to operate for cooling purposes, under different weather conditions around the world. In order to accomplish this objective, an own developed numerical model, based on finite control volume approach, was developed and validated against experimental data. The numerical tool is also used to improve the design and to select the most appropriate schedule of the system under the different analysed weather conditions.

Keywords: ventilated double skin facade, thermal energy storage, phase change materials, buildings, numerical study, climate conditions, potential.

1. Introduction

Apart from enforce stringent building codes that include minimum energy consumption for new and refurbished buildings, the ETP 2012 [1] highlights the necessity of using highly-efficient technologies in the building envelopes, equipment and new strategies to address the high energy consumption of the sector. The improvements in buildings envelopes have high potential in energy demand reduction and consequently in energy savings [2]. Within this context, the use of ventilated double skin facades (VDSF) in the building sector has recently become a topic of great interest by architects and engineers, not only because of their aesthetics and acoustic properties but also because they can absorb solar radiation during the heating season and avoid overheating during summer [3].

VDSF are based on a special type of envelope where a second skin, usually a transparent glazing, is placed in front of a regular building facade. The air space in between (the channel) can be mechanically or naturally ventilated to improve the thermal performance of the building [4]. Those facades, if well designed, can efficiently reduce the overall HVAC consumption in buildings [5].

It is well known that the use of adequate thermal energy storage (TES) systems in the building and industrial sector presents high potential in energy conservation [6,7]. The use of TES can overcome the lack of coincidence between the energy supply and its demand; its application in active and passive systems allows the use of waste energy, peak load shifting strategies, and rational use of thermal energy.

Within this context, the use of latent energy storage systems in buildings has been a topic of great interest in the literature [8,9] both in active [10] and passive systems [11]. In this study, macro-encapsulated phase change material (PCM) is introduced in the air chamber of a VDSF system. The addition of PCM is not only focused in absorbing the solar radiation and use it for heating purposes during the winter season, but also to be used as a cold storage system during the summer season and hence reduce the HVAC energy consumption, as well. This versatile VDSF with PCM in its chamber is designed and presented as a suitable tool to reduce both heating and cooling expenses making an intensive use of the PCM. Experimental measurements were driven in an experimental set-up in Puigverd de Lleida (Spain) showing high potential of this system, under dry Mediterranean continental climate, to reduce the electrical energy consumption for HVAC especially during the heating period [12], and determining crucial design and operational parameters to achieve energy benefits during the cooling season [13].

In addition, Soares et al. [14] investigated numerically the impact of PCM-drywalls in the heating and cooling energy consumption in a lightweight steel-framed when implemented under several European climates. The authors evaluated different thermo-physical properties of the PCM and design parameters such as air-infiltration rates, solar gains, internal gains, and set-points to conclude that PCM passive systems can contribute for annual heating and cooling and an optimum solution can be found for each European climate. This attempt to develop specific solutions for different locations based on their climate is seen as a good approach to foster the implementation of a specific technology.

Therefore, a similar approach has been used in this paper with the aim of evaluating the energy performance and the potential of using PCM in the previously described active ventilated facade if used under different weather conditions around the world for cooling purposes. A numerical model will be used not only to determine the potential of the system in different climates, but also to study the best operational schedule during the charge process in order to maximize the energy benefits. Moreover, this paper will evaluate the impact of different key design aspects of the ventilated double skin facade, such as the used PCM or the outer skin of the system.

2. Methodology

2.1 Prototype and operating principle description

The ventilated facade with PCM is located in the south wall with a metallic structure to hold the insulating panels that are used as the outer opaque skin (Figure 1). The air cavity is 15 cm thick and incorporates 112 PCM panels (SP-22 from Rubitherm, melting at 21.5 ºC and solidification at 18 ºC) creating 14 airflow channels. Moreover, the system is equipped with three fans located at the bottom and six gates distributed at inlet and outlet of the cavity, so different airflow paths can be programmed, as well as mechanical or natural ventilation conditions (Figure 2). Detailed description of the prototype can be found in de Gracia et al. [12,13].

The operating principle of this system during the cooling period is based on using the low temperatures at night (below the congealing temperature of the PCM) to solidify completely the PCM, and store cold to provide a cooling supply during the daytime when required by the demand.

During the charge process (Figure 2a) air is pumped from outdoors using the fans in order to intensify the convective heat exchange. The fans can work under different power rates as detailed in Table 1, however, they are usually programmed to operate at the lowest flow rate (Q_1) in order to maximize the discharge period. During charging, it is critical to reduce as much as possible their use while ensuring complete solidification of the PCM to achieve a better net energy balance.

Once the PCM is charged, the VDSF is used as a cold storage system and all the gates are closed before a cooling supply is needed in the inner environment. Then, instead of using conventional HVAC systems which implies the electrical energy consumption, the discharge process starts (Figure 2b). Once the PCM has been melted the facade is opened outdoors and natural convection avoids overheating inside the VDSF (Figure 2c). Moreover, during the night charge period, if the temperature at the outlet of the channel is lower than the set point at the inner environment, the system can also provide night free cooling as shown in Figure 2d.

2.2 Numerical model

A numerical model based on the finite control volume method has been developed in order to better understand the thermal performance of the VDSF with PCM, to optimize its operational schedule, and to improve its thermal design [15]. The energy equation is solved using a fully implicit scheme being a two dimensional coordinate system [16].

Moreover, empirical correlations of Nusselt number [17] were used to calculate the convective heat transfer coefficients between the air flow and the different solids of the VDSF except PCM. In the case of air-PCM convective heat transfer, a correlation which takes into account the perturbation in the Nusselt number due to the phase change has been used [18].

The PCM is assumed to be homogeneous and isotropic, and the phase change was modeled using an equivalent heat capacity method [19]. The numerical model was validated experimentally and is detailed in de Gracia et al. [15].

The numerical study will evaluate the energy performance of the VDSF under the following conditions:
(i) The whole system is at 24 ºC at 01:00 am, with the PCM fully melted.
(ii) The night charge process starts after 01:00 a.m. and it is performed until all the PCM is completely solidified.
(iii) The discharge process starts at 11:00 a.m. and it is performed until the power consumed by the fans is higher than the cooling power supplied by the system. Moreover, the authors considered that no more cooling supply is needed after 20:00.
(iv) Set point of the inner environment is 24ºC.
(v) The fans are working at the Q_1 flow rate.

2.3 Analyzed climate conditions

As it was previously stated, the main objective of this work is to evaluate the energy performance of this system if located in different places around the world. Since the system performance is mainly defined by the weather conditions, the Köppen-Geiger Climate Classification [20] was used to select representative locations to be evaluated (Figure 3).

This classification divides the main climate in A: equatorial, B: arid, C: warm temperate, D: snow and E: polar. Moreover, it defines the level of precipitation in W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal. Finally, it provides details about temperature as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d:

extremely continental, F: polar frost, T: polar tundra. The combination of the previous definitions gives an overall information about the weather conditions at each location.

In this study, all the possible climates were analyzed except those that do not need any cooling supply during the whole year (E: polar and mostly all D: snow main climates). The weather conditions were extracted from the weather data files for EnergyPlus [21] provided and developed by the US Department of Energy. The summer typical day of each location was considered in order to evaluate the potential of the VDSF for cooling purposes around the world.

3. Results and discussion

3.1 Potential of PCM solidification and free cooling supply

A list of the analyzed cities and their climate classification is given in Figure 4, as well as a summary of their climate conditions and the phase change range of the used PCM (SP-22). The PCM used in the VDSF finishes its solidification process at 17.5 ºC; hence night temperature below this value is required to operate the system using the cold storage sequence. Figure 4 indicates the suitability of the system for each case depending on whether or not this requirement is satisfied.

It can be seen that, due to the hysteresis of SP22, the use of the VDSF with PCM for cooling purposes is limited to certain areas of the planet with “warm temperate” and “snow” main climate, and not even to all the analyzed cities in these areas. In the case of implementing a PCM without hysteresis, such as RT21, the use of the system would be extended to all the areas with warm and snow main climate conditions.

Moreover, neither arid nor equatorial areas present suitable climate conditions to solidify the PCM during the summer period. However, from the weather data base it was observed that even though the system was discarded to operate during summer in arid areas, the VDSF would be able to provide cooling during autumn and spring periods, as shown in Figure 5 for Albuquerque (BSK). Nevertheless, the study of these periods is out of the scope of this work.

In order to provide significant net energy savings from the system, it is important to determine and minimize the energy consumption of fans, by reducing as much as possible the charge period (mechanical ventilation 55 W) while ensuring the complete solidification of the PCM. Table 2 shows the charge schedule and hence electrical energy required to solidify the PCM in the cities in which the PCM can be fully solidified during the night period. It can be seen that the time required to fully solidify the PCM varies between two and three hours, in addition the timing of this charge process depends on the outer thermal evolution. The amount of cold stored during the charge period is also shown in Table 2, with values around 8 MJ/day at all locations and showing the maximum value of 10.65 MJ/day in the city of Quito (Cfb).

As it was previously highlighted, the high hysteresis of the PCM limits strongly the suitability of the system to operate in certain climate conditions, hence the authors have also evaluated the charge process of the system if operating with a PCM with the same thermo physical properties of SP22 but with no hysteresis (congealing thermal range supposed to be equal as the melting thermal range at 23.5ºC - 19.5ºC). In this case, in addition to the eight cities included in Table 3, the system can be fully charged in Brasilia (Aw), Antofagasta (BWk) and Auckland (Cfb).

Moreover, fans can work at higher flow rates, which enable the full solidification of the PCM in certain climates where it is not possible when operating at the lowest flow rate (Q_1). As an example, Brasilia (Aw) presents a temperature below the congealing area during short period of time. In this case, the system cannot fully solidify the PCM if operating using Q_1, but it can achieve full solidification under Q_2 and Q_3 flow rate conditions if charging from 01:00 to 07:00 and from 02:00 to 06:00, respectively.

Similarly, depending on the outer temperature profile, heat transfer can be intensified during the hours of low temperature at night and hence reduce the electrical energy consumed by the fans. As an example, in the city of Berlin (climate Cfb) the system requires the use of fans at Q_1 from 02:00 to 05:00, which lead to an electrical consumption of 0.59 MJ. However, if the fans are used at a rate of Q_2 (2 hours) or Q_3 (1 hour) the system only consumes 0.54 MJ and 0.43 MJ, respectively to achieve the full solidification.

Furthermore, as it was previously stated, the VDSF can provide free cooling during the charge process of the PCM if the temperature at the outlet of the air channel is below the set point of the inner environment. Figure 6 shows the maximum potential of the system to provide a daily free cooling supply during summer, if pumping air from outdoors to indoors from 01:00 to 07:00 a.m. It can be seen that the potential is very heterogeneous depending on the climate conditions since there are cities with no potential (Kuala Lumpur, Singapore and New Delhi) and there are regions that can achieve values above 200 MJ/day. However, it has to be noticed that this free cooling supply can be released to the inner environment during the night period, where the cooling demand is lower due to the outer environmental conditions. Thus makes the versatile VDSF very suitable for buildings with high thermal inertia in the envelopes which provide an important thermal lag or to buildings with other peak load shifting strategies.

From Figure 6 it is not possible to determine a precise rule for the free cooling potential depending on the climate region, but it can be stated generally that in the “warm temperate” and “snow” main climate areas, there exists a high potential to use this technology with the exception of Chicago (Dfa). On the other hand, in “arid” and “equatorial” areas the free cooling is very limited except for Brasilia (Aw) and Antofagasta (BWk).

3.2 Cooling supply during discharge

The amount of cooling supply provided by the system as well as the cooling period is given in Table 4. As it was previously defined, the VDSF starts its discharge at 11:00 until no more cooling can be provided or there is no more cooling demand (20:00 h). The results for the VDSF with the metallic structure indicate that the system can provide a significant cooling supply between 4 and 6 MJ/day. It is important to highlight that even though the potential of free cooling is much higher than the potential of the cold storage sequence, the discharge of the cold storage is released during 3 or 4 hours inside the peak cooling demand period of the building and not during the night as the free cooling supply. Moreover, depending on the cooling requirements of the building and the climate region, the supply from the cold storage sequence could avoid the necessity of using any HVAC system to provide cooling.

The amount of cooling that the system can supply depends on the amount of cold charged during the nighttime and on the weather conditions (outdoor temperature and solar radiation). The heat gains during the storage and discharge periods limit strongly the energy performance of the system. These heat gains are significant because of the metallic structure used in the outer skin of the VDSF, which acts as a thermal bridge between the outer environment and the air channel.

Table 3 also shows the results during the discharge process if the structure was made of wood instead of steel. The replacement of the outer structure has a high impact on the energy performance of the system, extending the discharge period significantly and hence increasing the cooling supply in all the tested climatic regions. These energy benefits depend strongly on both the outdoor temperature and the vertical solar irradiance. Numerical results show that in areas with high vertical solar irradiance during summer, such as Stockholm, Quito, Berlin, Johannesburg or Montreal (see Figure 4), the cooling supply is increased more than 80% when improving the thermal resistance of the outer skin. On the other hand, these benefits decrease below 45% for places without high vertical solar incidence, such as Mexico, Brasilia or Antofagasta.

3.3 Net energy supply

The net energy supplied by the VDSF is an appropriate overall parameter to determine its potential to displace the electrical energy consumption of the building for HVAC purposes. In order to compare the cooling supply with the electrical energy consumed by the fans, the authors have assumed the use of a standard heat pump with COP of 3. Thus, the electrical energy savings due to the use of the VDSF with PCM can be quantified. In this chapter, the authors will distinguish between the net electrical energy savings that can be achieved from the free cooling supply and from the cold storage sequence. As it was previously discussed, these two cooling supplies cannot be compared between each other because they are aimed to supply cooling and different periods and with different demand requirements.

For the free cooling process, the fans are being used during 6 hours, consuming 1.2 MJ. However, the net energy savings achieved by free cooling (always subjected to the cooling demand during the night) justify their use in all climates where free cooling is possible.

As previously stated, the potential of free cooling depends strongly on the outer thermal profile, and so does the net electrical energy savings, varying from 76 MJ/day in Quito (Cfb) to just 5.2 MJ/day in Albuquerque (BsK) considering an internal set point of 24ºC and a COP of 3 for the standard HVAC system.

Moreover, Figure 7 shows the net electrical energy savings due to the cold storage sequence in the case of using a metallic or a wooden structure. In the case of using the metallic structure the savings vary between values around 1 MJ/day in Mexico DF and Quito, and no net electrical savings in climate regions with high vertical solar irradiance in summer, such as Stockholm.

As expected, the use of a wooden structure instead of metal provide a significant thermal benefit to the system in all the studied climatic areas, which lead to important increments in the amount of net electrical energy savings at each location. Numerical results demonstrated that in all the cities under the “warm temperature” main climate with suitable conditions for the operation of the system, the VDSF can provide net energy savings above 1.2 MJ, with the exception of Auckland (Cfb).

4. Conclusions

In the present paper, the potential benefits of an innovative VDSF with PCM, which were evaluated experimentally only for Mediterranean – continental climate, are extended by means of a numerical model to several locations representative of different climates all over the world. 11 cities with different suitable weather conditions to operate the VDSF were selected using the Köppen-Geiger climate map.

The VDSF presents three potential benefits: free cooling, cold storage, and prevention of solar radiation incidence. The "warm temperate" and "snow" main climate areas were found to present a high potential to provide free cooling. However, the potential is very limited in "arid" and "equatorial" areas except for Brasilia (Aw) and Antofagasta (BWk).

The energy benefits from the cold storage sequence depend strongly on the vertical solar irradiance and the heat gains of the structure (thermal transmittance and thermal bridges). The potential of this sequence to provide a cooling supply is limited to values below 12 MJ/day while free cooling can achieve values above 150 MJ/day depending on the region. However, the cold storage sequence is able to provide cooling during 3 or 4 hours at the peak cooling demand period of the building.

The reduction of the cooling demand due to prevention of solar radiation incidence was not studied in this paper.

Different charging strategies resulted in significant differences in the VDSF benefits. An optimization of the process and the implementation of a control strategy based on artificial intelligence algorithms, are key factors for the future development of this technology and thus, require further investigation.

5. Acknowledgements

This work was supported by the "Corporación Tecnológica de Andalucía" by means of the project "MECLIDE-Soluciones estructurales con materiales especiales para la climatización diferida de edificios" with the collaboration of DETEA. The work partially funded by the Spanish government (ENE2011-28269-C03-01 and ULLE10-4E-1305). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2014 SGR 123). The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PIRSES-GA-2013-610692 (INNOSTORAGE).

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