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Published in:
Journal of Physics: Conference Series

DOI (link to publication from Publisher):
10.1088/1742-6596/2042/1/012161

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Hu, Y., & Heiselberg, P. K. (2021). Development of strategy for combined smart ventilated window and PCM energy storage control for residential building energy saving. *Journal of Physics: Conference Series*, *2042*(1), [012161]. https://doi.org/10.1088/1742-6596/2042/1/012161

Journal of Physics: Conference Series

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To cite this article: Yue Hu and Per Kvols Heiselberg 2021 *J. Phys.: Conf. Ser.* **2042** 012161

Development of strategy for combined smart ventilated window and PCM energy storage control for residential building energy saving

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Abstract. The paper studies the energy renovation of a residential building with new façade solutions combining smart ventilated window (VW) and PCM energy storage and the corresponding control strategy to ensure energy savings. The study is carried out by Energyplus modelling comparing the energy consumption and thermal comfort of an apartment before and after renovation. A detailed control strategy is introduced and simulated. The modelling results of the apartment before and after retrofit indicate that with the designed control strategies, the average energy saving percentage of the apartment with PCM energy storage and VW compared to the apartment without PCM energy storage and VW is 29%. The rooms with PCMVWs achieve higher energy saving than the rooms with only VWs. The PCM energy storage improves energy performance of the VWs for both heating and cooling seasons. With the renovation, the thermal comfort of all the rooms are improved for cooling season.

1. Introduction

Ventilation is a good solution to guarantee good indoor air quality and thermal comfort. However, conventional ventilation methods are normally energy-consuming. Research shows that ventilation and HVAC systems account for about 40% of the total energy use in Europe [1]. In order to achieve building energy savings and decrease the carbon dioxide emissions from the building sector, it is essential to improve the building energy efficiency by adopting new ventilation technologies.

One of these is the Smart Ventilated Window (VW), which was initially developed by [2]. Their study indicates that with a good design, the VW can achieve good indoor thermal comfort with energy savings. Their design optimization recommends the ventilated window to have solar control and a double layer glazing facing outside and a single layer glazing facing inside, to achieve good energy efficiency and thermal comfort.

The limitations of the ventilated window is its poor cooling ability, especially during summer seasons [3]; and the heating ability is also limited and highly depends on the real-time solar radiation condition [4]. Possible solutions to improve the performance of the VW are either designing better ventilation control, or enhancing it with the assistance of other technologies.

Phase change materials (PCM) are materials that can change their phase and store/release large amount of latent heat during the phase transition period [1]. They are largely used for building heating and cooling applications. The combination of PCM and VW can improve the heating and cooling performance of the VW significantly, by making use of night cooling and passive solar energy for ventilation pre-cooling and pre-heating.

This research aims to design and test the ventilation control in a smart building for good indoor air quality and heating/cooling energy savings. Ventilated windows (VWs) and PCM energy storage combined ventilated windows (PCMVW) are modelled in a residential building, with a control strategy developed for both the VW and the PCMVW. Thecalculation model developed in the building simulation software EnergyPlus for the ventilated window combined with the PCM solar capture and energy storage unit is experimentally verified by [5]. It is used in this paper to test performance and the designed ventilation control strategies by calculating the energy demand of one apartment on the first floor of the building. The heating and cooling energy demand is calculated for the apartment before and after retrofit and the energy-saving potential is determined.

2. Modelling methods

The demonstration project is a multifamily apartment building located in Frederikshavn, Denmark. The renovation of the building includes installation of PCMVWs and VWs in the facades. Figure 1 shows the geometry of the apartment on the first floor after retrofit. The standard windows are replaced by 3 ventilated windows (VWs) and 2 PCM enhanced ventilated windows (PCMVWs) on the west and east façades of the apartment. The PCMVWs are installed in the living room, and the VWs are installed in the rest of the rooms. In the Energyplus model, the rooms, VWs and PCMVWs are divided into separate thermal zones.

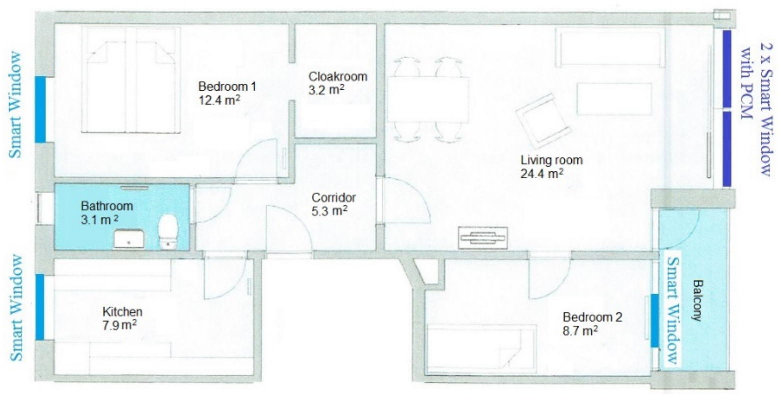

Figure 1. Dwelling in Munkeparken with installation of Smart Windows and Smart Window and PCM energy storage unit.

The ideal heating and cooling energy demand of the apartment both before and after retrofit is simulated in Energyplus. The energy saving percentage of the apartment with PCMVWs and VWs is then calculated by comparing the building energy demand before and after retrofit. The indoor temperature setpoint is 22°C -26°C. The apartments on the 1st floor and 2nd floor are evaluated respectively. The apartment on the first floor has the boundary conditions of internal ceilings and ground floors, while the apartment on the second floor has the boundary of internal ceilings and internal floors. The U values of the different constructions are shown in Table 4.

The PCMVW works differently in summer and winter. In summer, the PCM is cooled down by outdoor air during the night (Figure 2-1 and 2-2). The cold PCM is then used to pre-cool the ventilation air during daytime, when cooling demand is present in the room (Figure 2-3). In winter, the PCM stores the solar energy during the sunny day (Figure 3-1 and 3-2). The hot PCM then releases heat for the purpose of ventilation pre-heating, when heating demand is present in the room (Figure 3-3).

The control strategy of the ventilated window is shown in Figure 4(a). It adjusts the ventilation operation model depending on indoor air temperature. The ventilation pre-heating mode is on when the indoor air temperature is low, and the ventilation goes through the window cavity to be heated up by the heat accumulated in the cavity. The overheating preventing mode is on when the indoor air temperature is high, and the room is ventilated with bypass ventilation, while the window cavity is cooled down by self-cooling ventilation. As a reference case, the apartment with normal windows is ventilated directly from outdoors, as shown in Figure 4(b). The ventilation air flow rate is 30 m^3/h/person, which in average is 0.0039 m^3/s from each window.

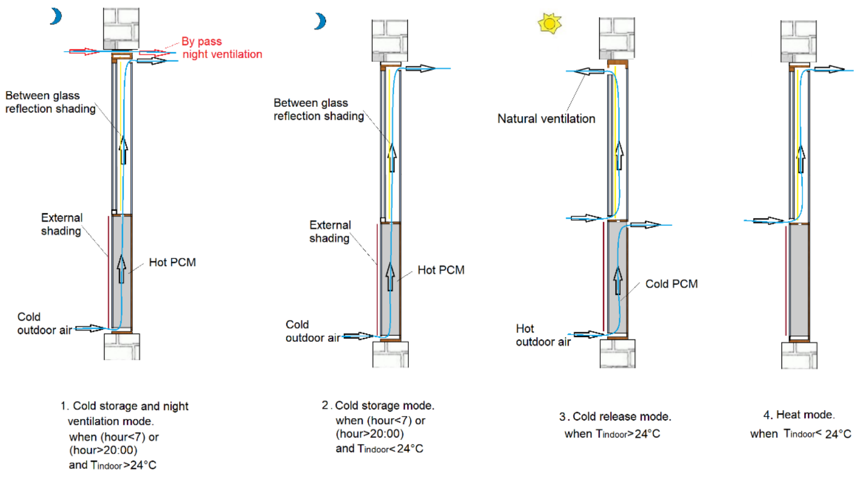

Figure 2. The summer control strategy of PCMVW.

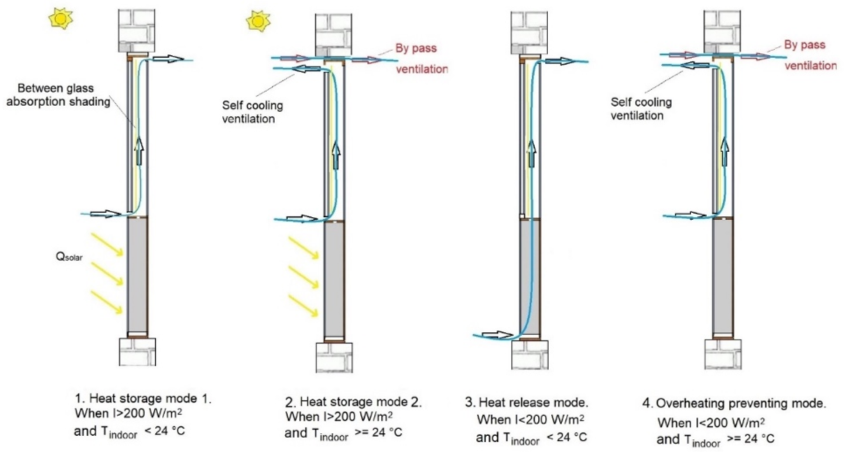

Figure 3. The winter control strategy of the PCMVW.

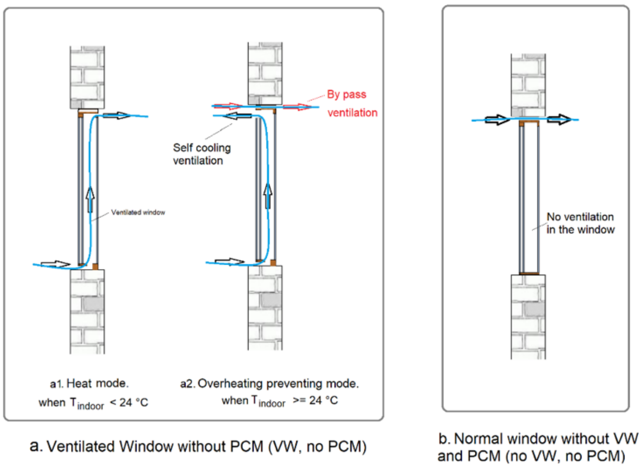

Figure 4. The control strategy of the VW and normal window.

The window with a cavity is made by a double glass in the external layer (U = 1.1 W/m^{2}K, g = 0.63) and a single glass in the internal layer (U = 5.7 W/m^{2}K, g = 0.79). The glass for the PCM box is a double glazing (U = 1.1 W/m^{2}K, g = 0.63). During the simulation, all the windows are equipped with advanced shading control. For the PCM, it is shaded with external shading during the whole summer, and unshaded during the whole winter. For the ventilated window and normal window, the between-glass shading is turned on when the indoor air temperature is high (T_{indoor} > 24°C). It is turned off when the indoor air temperature is low (T_{indoor} <= 24°C).

The PCM is heptadecane, which has a heat storage capacity of 190 kJ/kg. Table 1 shows the properties of the PCM. Figure 5 shows the heat capacity of the PCM measured by Differential scanning calorimetry (DSC) in a heating/cooling rate of 0.5 K/min.

Table 1. Properties of the PCM.

Density	0.88 kg/l (15°C); 0.77 kg/l (25°C)
Thermal conductivity	0.2 W/(m K)
Specific heat capacity	2 kJ/(kg K)
Heat storage capacity (13°C – 28°C)	190 kJ/kg; 53 Wh/kg
Melting	20-23 °C
Freezing	21-19 °C

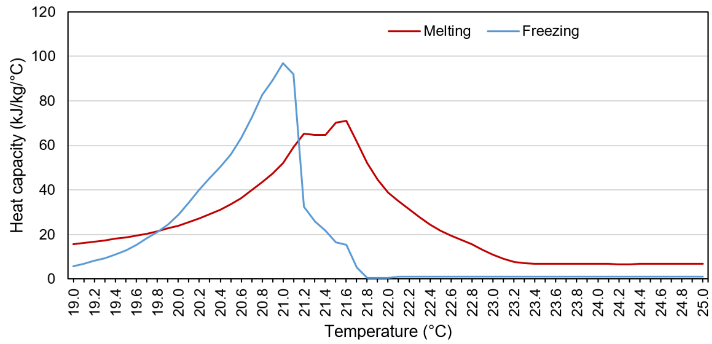

Figure 5. The heat capacity of the PCM, measured by DSC with 0.5 K/min heating/cooling rate.

Internal loads of the apartment include the people load and the equipment load. People load is set as 0.04 person/m^2, and the equipment load is 11.5 W/m^2. The occupancy schedule and the equipment schedule are cited from[5]. The weather data of Copenhagen from Typical Meteorological Year is used for the simulation. The data can be found in the EnergyPlus homepage [6].

3. Results

Table 2 shows the building energy demand of the apartment with PCMVWs and VWs, and the same apartment before renovation with normal windows for comparison. It is seen that all the rooms with PCM and VW have lower energy demand than the rooms without PCM and VW, especially the living room, which has 2 PCMVWs. The rooms with PCMVWs have an average energy saving percentage of 39%, while the rooms only with VWs have an average energy saving of 24%. With PCMVWs and VWs, the apartment has a big potential energy saving, especially in transition seasons and some summer months like May, September and October. For the whole apartment, the energy saving percentage is 29% after renovation.

Table 2. Building energy demand and energy saving of the apartment in 1st floor with PCMVWs and VWs and with normal windows and duct ventilation (kWh).

	Living room (PCMVW)	Room2 (VW)	Room1 (VW)	Kitchen (VW)	Whole apartment (After renovation)	Living room (Normal window)	Room2 (Normal window)	Room1 (Normal window)	Kitchen (Normal window)	Whole apartment (Before renovation)	Energy saving
May	0.08	0.00	0.00	0.00	0.08	1.72	2.41	1.48	6.44	12.06	99%
June	1.83	0.34	0.21	0.00	2.38	3.14	0.27	0.04	0.19	3.65	35%
July	5.26	0.88	0.17	0.00	6.32	13.04	1.59	0.28	0.00	14.92	58%
August	15.05	4.89	6.32	2.66	28.94	22.25	5.81	7.19	3.02	38.28	24%
September	1.75	0.71	0.27	1.77	4.49	5.00	4.76	3.60	7.97	21.34	79%
October	0.37	2.34	2.37	7.79	12.88	11.04	12.00	8.92	18.93	50.88	75%
November	46.66	40.80	35.94	45.86	169.27	73.21	50.71	44.81	55.13	223.86	24%
December	90.43	63.94	58.70	67.96	281.04	119.78	74.96	68.61	78.15	341.51	18%
January	85.08	62.46	57.64	66.97	272.15	116.91	73.81	67.86	77.76	336.33	19%
February	72.28	55.20	53.81	61.06	242.35	109.74	68.53	65.36	72.81	316.44	23%
March	24.00	31.14	28.67	38.70	122.50	65.85	47.52	42.92	54.17	210.47	42%
April	2.89	4.82	4.80	11.11	23.62	20.57	18.10	15.58	24.91	79.17	70%
Yearly	345.69	267.53	248.89	303.89	1165.99	562.26	360.47	326.68	399.49	1648.91	29%
Energy saving	39%	26%	24%	24%	29%	-	-	-	-	-	-

Even with the good energy saving potential, it is also essential to assess the thermal comfort of the apartment after renovation. The room operative temperature during occupant hours is sorted into 4 categories based on the recommendation of standard EN 15251 for mechanical heated and cooled buildings[7]. Figure 6 shows the time distribution in thermal categories for cooling seasons and heating seasons of all the rooms before and after renovation. During the cooling season, renovation with PCMVW and VW can improve the indoor thermal comfort for all the rooms. During the heating season, the room thermal comfort is quite high both before and after renovation.

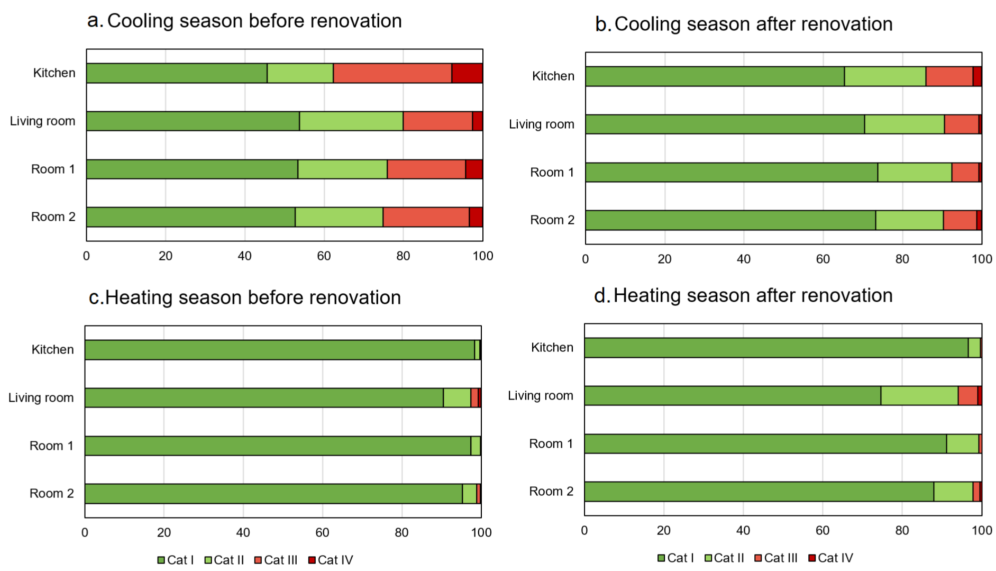

Figure 6. The time distribution (%) in thermal comfort categories.

4. Conclusion

The energy renovation of a residential building with smart ventilated window (VW) and ventilated window with PCM storage (PCMVW) is studied in this paper. The aim of this paper is to study the energy saving potential and thermal comfort improvement of the VW and PCMVW with the detailed control strategy.

The ventilation control strategy of the VWs is designed based on room temperature control including heating mode when the room air temperature is low, cooling mode and overheating preventing bypass mode when the room air temperature is high. The PCMVWs have two operational strategies: the summer night cooling control strategy, which is operating from May to September and the winter solar energy storage strategy, which is operating from October to April. In summer, the PCM is cooled down by outdoor air during the night. The cooler PCM is then used to pre-cool the ventilation air during the daytime when cooling demand is present in the room. In winter, the PCM stores solar energy during the sunny day. The warmer PCM then releases heat for ventilation air preheating when heating demand is present in the room.

In the apartment with the PCMVW and VW ventilation control simulated in Energyplus, all the rooms with PCM and VW have a lower energy demand than the rooms without PCM and VW, especially the rooms with PCMVWs. For the whole apartment, the energy saving percentage is 29.29% after renovation. The rooms with PCMVWs have an average energy saving percentage of 39%, while the rooms only with VWs present an average energy saving of 24%. The apartment has more energy saving in transition and some summer months. Meanwhile, the thermal comfort of each room in the cooling season is improved by installing either PCMVW or VW.

The research is carried out as part of the EU Horizon 2020 research and innovation program under grant agreement NO. 768576(ReCO2ST).

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