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Experimental study of the performance of a novel solution with double skin façade and diffuse ceiling ventilation

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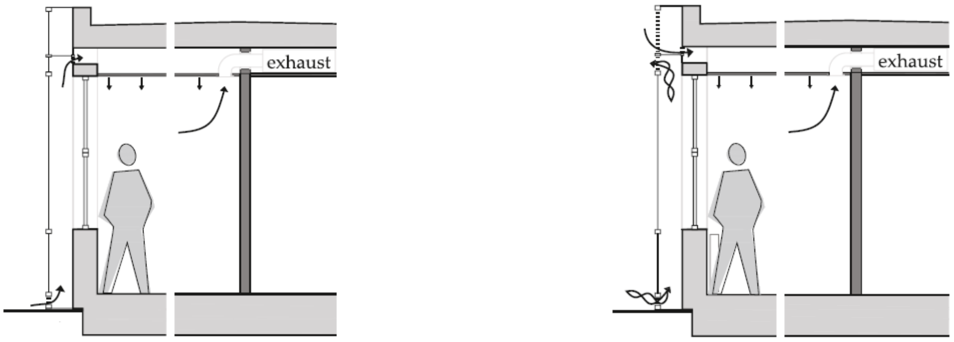
Abstract. In Denmark, about 80% of public schools were built before 1980, and most of them are with the Energy label D or lower. In addition, more than 60% of schools suffer from poor air quality and thermal comfort. The need for school renovation is undeniable. A novel renovation solution was proposed recently by combining double-skin façade (DSF) and diffuse ceiling ventilation (DCV). The integrated system can adapt its operating modes based on indoor and outdoor conditions. The performance of the above-mentioned solution was tested in a small-scale classroom and compared to a reference room with the traditional renovation solution. The results show that the novel solution was able to provide better indoor comfort than the traditional solution. Although significant overheating was observed in both rooms, the novel solution showed promise in mitigating the maximum operative temperature and shifting the peak hour. In terms of energy efficiency, the novel solution optimized the utilization of natural sources. The DSF was able to recover the transmission loss through the glazing and capture the heat gain by solar radiation. The heat recovery rate reached 1 when the solar radiation was strong.

1. Introduction

Approximately 80% of public schools in Denmark were built before 1980, and a majority of them have a low energy efficiency rating of D or lower. Additionally, more than 60% of schools face challenges with poor air quality and thermal comfort [1]. Therefore, the need for renovating these schools is indisputable. Current renovation solutions focus on installing mechanical ventilation systems, wall insulation, and replacing existing windows [2]. However, these solutions often require extensive construction work and significant installation space.

Recently, a novel renovation solution was proposed that combines a double-skin façade (DSF) and diffuse ceiling ventilation (DCV). Compared with traditional renovation solutions, the solution offers greater flexibility and a higher potential for utilizing passive energy resources. This innovative solution can adjust the operation modes based on indoor and outdoor conditions, to improve the indoor environment and reduce energy consumption, as shown in Figure 1. In heating mode, the outdoor air goes through the air cavity of DSF and warm-up by solar radiation or heat loss from the room. The pre-heated air further enters the DCV plenum and supplies into the room. In the cooling mode, the ventilated air removes the heat out of the DSF cavity and fresh air is supplied from the by-pass opening on the top and further supplied into the room through DCV panels. Previous numerical studies have demonstrated that the solution can achieve up to 11% lower total primary energy consumption than traditional renovation solutions [3][4].



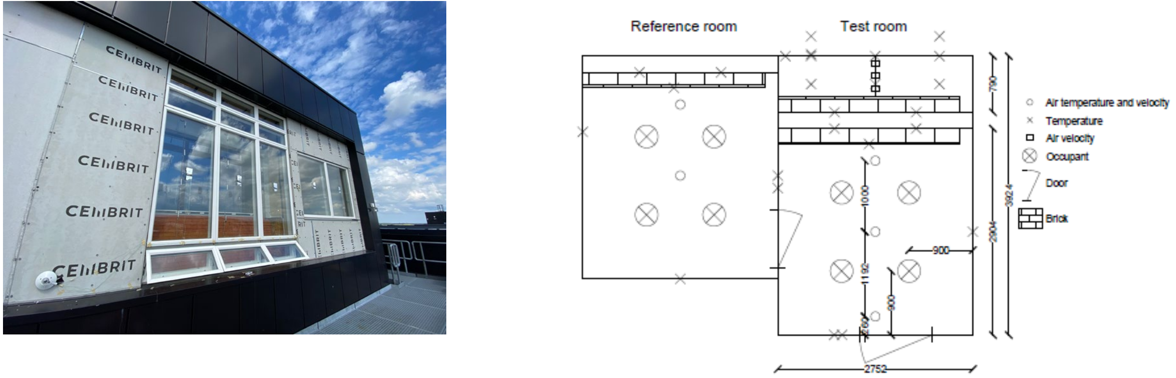
(a) (b)

Figure 1. Concept drawing of DSF-DCV solution with different operation modes (a) Heating mode (b) Cooling mode [3]

Although the individual system (DSF or DCV) has been intensively tested and applied in practice [5][6][7][8], the performance of the integrated solution has not been tested or documented. This study aims to investigate the performance of the novel renovation solution by experimental measurement. The system performance in terms of thermal comfort and energy efficiency (heat recovery rate) is compared with a traditional renovation solution under identical boundary conditions.

2. Experimental method

The experiments were conducted in a two-room laboratory with a south-facing external facade, see Figure 2. One room is installed with the novel solution of DSF and DCV, while, the other room represents a traditional renovation solution with a well-insulated external wall, double-glazing window, and mechanical ventilation. Both rooms have identical boundary conditions, including room geometry, internal load, and outdoor environment.



(a) (b)

Figure 2. Two-room laboratory (a) External facade of the laboratory (b) Planview of the setup in both rooms.

As shown in Figure 2 (a), the external layer of DSF consists of 3 big windows and 9 small windows, where the small windows are openable and are able to adjust operation mode. The interior facade of the DSF has the same dimensions as the traditionally renovated room. DCV is made of wood-cement panels, where the detailed information on the DCV panels refers to our other study [9].

Both rooms are used to simulate small-scale classrooms. 4 heat sources are placed in each room and heat loads are calculated and scaled down based on the typical classroom scenario. To evaluate the heat recovery rate of DSF, the air temperatures in the DSF cavity at different heights are measured by thermocouples. The air temperature, surface temperature and air velocity are measured in both rooms for the assessment of thermal comfort. The locations of heat sources and measurement positions are illustrated in Figure 2 (b).

The measurement includes two cases. The cooling case was measured in summer and the system was operated in cooling mode, and the heating case was measured in winter and the system was operated in heating mode. Detailed boundary conditions are shown in Table 1.

Table 1. Test cases

Case	Period	Heat load	Ventilation rate	Supply temperature in the Trad room
Cooling case	16.06.2022-27.06.2022	50W/m^2	6h^{-1}	18 ℃
Heating case	24.01.2022- 01.02.2022	50W/m^2	6h^{-1}	20 ℃

3. Results

3.1 Cooling case

During the cooling case, the operative temperatures in both rooms are illustrated in **Figure 3**. When the heat source was activated (16-06-2022 to 20-06-2022), the traditional renovation room experienced operative temperatures within the comfort level category B for only 19% of the operating hours, whereas the DSF-DCV room achieved 24%. In the absence of the heat source (20-06-2022 to 27-06-2022), about 27% of the operating hours the operative temperature in the traditional renovation room was within the comfort level category B, while the value in the DSF-DCV room was 37%.

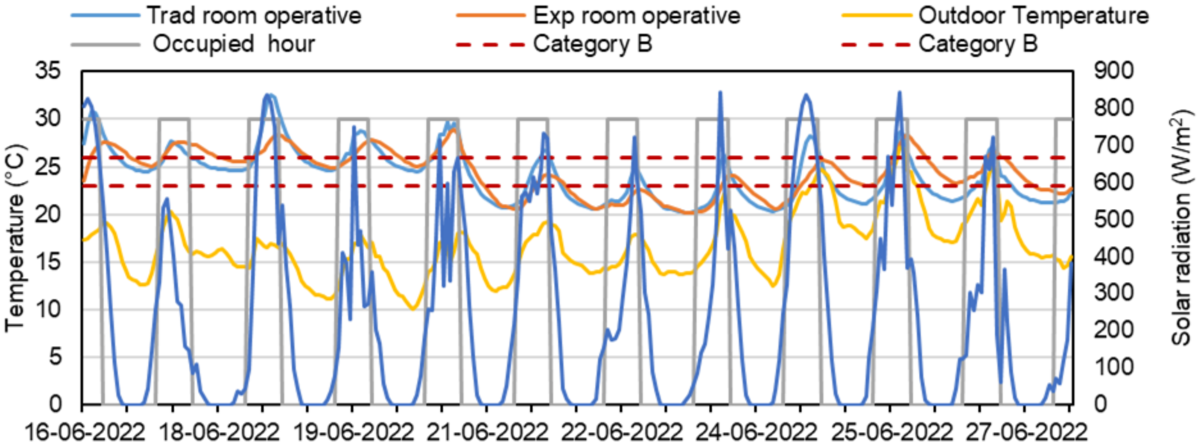


Figure 3. Operative temperature in both rooms of the cooling case

It is noteworthy that in the traditional renovation room, the supply temperature for the ventilation was 18 ºC, which represents mechanical ventilation with a cooling coil. The DSF-DCV was not equipped with a mechanical cooling unit, the supply temperature was equal to the outdoor temperature. However, the outdoor air went through the air cavity in the DSF and expelled part of the solar gain to the outside, which reduced the heat gain in the room. However, the measurement results indicate that solar gain was significant and solar shading is critical to prevent overheating in the room. In addition, it can be observed that the temperature variation in both rooms had slightly different patterns. In the room with DSF-DCV, the peak overheating temperature was lower and the peak was shifted compared with the traditional renovation room. It might be due to that the DCV enables forced convection between ventilation air and thermal mass in the ceiling slabs, therefore, the thermal mass mitigates the peak temperature in the room and shift the peak hour.

3.2 Heating case

During the heating case, the operative temperatures in both the DSF-DCV room and traditional renovation room are illustrated in **Figure 4**. The supply air temperature in the traditional renovation room was 20 ˚C which represents the mechanical ventilation with a heat recovery unit. No space heating was provided in both rooms. The operative temperatures were within the comfort category B 46% and 40% of the operating hours in the trad room and exp room, respectively. Overheating was observed in both rooms when the solar radiation was strong, which indicates that a shading device is needed even during the winter season to avoid overheating problems. Even though solar radiation plays important roles in both rooms, the mechanisms of heat gain from solar radiation are different. In the trad room, the heat gain from solar radiation is mainly through the façade. While, in the exp room, a part of the heat gain is from solar radiation through DSF, and the other part is by warming up the ventilation air in the DSF cavity. Therefore, the supply air is already pre-heated before entering the diffuse ceiling plenum, which could see from the air temperature gradient in the DSF cavity.

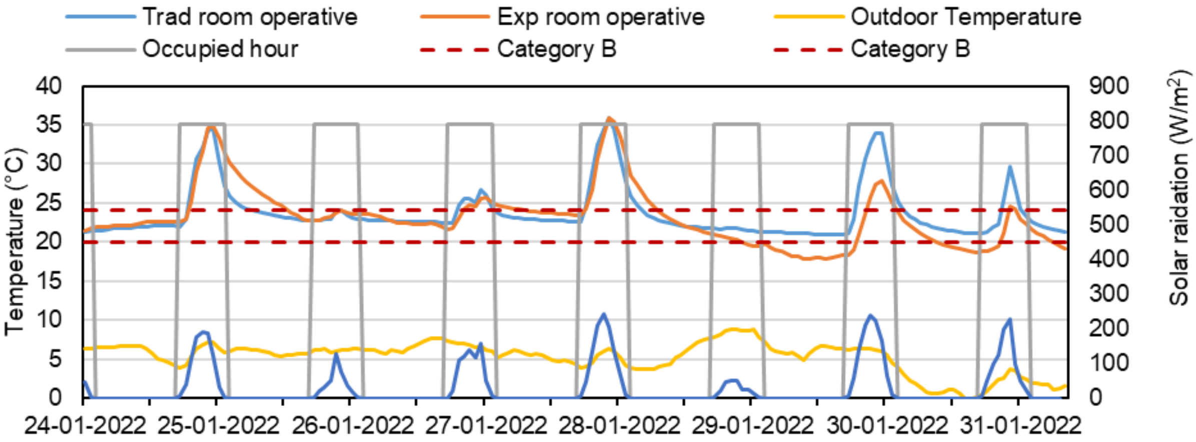


Figure 4. Operative temperature in both rooms of the heating case

The temperature gradient was strongly influenced by solar radiation, see **Figure 5**. A temperature rise to 15 ˚C was observed when the solar radiation was about 250 W/m^2. **Figure 6** shows the heat recovery rate of the DSF-DCV system as a function of global solar radiation. The heat recovery rate ranged from 0.1 to 0.62 in the scenario without solar radiation. Under this scenario, the supply air was warmed up by the transmission loss from the room to the DSF cavity. Under the scenario with solar radiation, it is a linear relationship between the heat recovery rate and global solar radiation. The heat recovery rate can reach up to 1 in some periods, where supply air was warmed up by both solar radiation and transmission loss from the room. Therefore, even though no heat recovery unit is installed in the integrated system, the system can reduce heat loss and utilize the passive heating strategy to fulfill the building regulation.

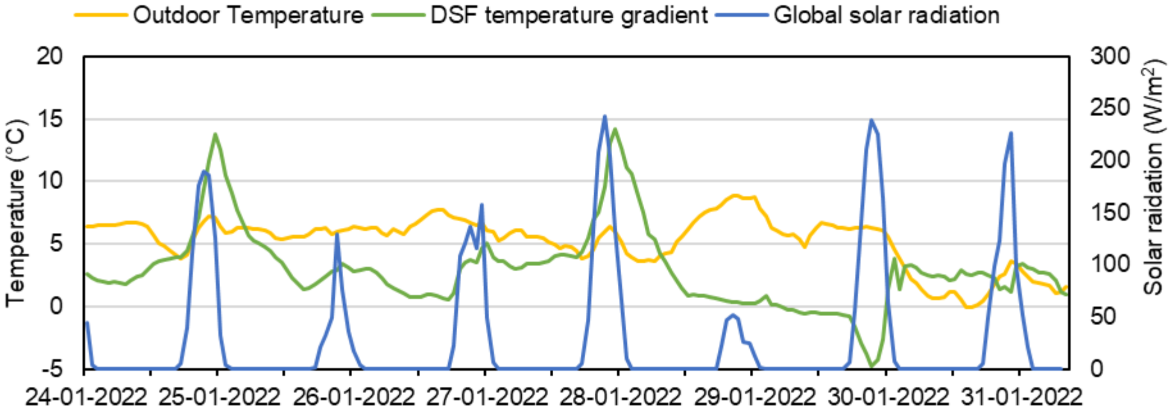


Figure 5. Air temperature gradient in the DSF cavity during heating case

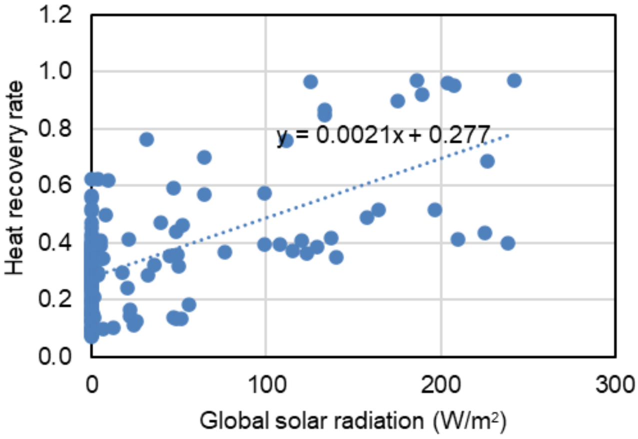


Figure 6. Heat recovery rate of the DSF as a function of solar radiation

4. Conclusions

A integrated solution with DSF and DCV was tested in a small-scale classroom, and its performance was compared with a traditional renovation solution. The measurements were carried out with different operation modes and weather conditions.

In terms of thermal comfort, the test results showed that the proposed solution was able to provide more comfort hours than the traditional solution. However, significant overheating was observed in both rooms, during the summer season and winter with high solar radiation Therefore, the study suggests the need for solar shading even in the winter season to avoid overheating. In addition, the solution showed promise in mitigating the max operative temperature and shifting the peak hour. This is because the DCV enables the further activation of ceiling thermal mass and shaves the peak load.

In terms of energy efficiency, the integrated solution optimized the utilization of natural sources. Even though no heat recovery unit was used in the novel solution, the DSF was able to recover the transmission loss through the glazing and capture the heat gain by solar radiation. The heat recovery rate reached 1 when the solar radiation was strong. In the future study, we could explore the potential to combine with a heat recovery unit, where the recovery heat from exhaust air could be used to warm up domestic hot water.

Acknowledgment

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