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APPLICATION OF PHASE CHANGE MATERIALS IN VENTILATION SYSTEMS – A REVIEW

Abstract: *Heat losses caused by ventilation systems significantly affect energy consumption in buildings. Therefore, it seems reasonable to look for solutions to improve the efficiency of heat recovery and storage in ventilation systems. One example of such solutions are thermal energy storage systems using phase change materials (PCM), which can be a way to improve the thermal performance of a building. Utilizing the increased energy absorption capacity of phase transition temperatures through phase change materials, increases the efficiency of energy accumulation and subsequent release. The use of sensible and latent heat of PCM materials can significantly affect the efficiency of heat recovery and storage in ventilation systems. The paper presents an overview of various applications PCM in ventilation systems. The study presents the method of conducting selected research and the results achieved.*

Keywords: *ventilation, PCM, heat transfer*

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Introduction

As stated by Tommerup and Svendsen (2006), Liddament and Orme (1998) and Jradi et al. (2018), up to 40% of the world's total energy demand is consumed by the maintenance and operation of buildings. According to Omre (2001) and Perez-Lombard et al. (2008), HVAC (heating, ventilation, air conditioning) systems consume between 40% and 60% of the building's energy demand, depending on the local climate. This has led to the modernization and introduction of new building laws and standards regarding the reduction of energy consumption and internal comfort (Annunziata et al. 2013), which also coincides with the energy and climate goals for the coming years of the European Union, which lists the construction sector as a priority in terms of improving efficiency and reducing energy consumption. However, as Werner (2016) expects, the demand for cooling capacity will increase by about 55-60%. This is due to the drastically increasing number of buildings in recent decades in which there is a demand for room cooling. Therefore, it is reasonable to look for solutions that will have an impact on reducing energy consumption, reducing dependence on fossil fuels, or reducing energy consumption during peak hours, but without compromising indoor air quality and the level of thermal comfort. One solution may be the use of PCM (phase-change material) materials for energy balancing. Phase-change materials, commonly referred to as PCM, are a technology used to store explicit and latent heat due to a larger capacity than standard materials. As a result, they have great potential for use in active HVAC applications. Figure 1 compares the principle of using a standard energy storage (blue dashed line) with a latent energy storage (solid green line) using PCM properties (Veje et al., 2019). As shown, PCM materials have a much greater potential for energy storage.

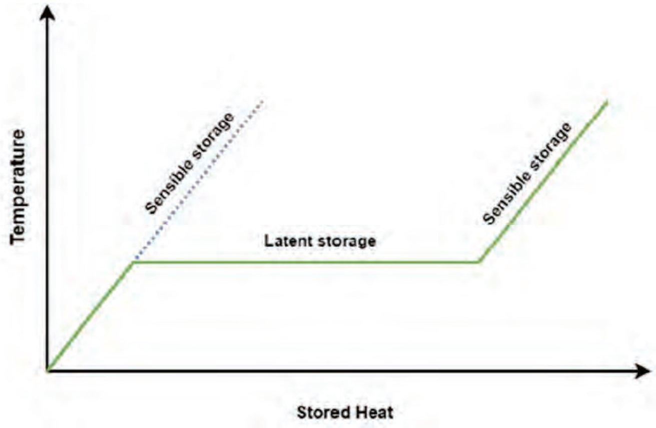

***FIGURE* 1.** *The principle of using latent energy storage compared to sensible energy storage (Veje et al., 2019)*

Phase transition materials can be divided into three groups: organic compounds, inorganic compounds and inorganic eutectics. PCMs store and release thermal energy as the ambient temperature fluctuates. As the temperature rises, it changes from solid to liquid, this process is endothermic and therefore absorbs heat from the surrounding air, lowering the local air temperature. When the air temperature drops, the PCM solidifies and the thermal energy is transferred to the environment, increasing the local temperature (O'Connor et al., 2016).

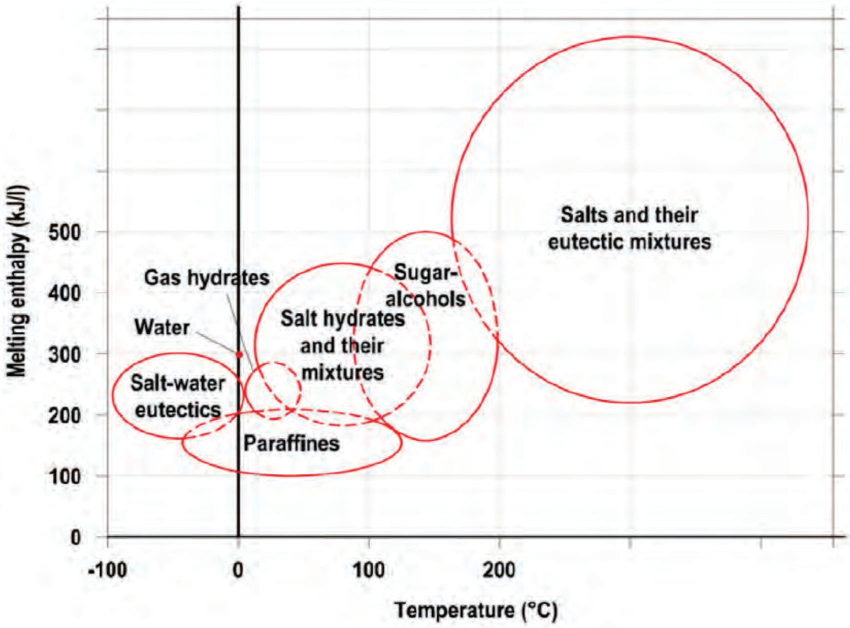

***FIGURE* 2.** *The melting enthalpy and melting temperature for the different groups of phase change materials (Baetens, 2010)*

As noted by Kauranena et al. (1991), it is important for systems using PCM to properly select the melting and freezing points of the material, adapted to local climatic conditions. Analyzing Figure 2, it can be seen that phase-change materials have a wide range of melting and freezing points, but attention should also be paid to thermal conductivity and volume changes. The most popular organic PCM is inexpensive paraffin wax, which has a wide temperature range from 20°C to 70°C.

Examples of PCM applications in ventilation systems

A common example of the use of phase-change substances is their use to cool rooms by storing cold at night and receiving them during the day. Studies of such a system were carried out by Takeda et al. (2004). They developed an experimental ventilation system that provides a direct exchange between the ventilation air and the granules containing PCM. As shown in Figure 3, the device is made of a rectangular body measuring 140 mm x 140 mm and a length of 900 mm, made of thermal insulation with a thickness of 100 mm. As a phase-change substance, Rubidem GmBH PCM GR granules with a particle diameter of 1-3 mm, consisting of 65% ceramic material and 35% paraffin hydrocarbons, were used. The experiment was carried out by periodically changing the temperature of the inlet air. A computer simulation model was also created, on which calculations of heat transfer between PCM granules and air were performed. A comparison of the results from the obtained simulations and experimental studies showed a similarity of the results. Thanks to simulations, the possibility of reducing the ventilation load was tested by using the tested device in 8 cities of Japan. It was found that the potential for reducing ventilation of such a system during the summer was the highest for the city of Kyoto at 62.8%, while in cities such as Tokyo or Fukuoka, which have a lower average temperature, the reduction rate was between 42.8% and 46.2%. A greater influence of the range of daily temperature variability than the average temperature was found.

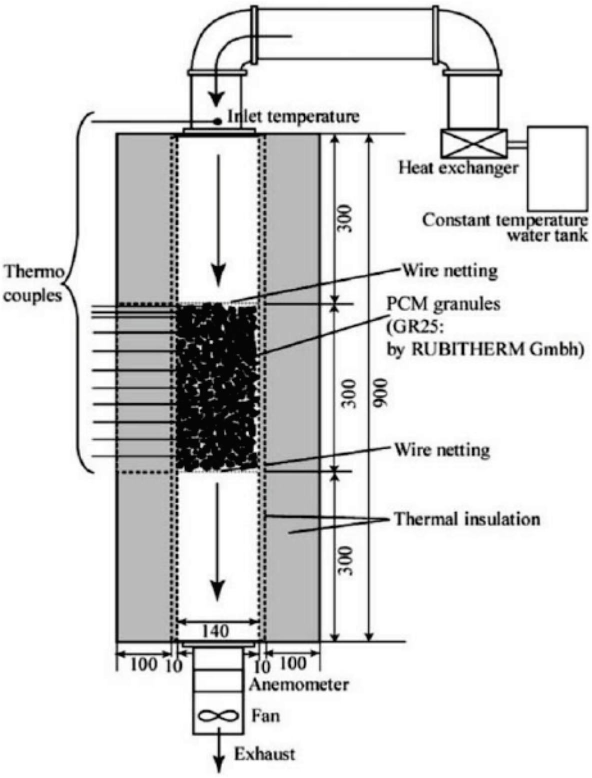

FIGURE 3. *Elevation view of the experimental apparatus (Takeda et al., 2004)*

Another example of the use of PCM materials in ventilation is the ventilation module presented and described by Ljungdahl et al. (2021). The operation of active cooling using PCM modules for air conditioning was investigated. 2 modules with different masses and thermal properties were made. Each PCM module measuring 460 mm x 520 mm x 1500 mm consists of 4 stacks of 25 aluminum plates filled with PCM measuring 450 mm x 300 mm x 15 mm, each with a 5 mm air gap between them, as shown in Figures 4 and 5.

The research was carried out in the temperate climate zone using the ventilation system of the office building. The system operated in two different phases, the PCM charging phase occurred at night, then the PCM solidified, while the discharge took place during the day, when the PCM melted. For a period of 5 days, the ventilation unit operated at a constant intensity of 500 m^3/h. Ambient air temperatures fluctuated between 12.0°C and 25.8°C. A series of measurements was used to validate the developed system model. The higher mass of the PCM has been found to reduce the performance of the PCM but increase peak heat transfer. In addition, it was found that by optimizing the volumetric flow and melting point of PCM, the cooling capacity was increased by 38.4% and the peak cooling capacity by 71.1%.

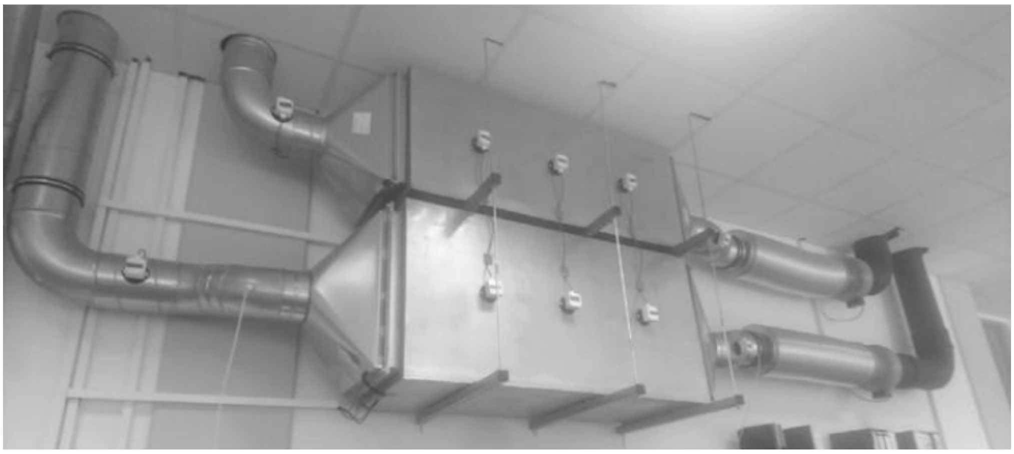

FIGURE 4. *PCM-driven ventilation system experimental setup (Ljungdahl et al., 2021)*

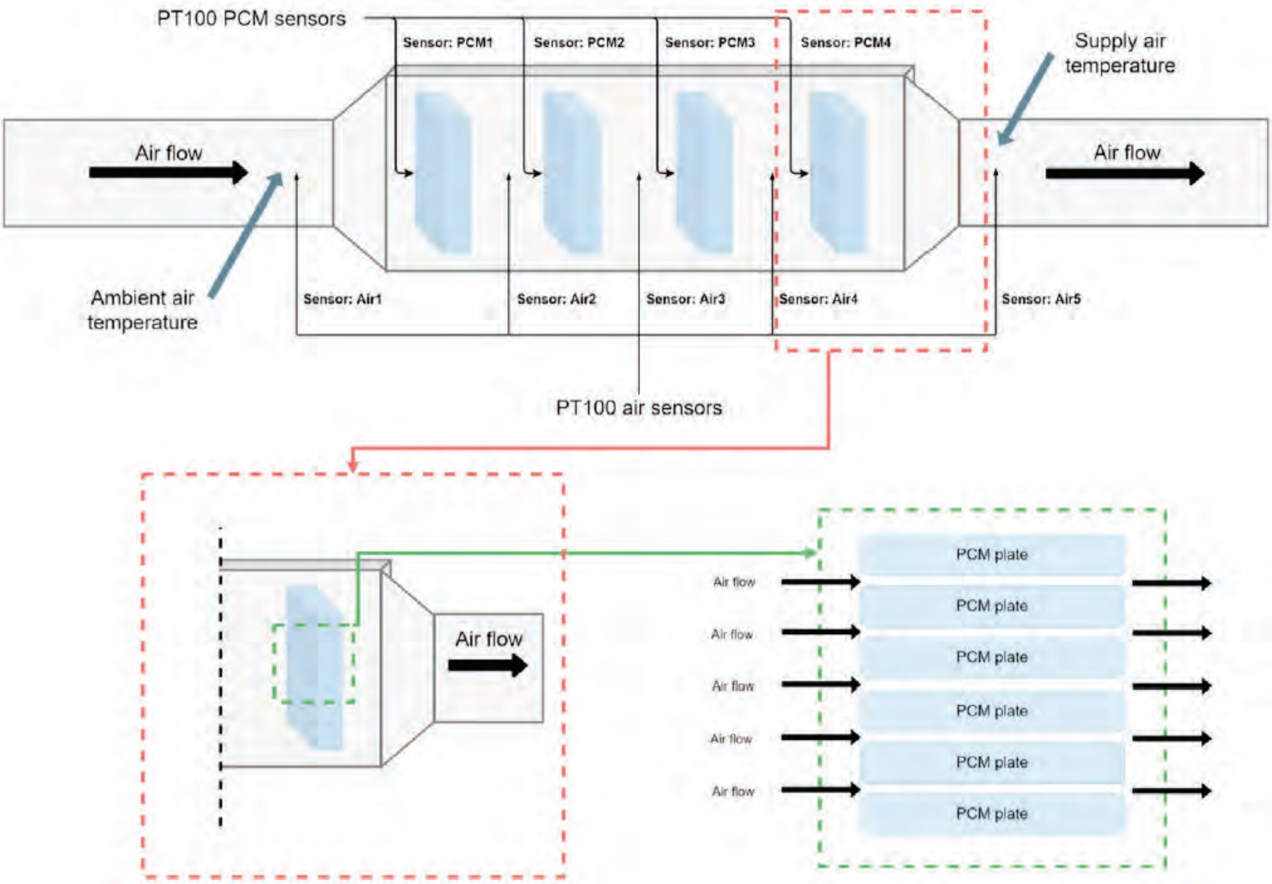

FIGURE 5. *Top: Schematic of the experimental setup with placement of sensors. Bottom: The construction of a single stack with parallel PCM plates above each other with a small air gap in between (Ljungdahl et al., 2021)*

Attempts to reduce energy consumption in a building through the use of a latent heat storage unit were made by Chen et al. (2016). The system stores the coolness in the LHTES (Latent heat thermal energy storage) unit from the outdoor night air and releases it when cooling fresh air during the day. The system was quantified to test the potential for energy savings delivered in 8 cities located in 4 different climate zones in China. The system consists of an LHTES unit, an air filter, fans, air dampers and ducts as shown in Figure 6.

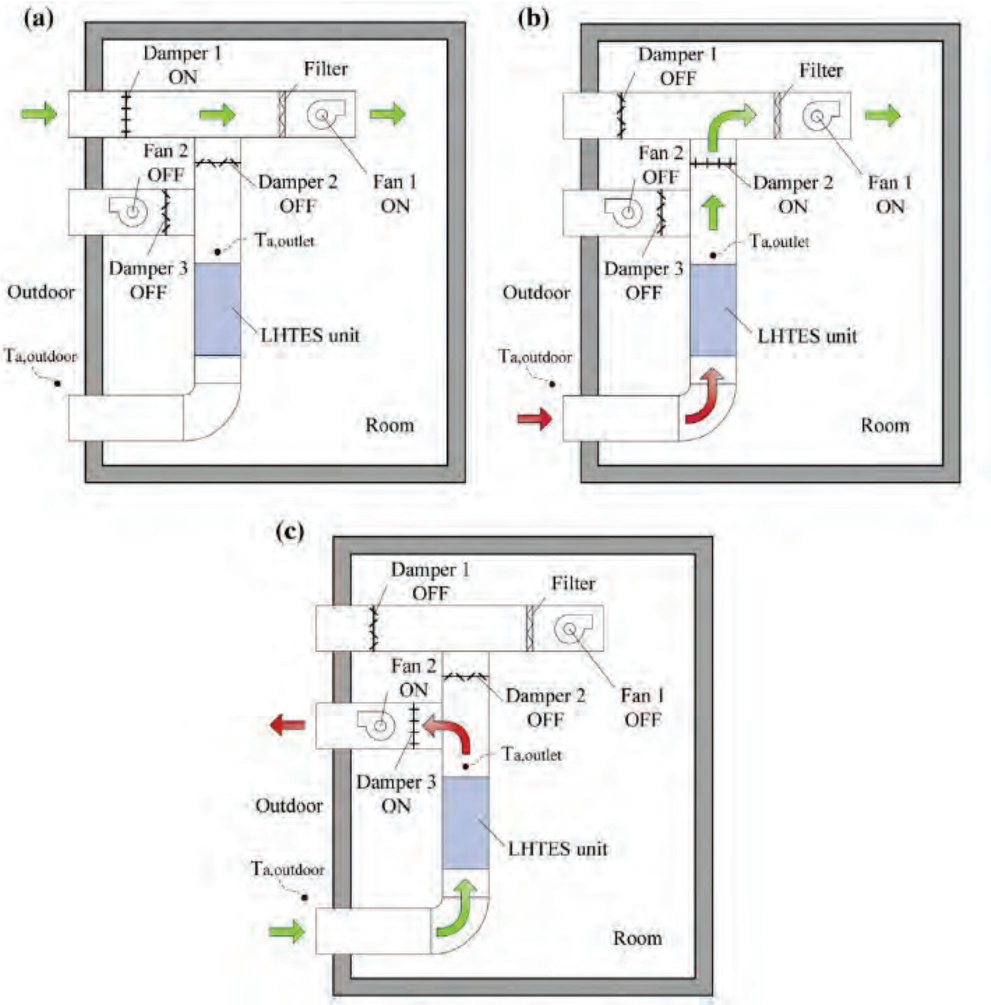

***FIGURE* 6.** *Schematic of the ventilation system with a LHTES unit: (a) direct ventilation, (b) discharging, and (c) charging modes (Chen et al., 2016)*

The heat storage unit consists of several PCM-filled plates, arranged parallel to each other as shown in Figure 7. Outside air flows through the passage between the plates and exchanges heat with the PCM to store and release energy. A number of simulations were carried out to determine the optimum melting point for LHTES (Latent Heat Thermal Energy Storage) systems in eight cities, which range from 21°C in Harbin (cold climate) to 29°C in Guangzhou (hot climate). Seasonal total net electricity savings range from 24 kWh in Shanghai to 87 kWh in Beijing. In general, the higher the range of daily temperatures or fresh air cooling demand, the greater the potential cooling energy demand and net energy savings.

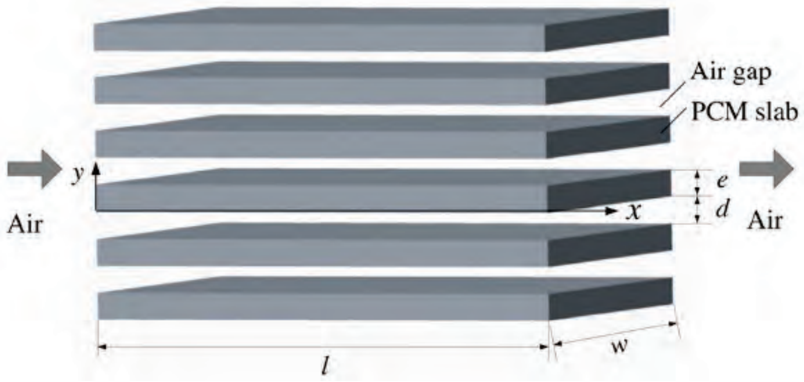

***FIGURE* 7.** *Schematic of the thermal energy storage unit (Chen et al., 2016)*

Sun et al. (2020) conducted numerical studies of a ventilation system integrated with inorganic PCM panels with increased thermal conductivity. The ventilation system was placed in the space above the test room with an internal space of 350 x 350 x 350 mm as shown in Figure 8.

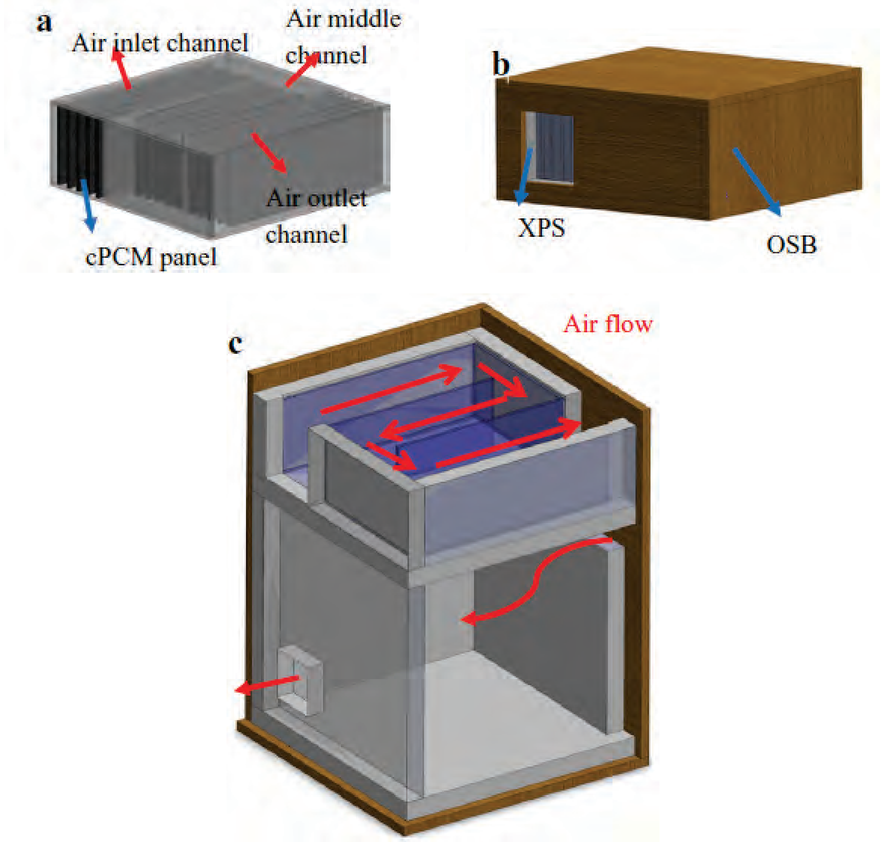

FIGURE 8. Air-PCM unit (a); insulation materials (b) and installation location of the ventilation system (c) (Sun et al., 2020)

The overall thermal performance of the ventilation system has been improved by adjusting the inlet conditions and thermal properties of the PCM. With an inlet air temperature ranging from 17.4°C to 33.1°C, the influence of the inlet air flow rate and the thickness and thermal conductivity of the panels was investigated, which was aimed at bringing the temperature of the exhaust air closer to the range of thermal comfort. It has been shown that temperature fluctuations at the outlet decreased with a decrease in the inlet air flow rate or an increase in the thickness of the panels. In addition, a PCM utilization index was introduced to assess PCM performance during the melting and solidification process. It was found that narrowing the PCM phase transition temperature range in the outlet channel could further lower the maximum outlet temperature and improve the PCM utilization rate. In addition, when the inlet air flow rate was 11.47 kg/h and the thickness of the PCM panels was 12 mm, the ventilation system with panels with a thermal conductivity of 13.0 W/(m^2K) showed the smallest fluctuations in the outlet temperature of 22.5-27.9°C.

Stitiha et al. (2018) presented the use of LHTES (Latent heat thermal energy storage) heated by a solar hot air collector, mounted on the façade of the building. The installation consisted of a solar air collector, an LHTES exchanger, ducts and a fan. The air heat was transported by a fan from the solar collector to the LHTES unit, where it gave off heat, as a result of which the PCM melted. At night and at times when the solar intensity was weak, the heat stored at LHTES was used to heat the ventilation air and delivered to the office room where the system operated from 8:00 to 16:00. The exchanger contained 29 storage plates, filled with Rubitherm RT22HC paraffin, which has a melting range of 20-23°C. Plates measuring 0.45 m x 0.3 m x 0.15 m were set horizontally, and the air gap between them was 10 mm. Each plate was filled with 1003 g of phase-change substance.

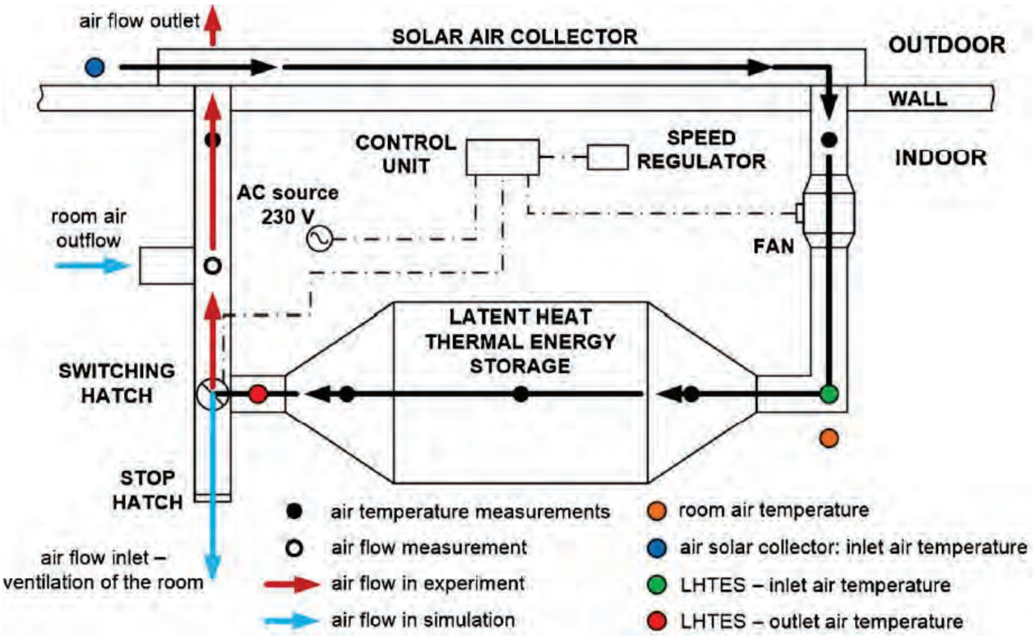

FIGURE 9. *Experimental setup (Stitiha et al., 2018)*

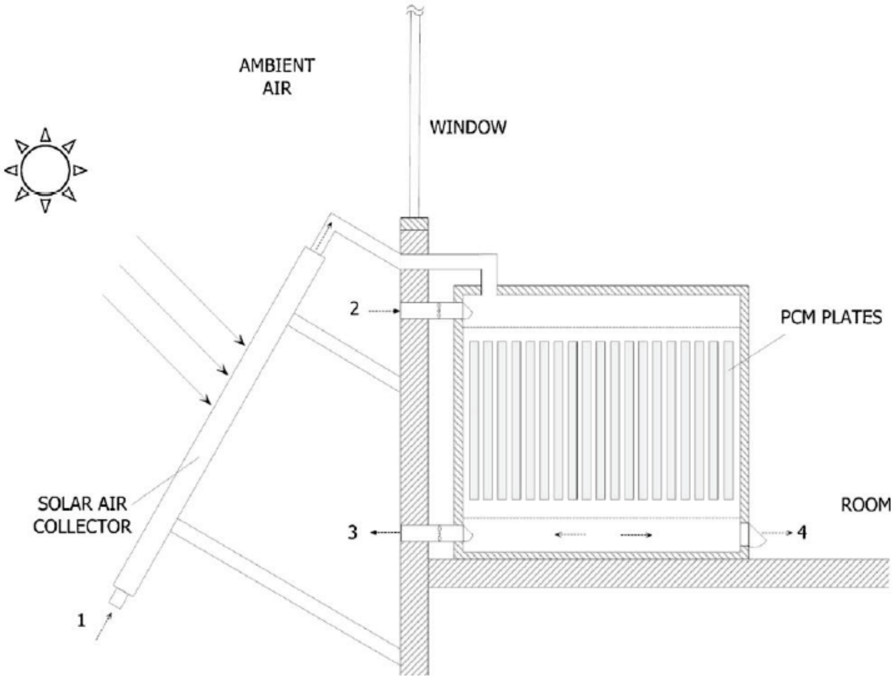

FIGURE 10. *Schematic of the system (Stitiha et al., 2018)*

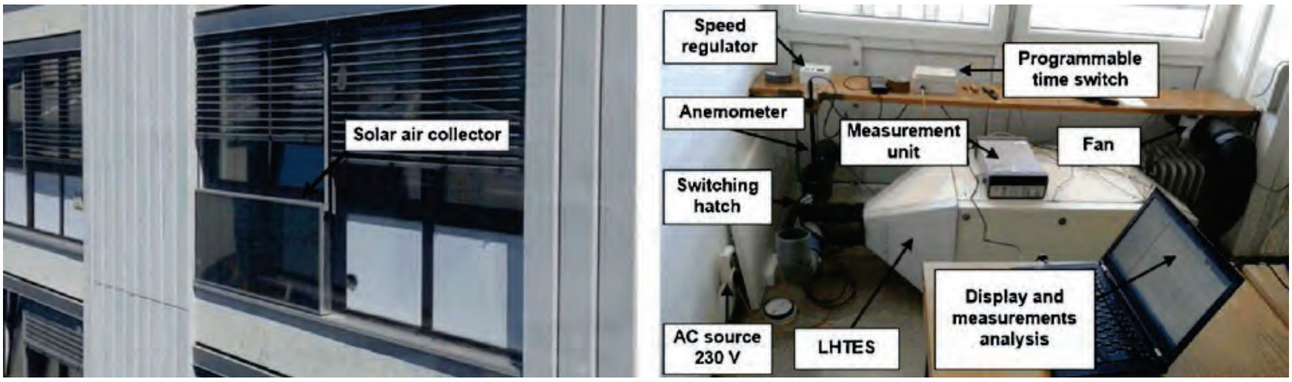

FIGURE 11. *The LHTES unit with CSM plates (left) and solar air collector (right) of the experimental system (Stitiha et al., 2018)*

On the basis of the conducted experiment, the simulation model was validated. A simulation was carried out for the heating period (October to April) in Ljubljana, Slovenia, based on weather data distributed using TRANSYS 17. The results of the simulation showed that the highest coverage rate for ventilation heat loss was in the transition period and for April it was 92% and for October 89%. The lowest value was reached in December and amounted to 44%. The average coverage rate during the heating season was 67%, while the same system without the use of LHTES covered the ventilation heat loss in 53% during the heating season.

Yang et al. (2019) proposed the use of a cylindrical ring made of PCM, used to regulate the temperature of supply air in ventilated buildings exposed to changing thermal conditions. The ring with a length of 3.3 m, an internal diameter of 0.1 m and an external diameter of 0.18 m was filled with PCM (OP24 from Ruhrtech). A constant air speed of 1 m/s was assumed at the inlet, which was regulated by the fan. The temperature of the inlet air was regulated by the heater. The period of fluctuation was 4.5 hours. The ambient temperature was 10°C.

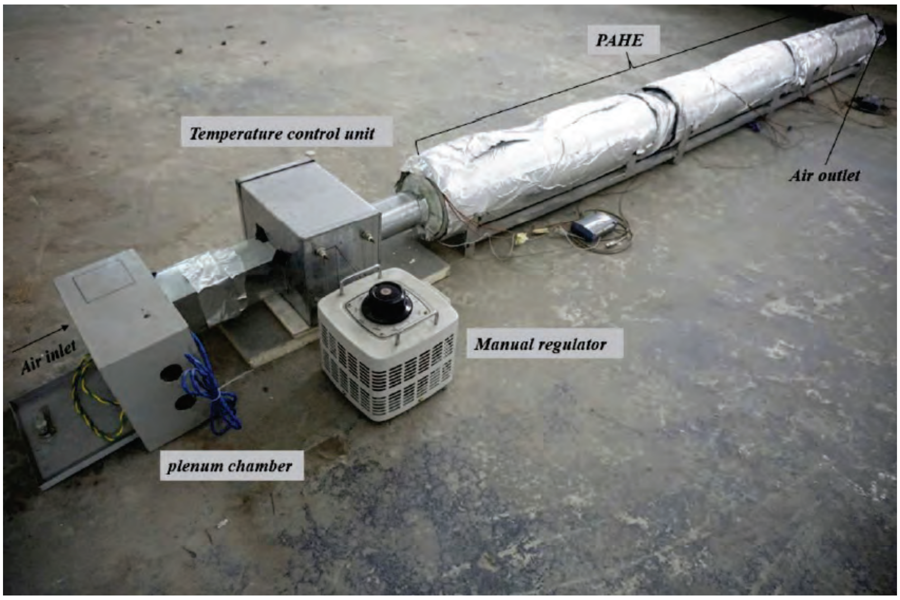

FIGURE 12. *Image of the experimental apparatus (Yang et al., 2019)*

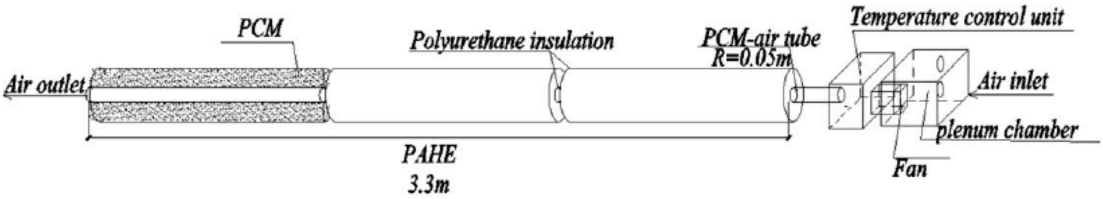

FIGURE 13. *Schematic and dimensions of the experimental PAHE tube (Yang et al., 2019)*

The results of experimental studies were compared with the results of simulations. Forced convection inside the plant increases heat transfer between air and PCM. The transfer of overt and latent heat contributes to the reduction of air temperature fluctuations. The simulation included real meteorological data from two transitional seasons and summer and showed a maximum reduction in air temperature of 5.4°C.

Dechesne et al. (2014) designed and investigated a PCM heat exchanger coupled to a building ventilation system. The PCM is designed to store heat during the day (e.g. by cooling photovoltaic panels) and return it to the building at night to heat rooms or store coolness at night and give it back during the day. The construction of the exchanger is based on corrugated cells that can be easily filled. They were placed side by side in a way that allowed air to flow between them. In order to optimize the geometry, a semi-empirical model was made. Based on the results, a prototype was created.

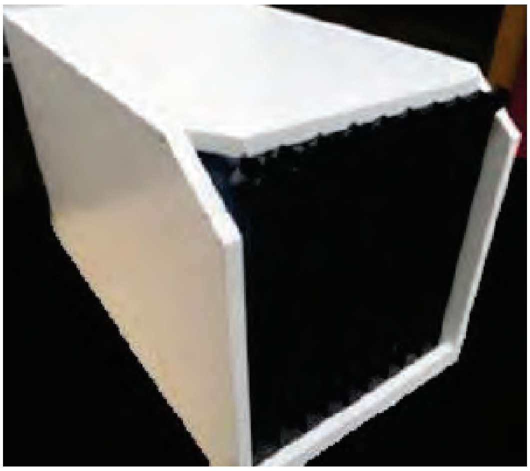

FIGURE 14. Tested PCM Module (Dechesne et al., 2014)

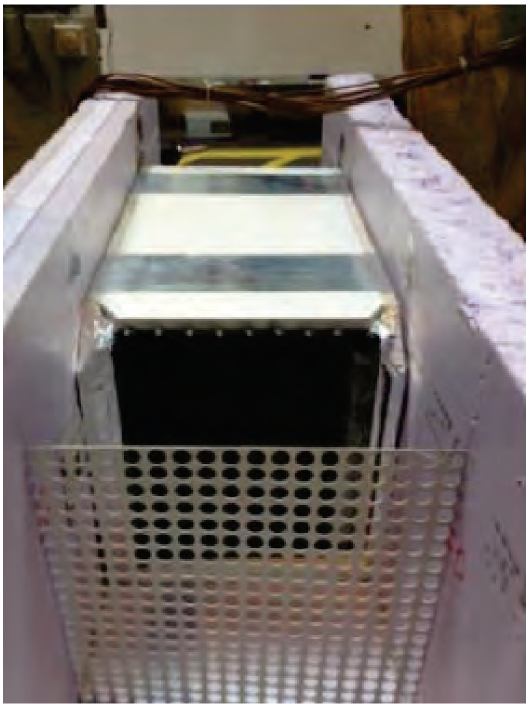

FIGURE 15. Heat exchanger box (Dechesne et al., 2014)

The prototype was filled with a phase-change material in the form of fatty acids and placed in a 60 mm thick box insulated with polystyrene foam. The day before charging/discharging, the PCM was supplied with air at a temperature of 15°C or 30°C. During the measurements, air was supplied with a temperature of 15°C or 30°C and a flow of 45 m^3/h. It was proved that in the first five hours, a single module can deliver an average of over 90 W of cooling power and approx. 80 W of heating power.

Dallaire et al. (2022) investigated the LHTES system integrated into the VEX308 market ventilation system for refrigeration applications. Taking into account dimensional and operational constraints, they developed a unique configuration of uniform wedge-shaped airflow, up to two parallel PCM stacks.

Inside the insulated LHTES enclosure, measuring 825 mm x 2072 mm x 500 mm, 48 PCM boards were located in 2 stacks of 24 boards with 1.5 mm spacing between them. The plates contained an inorganic phase-change compound SP21EK manufactured by Rubitherm Technologies GmbH. The flow rate during the LHTES unloading and charging cycles was kept constant at 600 m^3/h. The inlet air temperature was kept constant at 27°C during unloading and 13°C during unloading. C when the system is booting. The charging and discharging time of the system took an average of 3.4 hours. The proposed system achieved an average efficiency of 89% energy recovery.

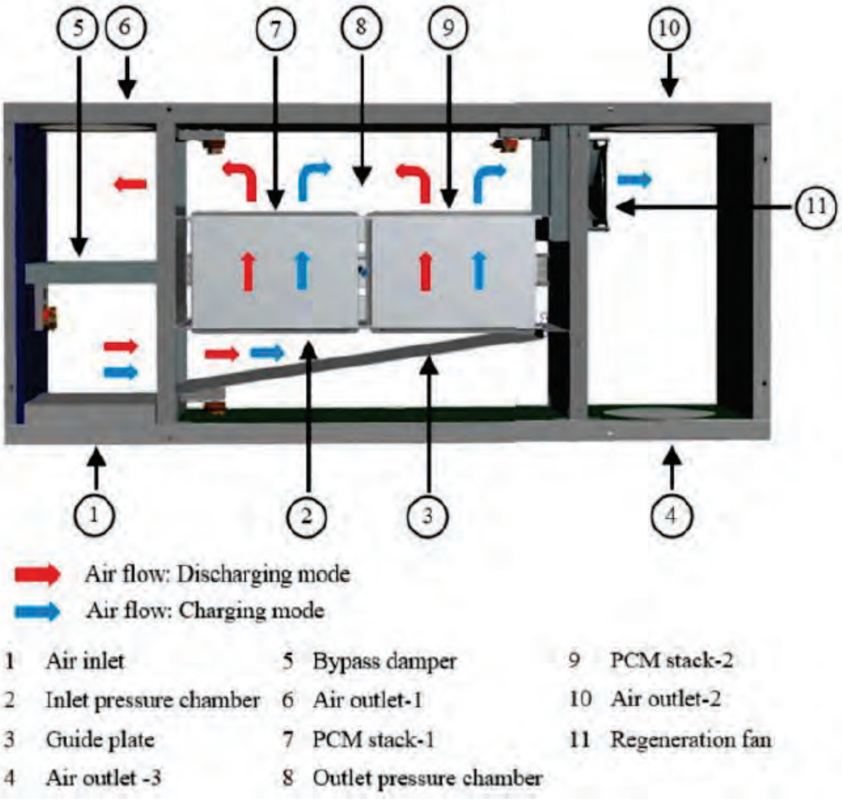

FIGURE 16. *Schematic of the LHTES system (Dallaire et al., 2022)*

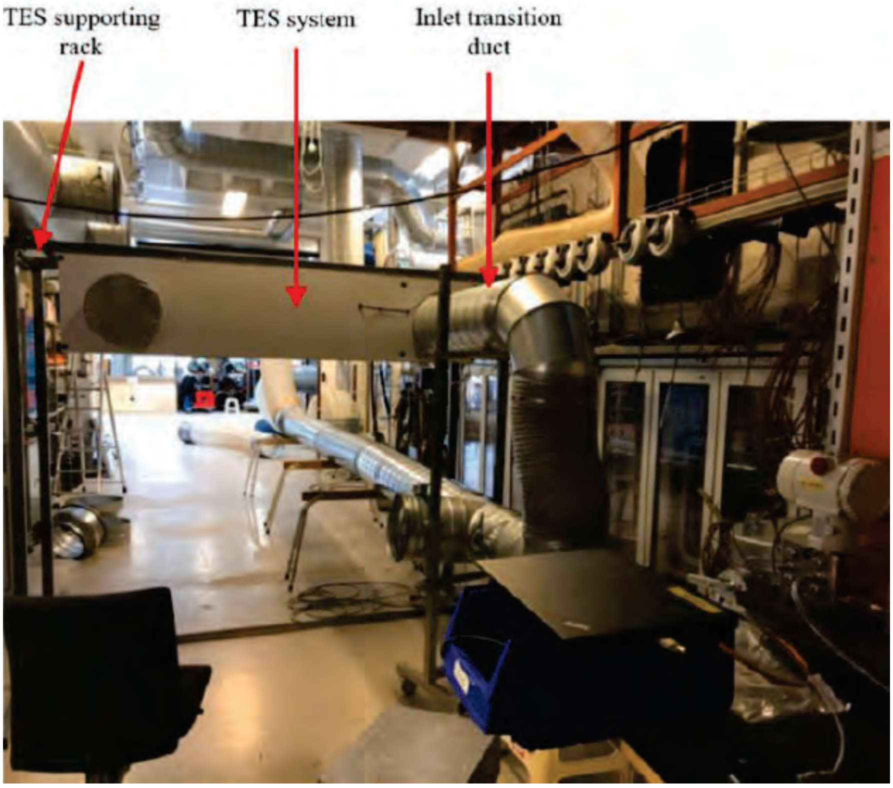

FIGURE 17. *Overview of the LHTES system hooked up to the permanent testing. Facility at DTI (Dallaire et al., 2022)*

Hu et al. (2022) proposed an integrated PCM HVAC system to ensure the energy flexibility of the building. The system consists of a PCM storage tank, a heat pump and ventilation ducts, as shown in Figure 18. The integration of PCM into the heat pump system is shown in Figure 19.

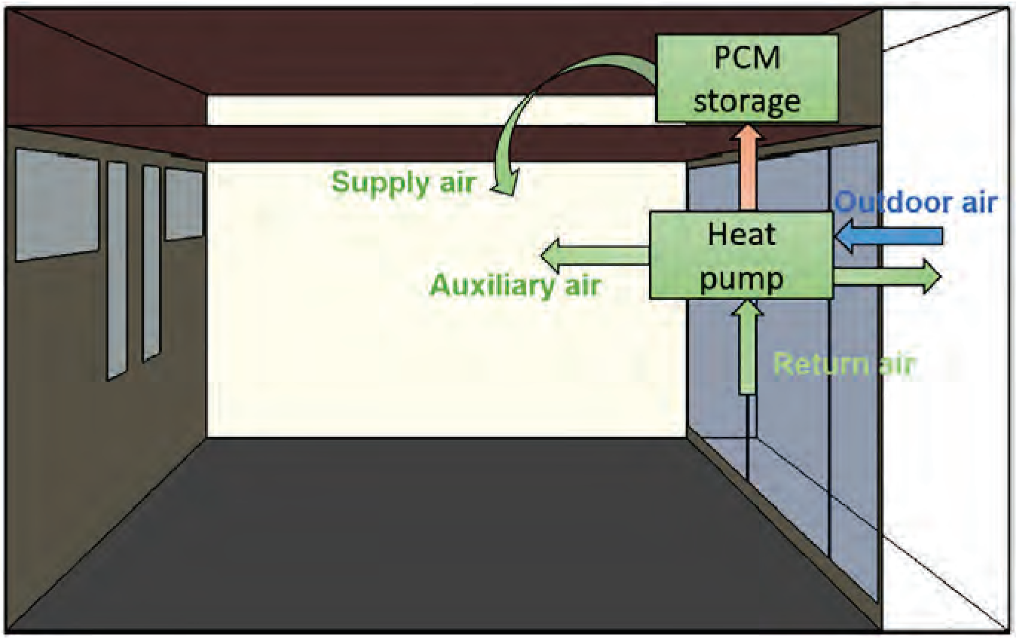

FIGURE 18. *The system configuration of the PCM storage integrated with heat pump (Hu et al., 2022)*

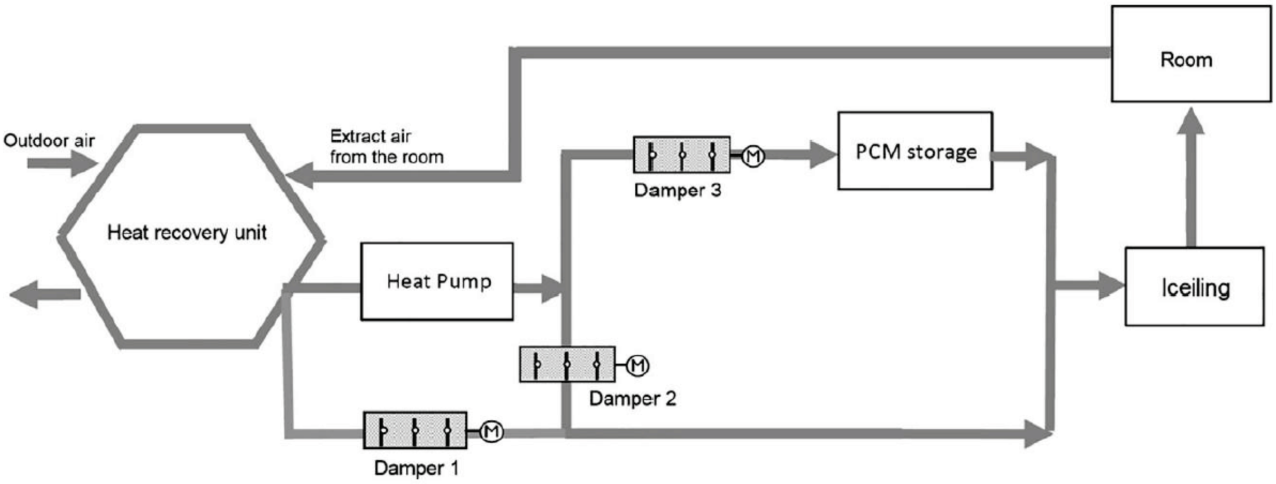

FIGURE 19. *Integrated PCM into heat pump air system (Hu et al., 2022)*

Thanks to this combination, the system can operate in three modes: PCM charging/discharging, PCM bypass and heat pump bypass. The study used PCM ATS 30, placed in plastic plates measuring 0.34 m x 0.22 m x 0.01 m, whose phase transformation occurs at temperatures between 28-33°C. In the experiment, three sets of PCM warehouses were tested: a large one with 52 pieces of plates, a medium with 36 plates and a small one with 20 boards.

PCM is used to move peak hours on the network, which requires control based on the price of electricity. When the price is low, PCM stores energy from the warm air supplied by the heat pump. When the price of electricity is high, the heat pump is turned off and the PCM gives off heat to the ventilation air. On the basis of the conducted research, a simulation of electricity cost control and energy saving potential was performed. It has been shown that an integrated HVAC system with PCM storage effectively reduces the load on the network during peak hours, allowing to achieve 7% savings on energy bills, while maintaining similar thermal comfort in the room. The payback period was estimated at 7 years.

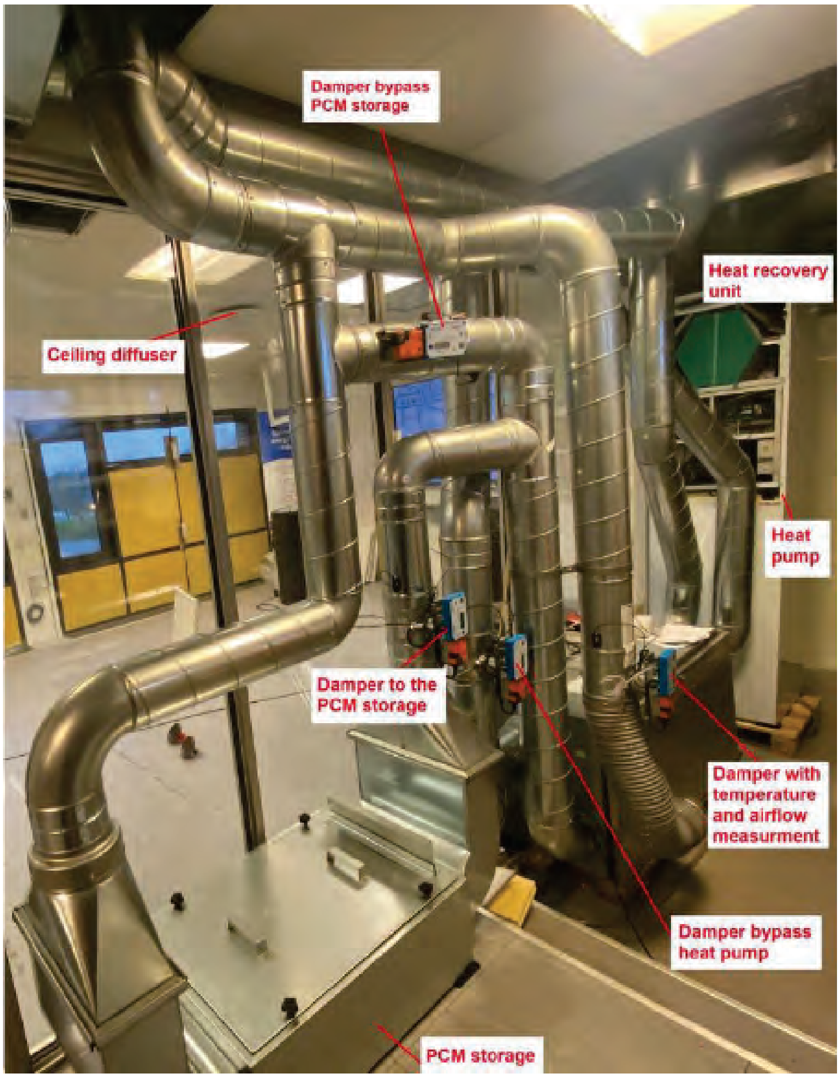

FIGURE 20. *System setup in the lab (Hu et al., 2022)*

Summary

The use of PCM in ventilation systems at the moment is a relatively new solution that has not yet been used commercially. Research on the use of phase-change properties in active ventilation systems is still ongoing. PCM has a significant advantage in the possibility of energy storage at certain temperatures compared to standard materials, unfortunately you should also pay attention to many factors that make it difficult to use them. Limited temperature ranges of effective operation, volume variability, low conductivity or phase distribution are limitations that hinder the possibility of using PCM. As noted by Veje et al. (2019), new, cheaper and more efficient materials need to be developed for use as PCM. The use of more compact designs and better storage materials should increase the storage capacity of thermal energy in complete systems. It is also important to work on improving the thermal conductivity of storage materials, because conductivity sets the limit of the speed at which heat can be charged and discharged into a facility or storage system.

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