NeGeV: Phase Change Materials for Innovative Cooling Solutions

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Background

Cooling and heating technologies employed in the HVAC industry range from simple natural cooling to advanced Direct Expansion (DX)-solutions. The majority of current active cooling solutions are still dominated by the use of refrigerants in compressor-based technologies, with continuous improvements targeting higher performance compressors, better components integration and less harmful refrigerants. The introduction of 'Eco Design' concepts renders many of the existing product lines obsolete, forcing the industry to develop new, more efficient products (European Union 2016). Thus, there is an increasing need to improve the energy efficiency of the built environment without compromising the indoor air quality and thermal comfort levels. In addition, with the tight regulations and standards regarding HVAC systems and the limitations on the use of conventional systems with harmful refrigerants and working fluids, there is a large potential for environmentally friendly HVAC solutions making use of efficient and innovative technologies. In this context, utilizing Phase Change Materials (PCM) as a short-term storage medium for thermal energy emerges as an innovative and environmentally friendly alternative.

PCMs are special substances capable of absorbing or releasing large amounts of 'latent' heat when they undergo a change in their physical state. They are characterized by specifically designed phase change temperatures, allowing for larger energy storage densities compared to sensible storage mediums and techniques. Large amounts of energy can be stored in the isothermal process of solidifying the PCM and then later discharged by melting the material.

The potential of PCM as an eco-friendly solution for thermal energy management and in balancing energy oscillations in buildings has been addressed in a number of scientific articles and experimental cases (Kasaeian et al. 2017). The majority of the work concerning the use of PCM for air conditioning in buildings have been concentrated on passive solutions (Ning et al. 2017), mainly integrating the PCM within the building envelope components. On the other hand, active integrated solutions and systems are still less mature, where PCM-based products in this section are generally at a research and laboratory testing level (Stein und Partner 2018). So far it has been tested in laboratory settings with promising results and in a few one-off projects (Khan et al. 2011).

Proposed Cooling Concept

While the use of PCM for heat recovery in active ventilation systems has been investigated in a few studies demonstrating promising potential, such solutions have yet to find a way to the market as additional investigation in terms of design, control and optimization of the system is still needed and major challenges are to be dealt with. To overcome the current technical and market challenges, the proposed system concept makes use of an innovative PCM based module, as a thermal energy management unit, to provide the cooling needs and replace the conventional energy-intensive cooling techniques. This will cause an unprecedented increase in energy efficiency and will decrease the need for environmental harmful refrigerants and working fluids. The work is carried out under the 'The Next Generation Ventilation (NeGeV)' project, funded by EUDP, aiming to develop the next generation of HVAC systems by demonstrating an innovative, cost-effective and scalable solution to provide thermal comfort in buildings.

The project will develop a prototype where PCM is used in a module as an energy storage and thermal energy management unit in a decentralized HVAC solution. The overall system concept is illustrated in **Figure 1**.

The heart of the proposed system is a PCM module containing an appropriate mass of PCM material in a rack of panels that ensures proper conditioning of the ventilation air. The PCM module, shown in **Figure 2**,

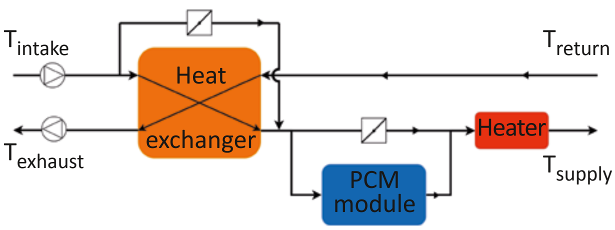


Figure 1. NeGeV Project Concept.

benefits from the necessary outdoor temperature difference between night and day, and is charged during the night, by having the cold outdoor air directed around the PCM panels, lowering the temperature of the phase change material employed. During the charging phase, the PCM will solidify, and the outlet air from the PCM module will be heated up and can either be used as heat recovery in the building if necessary or expelled outside. In case of cooling demand during the day, the supply air is directed through the PCM module which absorbs heat and thereby discharges the module while cooling the ventilation air, resulting in melting of the PCM. The only additional energy requirement is the load on the Air Handling Unit (AHU) fan. due to the integration of the PCM module and the corresponding increased pressure drop.

Regarding the PCM design, the development in the last two decades has mostly targeted available melting temperatures and long-time stability of the PCMs, where the specific storage capacity has been almost stable. NeGeV considers the latest developments in the field and focuses on applying the concept on the smaller

Figure 2. The NeGeV prototype PCM module with the CSM casings from Rubitherm inside.

air volume products – eg. the compact AHU family from the project partner Exhausto (https://www.exhausto.com/). By developing a full-scale prototype of the PCM module suitable for an AHU, the project demonstrates the true feasibility of the concept in a commercial application. The PCM panels have a lifetime depending on the number of charge/discharge cycles, but the design will show an easy replacement and the PCM panels can be regarded as spare parts.

The full-scale prototype of a HVAC-solution will in part be built on an existing HVAC-platform (VEX308) which is a low volume stand-alone HVAC solution for classrooms and offices, currently developed by the project partner Exhausto, shown in **Figure 3**. This existing platform is chosen to reduce costs and technical risks. The current VEX308 unit has been widely implemented in school classes and teaching rooms but with limited applications in office buildings. This is due to the high cooling demands in offices and the need for a cooling system. Thus, the proposed NeGeV prototype with its cooling capability will help providing large potential in terms of implementations in office buildings.

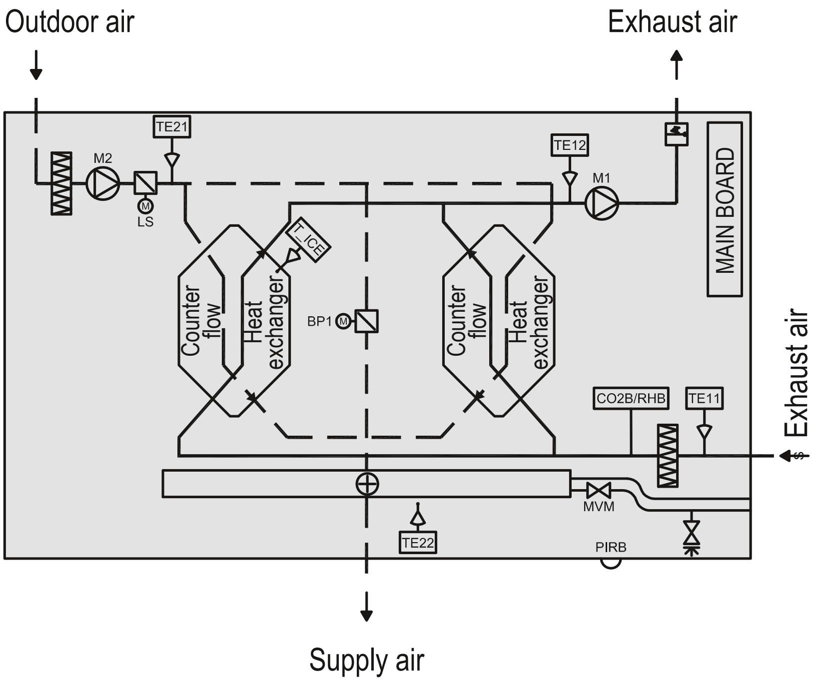


Figure 3. Exhausto VEX308 system layout.

Phase Change Material Selection and Design

The PCM selection is critical for the efficiency and effective utilization of the latent thermal energy. There are three different PCM candidates developed and produced by the project partner Rubitherm for the system (https://www.rubitherm.eu/). The basic material properties are documented by test and measurements in Rubitherm's laboratories. The PCM candidates are of salt hydrate type with comparable thermal properties. The main difference lies in the melting and freezing temperatures of the materials, the properties of the candidates can be seen in **Table 1**. The PCM casing is an already developed and well tested Compact Storage Module (CSM) plate casing, and is shown in **Figure 4**. The CSMs comes in different sizes, the largest with a height of 15 mm.

Table 1. *Thermal and physical properties of three PCM Candidates.*

	SP 21	SP 22	SP 24
Specific heat capacity [kJ/kg]	2	2	2
Conductivity [W/(m·K)]	0.5	0.5	0.5
Density (solid) [kg/m^3]	1 500	1 500	1 500
Density (liquid) [kg/m^3]	1 400	1 400	1 400
Latent heat of fusion [kJ/kg]	140	140	150
Melting temperature [°C]	22–23	22–24	24–25
Freezing temperature [°C]	19–21	21–22	23–21

Figure 4. The CSM casing from Rubitherm.

System Performance Preliminary Assessment

To quantify the added benefit of the PCM module and demonstrate the expected performance of the system concept, a detailed dynamic energy performance model for the proposed ventilation unit, consisting of the VEX308 and the PCM module is developed. In the system modelling process, the VEX308 is considered as a counter flow heat exchanger with an overall heat transfer coefficient calculated based on the number of transfer units method. The heat transfer in the PCM module between the PCM and the air is calculated through estimation of the convective heat transfer coefficient, using correlations for the Nusselt number for flow between two isothermal plates (Arnold et al. 1976). The latent part of the storage is modelled using an apparent heat capacity method, where the specific heat capacity includes the latent heat of the PCM and the melting/freezing temperature.

A case study of a small office of 30 m² in Denmark was considered to assess the system performance, with a maximum occupation of 4 people, the small office performance has been simulated for a standard Design Reference Year (DRY).

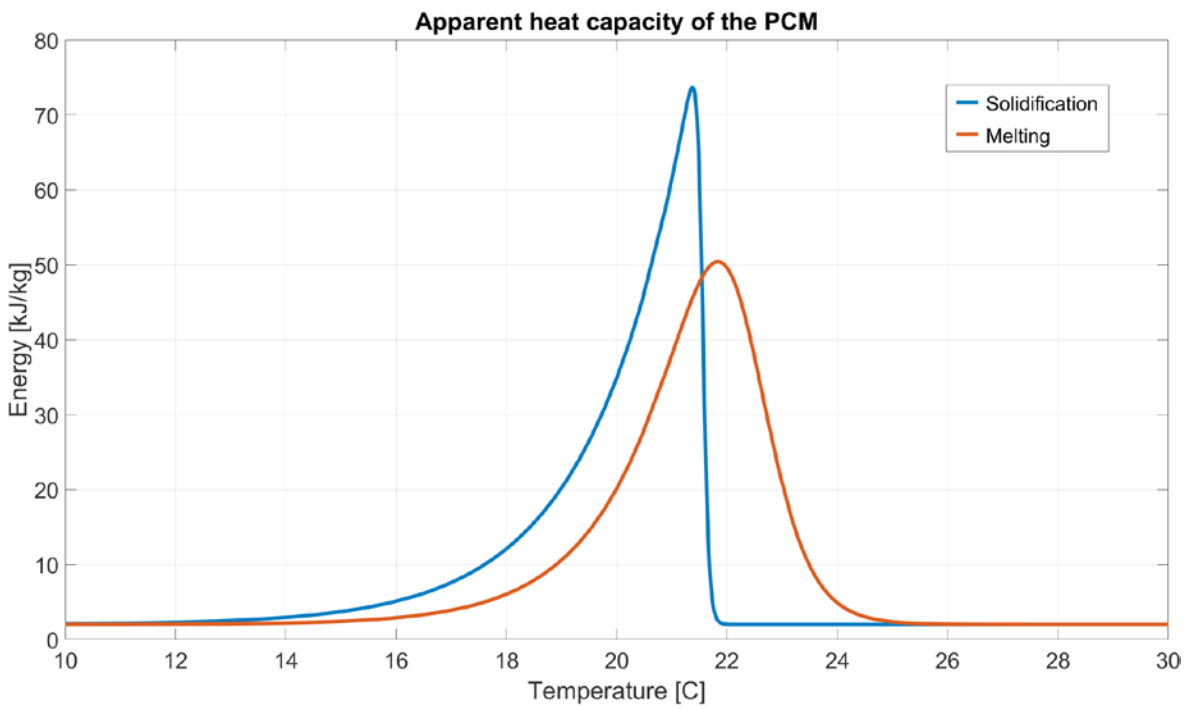
For this case study the Rubitherm PCM SP 21 has been chosen based on its melting/freezing temperature combination, that is inside the desirable range, below the temperatures during summer days and above the normal night time temperatures during summer nights. A PCM mass of 100 kg has been utilized for this system performance assessment.

The internal temperature inside the office space, the PCM temperature as well as a multitude of other variables have been modelled using a large number of inputs; internal heat generation, solar radiation, ambient temperature profile, PCM thermal properties, etc. A room thermal comfort range of 21°C – 24°C has been adopted.

The performance of the system has been evaluated based on the thermal indoor climate requirements as specified in the Danish Standard: DS469:2013 – "Heating and cooling systems in buildings". Here among others two indoor temperature requirements are specified:

- Room temperatures should not exceed 26°C for more than 100 hours a year,
- Room temperatures should not exceed 27°C for more than 25 hours a year.

These room temperature requirements have been utilized to define a Key Performance Indicator (KPI) based on thermal Comfort Violations (CV) that



Energy content in melting and solidification of SP21 PCM, as a function of temperature.

multiply all violations of these requirements with the time period in which they occur and add all the violation time periods up.

Based on the successful performance simulation, it has been shown that the room temperature exceeded 27°C for 13.6 hours and exceeded 26°C for 19.6 hours, over a year period. This has resulted in no violations for thermal comfort and a CV of 0.00°Kh. A reference simulation where the PCM module has been removed has been conducted using the same inputs resulting in a CV of 86.8°Kh, demonstrating the substantial added value of the proposed cooling solution in terms of thermal comfort improvement.

An extreme case simulation has been conducted where the year input data has been replaced with a five-day time period measured at the University of Southern Denmark campus during the record-breaking summer of 2018, where the day temperatures exceeded 30°C and night temperatures were close to 20°C. In this case the DS469:2013 does not apply, but the CV can still be evaluated for measuring performance. The system manages to provide substantial additional thermal comfort. For this period the system obtains a CV of 111°Kh. Again, a reference simulation where the PCM module is removed is conducted here a CV of 228.3°Kh is achieved, which again shows the added value of implementing the PCM module.

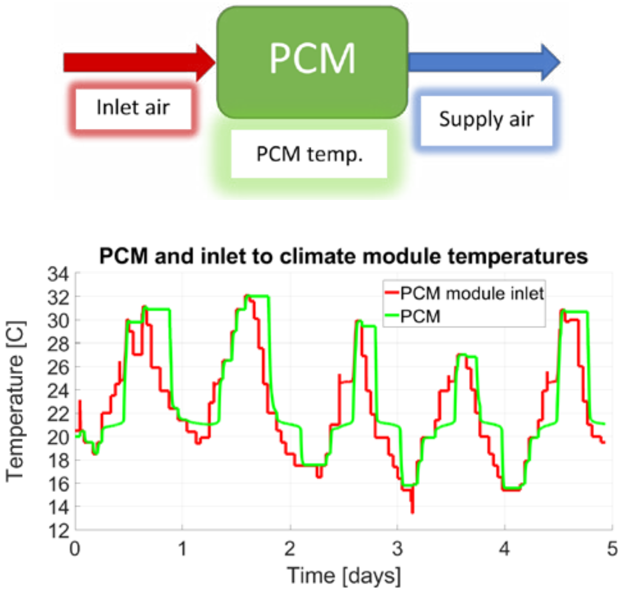


Figure 5a. PCM module inlet and PCM temperature.

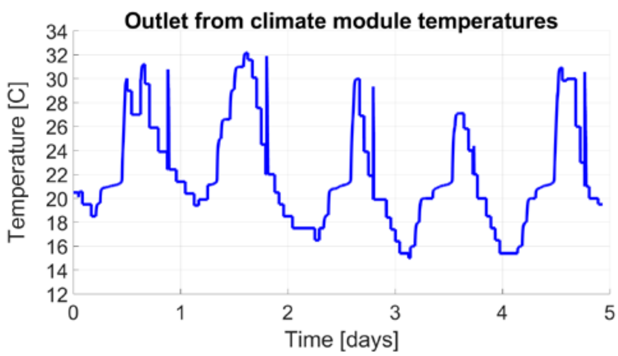


Figure 5b. Outlet from climate temperature.

The PCM temperature, supply temperature and the inlet temperature to the PCM module for the extreme case can be seen in **Figure 5a** and **Figure 5b**. The PCM reduces supply temperature close to the PCM temperature during the first part of the day. It can be observed that during the night, the PCM is solidified, enabling the system to provide cooling during the day.

In order to achieve better performances in these ambient temperature ranges, a PCM with higher melting/freezing temperatures would make a better alternative.

System Energy Performance Assessment

Considering the technical and economic perspectives, the proposed system feasibility has been investigated by comparing the yearly electricity consumption of the NeGeV solution to the Best Available Technologies (BAT). In most cases the BAT would be DX, refrigeration based cooling. The DX system is assumed to have a unit pressure drop of 15 Pa and an average COP over the entire year of 2. The pressure drop in the PCM module was found to be highly dependent on the flow rate and varies between 20 Pa for the lowest flow rate of 150 m³/h to 125 Pa for the highest flowrate of 850 m³/h.

Moreover, the DX solution used a total of 220 kWh of electricity for the entire year while the NeGeV solution used a total of 109 kWh (including ventilation fan power), thus a substantial energy reduction is possible. Both systems maintained the same degree of thermal comfort for the simulation meaning that the provided service is the same. Combining this with the low material and maintenance costs of the system, a low payback period of a few years can be expected. The accumulated energy consumption for the ventilation system for the two solutions can be seen in **Figure 6**. The energy consumption for the winter, early spring and late autumn are very comparable for the two systems, but during the hot summer months the proposed NeGeV solution uses substantially less electricity, since only the added pressure losses have to be compensated for.

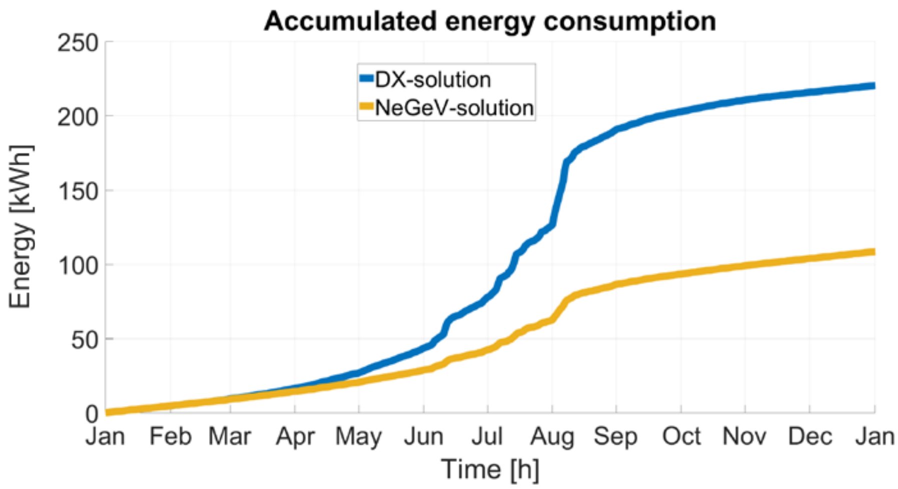


Figure 6. The accumulated energy consumption for the DX- and NeGeV-solution for one-year simulation.

Conclusion

The proposed innovative PCM-driven ventilation solution is intended to be used in small/medium sized offices environments as a base for further expansion. For this scope it was demonstrated that it is substantially less energy intensive than the current available BAT while being cheaper to manufacturer and maintain. This comes at a price, as the proposed system requires different control and management scheme, considering full and part charging and discharging of the PCM.

Historically one of the issues with PCM systems have been the spatial requirements which are especially an issue when the solution is decentralized and placed inside the building. However, with no need to store the energy seasonally, but instead just in cycles of 1 day, allows for a drastic reduction in the amount of PCM required for the proposed solution. Therefore, the size of the PCM module is comparable or smaller in size to that of a standalone ventilation unit.

Major challenges are dominating the ventilation and cooling sector at present including high energy consumption, low energy efficient products, high emissions and less flexibility. Utilizing high latent energy content in PCMs for cooling in an integrated PCM module has the potential to serve as an alternative technology for active cooling in buildings, while completely avoiding the use of refrigerants. ■

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