# Final report

## 1. Project details

| | |
|---|---|
| **Project title** | Next Generation Ventilation ('NeGeV') |
| **File no.** | 64017-05117 |
| **Name of the funding scheme** | EUDP |
| **Project managing company / institution** | University of Southern Denmark |
| **CVR number** (central business register) | 29283958 |
| **Project partners** | Exhausto, Rubitherm Technologies GmbH, Danish Technological Institute, BITZER Electronics A/S |
| **Submission date** | 23 November 2021 |

## 2. Summary

The NeGeV project goal was to develop the next generation of HVAC systems by demonstrating an innovative, cost-effective, and scalable solution to provide thermal comfort in buildings. The proposed ventilation system makes use of an innovative Phase Change Material (PCM)-based module to provide the cooling needs, replacing conventional active energy-intensive cooling techniques.

The goal was obtained by completion of a set of project objectives comprising the development of a prototype HVAC system based on an existing commercial product. The prototype was constructed by development of a PCM based energy storage module (climate module) with novel heat exchange design and advanced integrated controls.

A modeling and design tool was developed for model-based performance evaluation and used for optimizing the system design of the prototype. Additionally, detailed CFD modeling assisted the mechanical design phase and detailed Laser-Doppler Anemometry measurements was done to validate the models. The prototype was tested in the laboratory of Danish Technological Institute in different design states for evaluating the optimality of design steps and evaluate the overall cooling performance of the system.

The prototype and associated system modeling tools are to be further investigated and evaluated for future commercial exploration and development. Further development and in situ demonstration of the optimal control of the system needs to be conducted and further optimization of the airflow and pressure drops leading to thermal maldistribution merits more development to harvest the full potential of the PCM. Commercially, when the remaining technical details are overcome, the further development of prototypes for regional climate zones for widening the marked area are needed.

Danish Summary:

Projektets formål var at udvikle næste generations HVAC-systemer ved demonstration af en innovativ, omkostningseffektiv og skalerbar løsning, for termisk komfort i bygninger. Det foreslåede ventilationssystem er baseret på et innovativt PCM-baseret modul (modul med faseskiftende materialer) til at opfylde kølebehovet og erstatter konventionelle energiintensive køleteknikker.

Dette blev opnået ved at gennemføre en række specifikke projektmål, der omfatter udvikling af en prototype HVAC-system baseret på et eksisterende kommercielt produkt. Prototypen er konstrueret ved udvikling af et PCM-baseret energilagringsmodul (klimamodul) med nyt varmevekslerdesign og avancerede integreret styring.

Et modellerings- og designværktøj blev udviklet til modelbaseret performanceevaluering og brugt til at optimere prototypens systemdesign. I tillæg udførtes detaljeret CFD-modellering som assistance til den mekaniske designfase, og detaljerede Laser-Doppler Anemometry-målinger blev udført for at validere modellerne. Prototypen blev testet i Teknologisk Instituts laboratorium i forskellige designfaser for at vurdere optimalitet i designtrin og evaluere systemets samlede køleydelse.

Prototypen og de tilhørende systemmodelleringsværktøjer skal videreudvikles og evalueres yderligere med henblik på fremtidig udvikling til kommerciel introduktion. Yderligere udvikling og in situ demonstration af optimal styring af systemet skal udføres, og yderligere optimering af luftstrøm og trykfald, der fører til termisk mal-distribution behøver mere udvikling for at udnytte det fulde potentiale af det faseskiftende materiale. Når de resterende tekniske detaljer er overvundet, er der kommercielt behov for yderligere udvikling af prototyper til regionale klimazoner til udvidelse af markedsområde.

# 3. Project objectives

The NeGeV project goal was to develop the next generation of HVAC systems by demonstrating an innovative, cost-effective, and scalable solution to provide thermal comfort in buildings. The proposed ventilation system makes use of an innovative Phase Change Material (PCM)-based module to provide the cooling needs, replacing conventional active energy-intensive cooling techniques.

The goal was obtained by completion of a set of project objectives comprising the development of a prototype HVAC system based on an existing commercial product. The prototype was constructed by development of a PCM based energy storage module (climate module) with novel heat exchange design and advanced integrated controls using complex algorithms to forecast and optimize operation, based on a wide range of data on building latency, outdoor temperature, use patterns etc.

The project objectives were met by combining results from 6 technical work packages comprising objectives in relation to:

WP1: Defining ventilation system and application

WP2: System energy balance model

WP3: PCM-materials and casing

WP4: Climate module – energy storage, heat exchanger and charger

WP5: Controller

WP6: Prototyping and tests

# 4. Project implementation

The NeGeV project was launched in April 2018 and has run over 3 years and 3 months. The project management was reasonably uncomplicated and regular half year project meetings was conducted leading to a good, coordinated effort to meet the project goals and objectives.

Overall, the project reached its goals and objectives, and in addition a few additional results was obtained on detailed technical issues that needed further analysis. The project developed approximately according to the time plan and milestones were achieved, however with some delay due to the unforeseen effects of the Covid pandemic. The majority of these were delays encountered during manufacturing of the modules and some technical difficulties were encountered during the tests. These led to other delays regarding the energy model calibration and validation that was needed for final prototype optimized design and commercial performance evaluation. The final report on model based commercial evaluation are being completed and will be published after project end date.

# 5. Project results

The aim and objective of the project was obtained in accordance with the original project plan. The Project was split into 6 technical work packages and a project and management package (WP7). Results from technical WP’s are described here, the work from each WP was documented in reports and papers as listed under WP7.

The project did not have direct commercial milestones or deliverables and therefore there has not been any direct commercial results produced during the project. However, the commercial partner Exhausto are currently deciding a go/no-go to enter into a project development phase to commercially launch the concept. The technology is to be used in a wide range of products primarily aimed at segments such as office, living (hotels, apartments etc.) and public (schools, retail stores etc.).

**WP1: Defining ventilation system and application**

Through a series of project meetings and bilateral meetings between the project participants, a common understanding of the overall project goal was established and specific criteria for the other work packages was defined. Relevant conditions for the market, buildings, installations, and climate were described and a report prepared for documentation of the work package's results, which gave all participants a solid basis for the remainder of the project.

A project paper presenting the purpose, method, organization and expected results of the project was completed and published. As a result of a request from EUDP, WP1 was expanded with an activity on completion of a Proof of Concept (POC) report for evaluation and decision on stop/go after the project's first year. Based on the model work in WP2 the POC report was completed, and the project received a “go” for further progress.

The main results of this work were a partner wide consensus of the overall specific project objectives and main deliverables, including how each WP would contribute to these.

**WP2: System energy balance model**

The work under WP2 was in principle built up on the initial findings and results attained in WP1. To meet the deliverable of completing and submitting the POC report the first technical activity was established under WP2 to assess and evaluate the overall technical end economic feasibility of the proposed ventilation solution using phase change materials.  To quantify the added benefit of the climate module and demonstrate the expected performance of the system concept, a dynamic energy performance model for the proposed ventilation unit, consisting of the Exhausto VEX308 and the PCM climate module was developed.

In the system modelling process, the VEX308 was considered as a cross flow heat exchanger with an overall heat transfer coefficient calculated based on the number of transfer units (NTU) method. The case studied in the model was a small office of $30m2$, for approximately 2-4 people. A Key Performance Indicator (KPI) related to the indoor thermal comfort violations was implemented. The initial results were reported and the KPI for the NeGeV solution was found to be 25.61°$Kh$, compared to the system with no cooling and only pure ventilation with KPI 228.3°$Kh$. The cooling system therefore provides a large quantifiable added thermal comfort to the thermal zone.

After the initial proof of concept, the energy model development was further developed. Recent studies and evaluations in the field of PCM driven HVAC units were reviewed and mathematical equations and balances describing PCM performance were derived in addition to HVAC system energy flow equations including the employed heat exchanger. This resulted in development of an energy model as a basis of a simulation and design tool suite which delivers clear design, operation, and control parameters to predict energy capacity demand and system dynamic performance under given conditions in addition to serving as a basis for system operation, control, and optimization. The one-dimensional model was used to assess the performance of the overall system, including predicting the dynamic temperature profile of the PCM and air. In modelling the behavior of the PCM, the apparent heat capacity method is used, characterizing the effect of enthalpy and its evolution in time by considering an apparent heat capacity during thermal phase changes. In the energy modelling process, the hysteresis of the PCM behavior was also considered as a major factor in controlling the charging and discharging processes. The PCM is discretized in the vertical direction perpendicular to the air flow direction. In collaboration with WP3, a PCM candidate, SP21, was chosen for the current application and the energy performance simulation of the proposed system was reported under standard Danish summer weather profile as well as hot Danish summer conditions.

After successful implementation of the 1D system energy model, a 2D numerical PCM model has been developed to consider air flow dynamics in the air channel as shown in Figure 1. The 2D numerical PCM model was combined with the other ventilation system components including fans, heat exchangers and the required controls along with an upgraded room model to form a holistic PCM-driven ventilation system complete energy performance model. Using the upgraded model, yearly performance simulations were carried out and dynamic time series inputs were considered to evaluate the performance of the system and compare it to other cooling options. In this regard, the performance of the PCM cooling solution is evaluated in comparison with a night ventilation scenario and a baseline scenario using conventional vapor compression cooling. Operation of each system is evaluated using KPIs for thermal comfort in the room and the system yearly energy consumption.

The analysis showed that the PCM based cooling solution was able to provide improved levels of thermal comfort compared to night ventilation (NV), with comparable levels of electricity consumption. Table 1 presents the KPIs for the different solutions as reported by the simulations. The DX solution provides the best thermal comfort but also uses the most electricity while the NV system provides the least thermal comfort but uses the least amount of electricity. The PCM module presents itself as a middle ground, with electricity consumption that is close to that of the NV system. The investigation results demonstrated that active PCM cooling systems have the potential to provide benefits when compared to conventional cooling solutions, given that the design is carefully considered for the local environment.

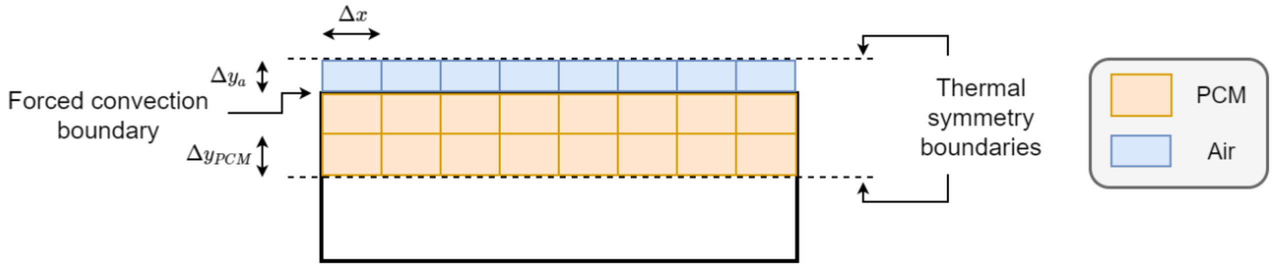



Fig. 1. Two-dimensional discretization scheme for the air-PCM dynamics.

Table 1: Yearly thermal comfort violations and yearly electricity consumption for each system.

| | DX | NV | PCM |
|---|---|---|---|
| Yearly electricity consumption [kWh] | 1810 | 1783 | 1791 |
| Yearly thermal comfort violation [°Ch] | 0 | 71.7 | 32.9 |

A parametric analysis was carried out to assess the impact of different parameters on the performance of the proposed ventilation/cooling system. Parameters considered include air volume flow rate, PCM melting temperature, PCM mass, number of PCM stacks and channel height. The phase change temperature and the PCM mass showed minimum thermal comfort violations at a melting temperature of 23.82°C. Combining the optimal melting temperature with an additional 100-150 kg of PCM, the thermal comfort violation could almost completely be removed as highlighted in Figure 2.

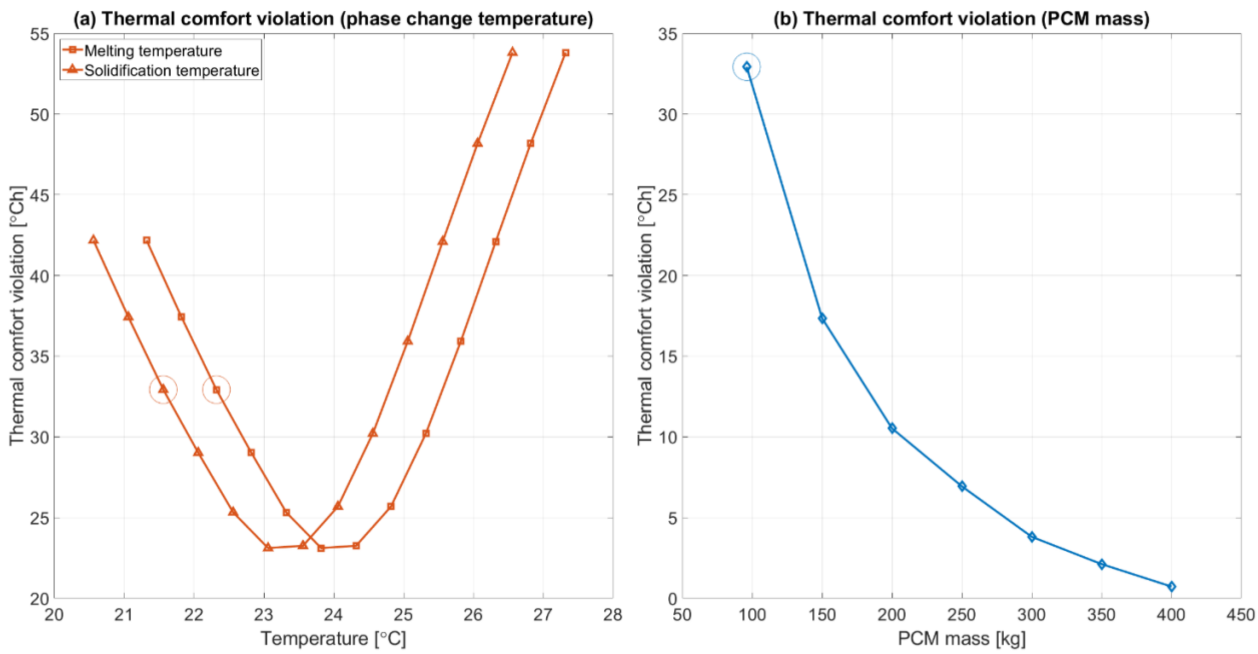



Fig. 2. Accumulated yearly thermal comfort violations for (a) different PCM phase change temperatures and (b) PCM masses

Moreover, the impact of domain discretization on the accuracy of a 2D model of PCM module for was performed. The mesh independence was conducted on 22 different mesh sizes ranging from 70 to 10.870

nodes. Convergence criteria was evaluated based on average air supply temperature and total heat transfer between the PCM and the air within the simulation time interval. Less than 0.1 % change in the air supply temperature and the heat transfer between the PCM and the air was achieved with 5250 and 9870 nodes, respectively. Thereby highlighting that a relatively small number of nodes can be considered to achieve sufficient accuracy to conduct analysis of PCM applications. The developed dynamic energy model was also communicated and delivered to WP5 to aid the design and development of proper system components controls as well overall system control strategies. In this regard, additional simulations were carried out to ensure the selection of optimal control conditions and system operational management framework.

The energy system model was calibrated using actual data collected from real system testing. A preliminary calibration and validation of the developed model, using data collected from an actual system running at the premises of project partner Rubitherm in Berlin was completed. The developed model was validated against data from an in situ active PCM cooling application that in this investigation consisted of a PCM module with 4 stacks of PCM plates, serving as a heat exchanger between the ventilation air stream and the PCM. A picture of the setup is shown in Figure 3. Inside the module the PCM is encapsulated in aluminum containers. The containers are placed in horizontal stacks each of 25 panels with 5 mm air space between them. 4 stacks are placed in series in the direction of the air stream. A total of 9 temperature sensors are utilized for monitoring the PCM temperature in each stack and the air temperature before and after each stack. It was shown that the developed model predicts well the system performance with an average deviation of less than 2% for the PCM temperature and less than 4% for the air temperature. Further validation of the developed system energy model was carried out considering actual testing of the NeGeV prototype at DTI premises. Moreover, simulation of melting front of PCM was carried out through extrapolation of internal PCM measurements from actual system testing to aid further model development and validation. Based on the comparison reported, the model was found to predict the air and PCM temperatures with an acceptable level of accuracy.

Figure 3. The actual PCM-driven ventilation system running at the premises of project partner Rubitherm in Berlin

Overall, the results attained under WP2 are sensible and feasible from the physical and technical perspective. In terms of the comparison of the NeGeV ventilation/cooling solution with conventional DX cooling systems, the results attained are to some extent expected with the DX cooling system being the energy intensive solution allowing absolute thermal comfort. On the other hand, the NeGeV solution allows reducing energy consumption with the corresponding environmental added value, but with some compromise on the thermal comfort levels compared to DX solutions.

One underestimated point at the start of the project was assuming that constant melting/solidification PCM temperature profiles have minimal impact on the performance. However, due to further investigation under WP2 and the review of recent reports and studies, the impact of hysteresis of the PCM behavior was considered as part of the developed energy model, as a major factor in controlling the charging and discharging processes. It was found that hysteresis influences the operation of the PCM module in a negative way by requiring lower nighttime temperatures for solidification and higher day time temperatures for melting. This results in increased difficulty with charging or discharging of the full thermal capacity of the PCM, compared to an ideal material without hysteresis.

**WP3: PCM-materials and casing**

WP3 addressed the development of PCM material and casing and the potential technical and economic/environmentally issues that could be associated with using PCM in an HVAC application. The choice of PCM is critical for the efficiency and effective utilization of the latent thermal energy. There are three different PCM candidates developed and produced by Rubitherm for the system. The PCM candidates are of the 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 are found in Table 2.

Table 2: PCM properties

| | 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/$\mathrm{m}^3$] | 1500 | 1500 | 1500 |
| Density (liquid) [kg/$\mathrm{m}^3$] | 1400 | 1400 | 1400 |
| 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 |

The dynamic energy balance model has shown that the optimal PCM depends on the climatic conditions in Denmark. It was found that the lowest KPI for thermal comfort was achieved at a phase change temperature of 22.0°$C$ in the extreme case, while for year case the lowest KPI was achieved with a phase change temperature of 19.1°$C$. The PCM with a melting temperature of 21°$C$ serves as a compromise for both cases. Further testing of the prototype will attempt to investigate if this melting point choice was suitable. As the goal is to use the PCM as much as possible throughout a year the ideal PCM choice is of paramount importance.

When using PCM, many factors play an important role for choosing an encapsulation. The PCM used in this project is a salt hydrate, a mixture of water and salts. For this reason, the encapsulation must above all be corrosion resistant. Conventional plastic encapsulations were not considered as their low thermal conductivity hampers the heat transfer considerably. As standard metals react with the inorganic PCM chosen the metal encapsulation requires a corrosion protection that is resistant to crystals that grow in the phase change. The protecting layer must withstand hundreds of cycles and changing temperatures.

The PCM casing chosen is an already developed and well tested casing: The CSM (compact storage module) plate that is shown in Figure 4. The CSM is available in the dimension 300x450mm and two thicknesses of 10 and 15mm. For this project a height of 15mm was chosen as more PCM can be arranged in the same volume than for the thinner panel.

Figure 4: The CSM casing from Rubitherm.

The CSM plate consists of two coated aluminum half-shells. The half-shells are glued together and additionally mechanically joined (flanged). In the middle there are two connection points to avoid bulging during the phase change. The surface is structured on both sides. This significantly increases the stability of the surface and prevents laminar flow on the surface.

The main challenge when using salt hydrates is avoiding a separation of the different components. Consequences of separation can be increased hysteresis, supercooling or reduced capacity. The higher the liquid column, the larger the probability that light and heavy particles will separate. For this reason, various separation studies have been carried out. PCM was cycled in a column with a high of 50mm and after a few cycles PCM was taken from different heights and measured in the 3-layer calorimeter.

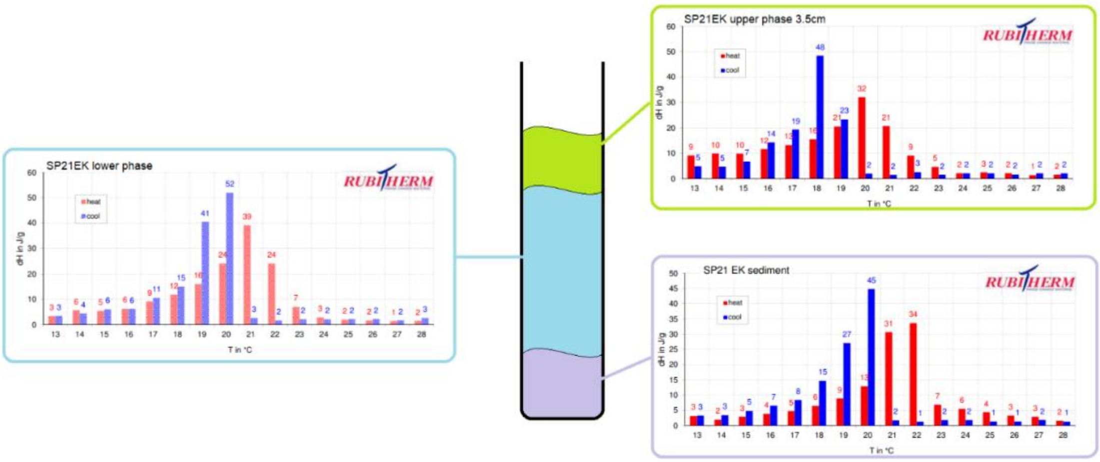
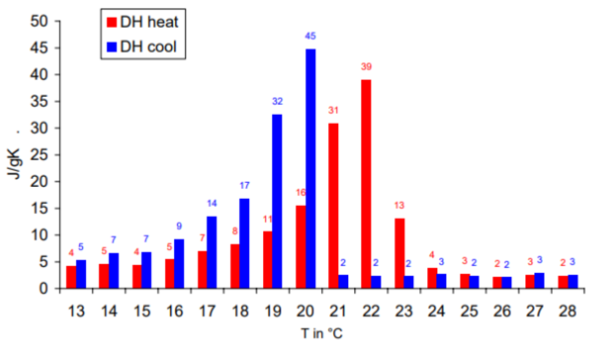



Figure 5 Separation

In Figure 5 the different results are shown. Slight differences were seen over a total height of 50 mm. However, the total capacity is not affected by this. The total height in the CSM plate is 15mm, which is significantly lower than in the test setup. In the installation situation, therefore, no negative influences from the separation are expected.

A sample of SP21E was measured before and after 5000 cycles. With a daily use of the storage, this corresponds to approx. 13 years. The result is shown in Figure 5 and Figure 6. Important criteria are no shift of the melting range and no changes in capacity. The melting range is slightly flatter but does not change significantly regarding the temperature range. The capacity is 156kj/kg before cycling and 155kj/kg after 5000 cycles which is identical within the error margin of the measurement method (three-layer calorimeter).



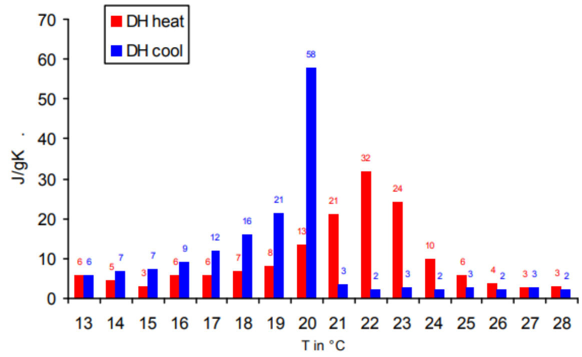




Figure 5 (left) SP21E before cycle treatment. Figure 6 (right) SP21E after 5000 Cycles

Together with the University of Stuttgart, the global warming potential (GWP) of the PCM and the encapsulation was investigated.

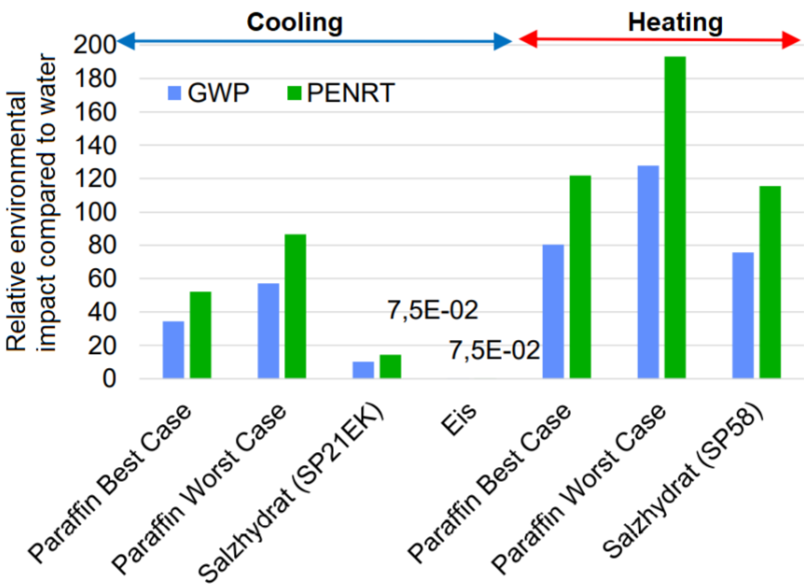



Figure 7 Environmental impact compared to water

The standard storage medium in most cases is water. It is cheap, available everywhere, non-toxic, and easy to process. Figure 7 shows the impact of alternative storage materials on nature compared to water. Ice, like water, has no influence on nature. The disadvantage is that ice can store energy only at 0°C. Alternatives are paraffins and salt hydrates. SP21EK has a low impact on nature and is therefore optimal for the project.

PENRT Primary energy non-renewable (PENRT) describes the energy taken from the environment, for example in the form of crude oil, natural gas, hard coal or hydropower. It is the calculated usable energy content that has not yet been converted.

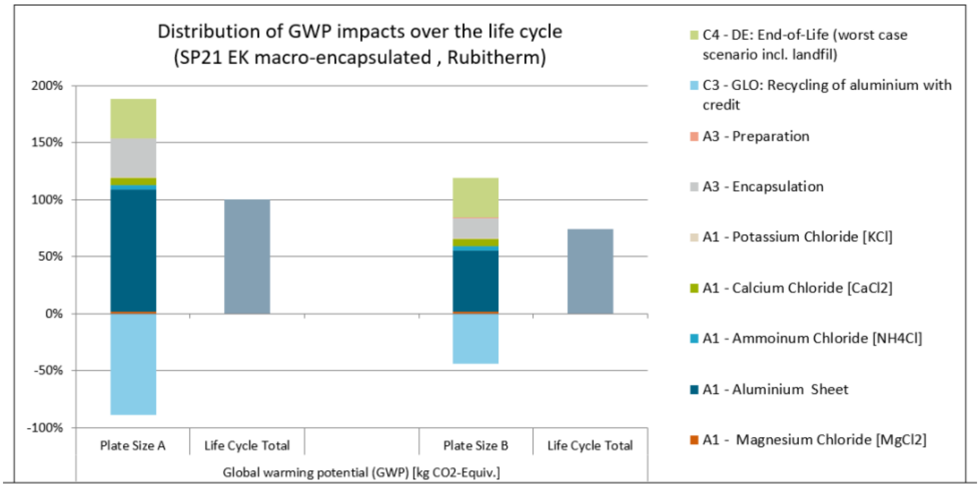



Figure 8 GWP over life Cycle

Encapsulation has a high influence on the GWP. Figure 8 shows the GWP of PCM and encapsulation. The extraction and processing of aluminum requires a lot of energy. The dark blue bar shows the impact of the aluminum sheet. In a direct comparison the magnesium chloride (orange bar) and the ammonium chloride (cyan bar) have much less impact as the aluminum sheet. If these 3 components are considered, 90% of the $CO_2$ goes back to the aluminum. This can only be reduced by recycling at the end of life.

According to manufacturer 60% recycled and 40% virgin aluminum is used for the CSM plate. This results in a $CO_2$ footprint of 6,2kg per kg aluminum. As a comparison, calcium chloride (a major component of SP21EK) has only 0.89kg/ $CO_2$ per kg. The goal is to increase recycled part of the aluminum as this is the main driving force in the GWP.

**WP4: Climate module – energy storage, heat exchanger and charger**

The aim WP4 was to develop a mechanical design of the climate module and to optimize the airflow distribution and heat exchange between ventilation air flow and PCM, and to integrate the system with the ceiling mounted decentralized ventilation unit VEX308 air handling unit from Exhausto. CSM plates from Rubitherm was used for the system as described in WP3. A heat exchanger was designed by stacking the CSM modules with a certain distance where the air flow from the ventilation system could transfer heat from air to the PCM material through the aluminum plates. In case of cooling during the day the ventilation air is directed through the discharged climate module where the heat absorbs and charging the module while cooling the ventilation air. During the night the module releases heat.

The first prototype of the climate module, shown in Figure 9, was a stand-alone platform that should generate experimental data to validate the functionality and to validate a CFD simulation of the air inlet uniformity, pressure loss and heat transfer. This first test had a significant importance because further improvements in design and operation parameters of the protype was done based on the results of these tests.

Figure 9. Stand-alone climate module. Left: aluminum case with encapsulated PCM. Right: climate module with stacked PCM cases.

The first prototype consists of an aluminum casing with a height of 1036.15 mm and with the possibility of mounting 55 CSM plates with 1.5 mm gap size and 50 plates with 3 mm gap size. It has a single air inlet at the top and single outlet at the bottom on the left side (see Figure 9). The inlet chamber has a wedge-shaped design to ensure an even pressure distribution from top to bottom at the inlet to the gaps between all the PCM plates. The purpose of providing two types of plates arrangement was to analyze the effect of gap sizes between the plates on the air flow distribution, pressure, and heat transfer rate.

The idea of wedge-shaped flow region for both inlet and outlet chambers were suitable for pressure loss compensation and gave uniform pressure distribution in both inlet and outlet chambers. The maximum pressure difference between the two chambers was approx. 80 Pa for the 1,5 mm gap size at 800 $m^3/h$, which was below the system requirements for integrating with the VEX308 decentral ventilation unit.

Based on the results from both the configurations, 1.5 mm gap system was used for the design of the integrated climate module and VEX308 air handling unit, because it was capable to store more energy. The development of the prototype where the climate module is integrated with the VEX308 was based on the following specifications:

- The climate module is mounted behind the VEX308 unit, which also determine the exterior dimensions
- The module consists of 48 CSM plates in 2 parallel stacks with a gap size of 1,5 mm.
- The inlet chamber is designed with a wedge-shaped flow region by use of a guide wall and the flow is aligned parallel to the gaps between the CSM plates in the 2 stacks
- The climate module is insulated with 50 mm at sidewalls and there must be possibilities for inspection, cleaning and repairs of pipes, dampers, electrical devices, PCM panels etc.
- Possibilities for smart solutions to replace the PCM stack e.g. telescopic solution

To make the simulations of the entire climate module feasible, the full 3D CAD model was simplified significantly by modelling the spacings as constant thickness without any detailed topography and without the detailed features near the inlet and outlet to the stack spacings, as seen in Figure 10. This allowed a high-quality simulation mesh without excessive resolution required to resolve small geometric details. The model provided overall insight into the flow in the climate module.

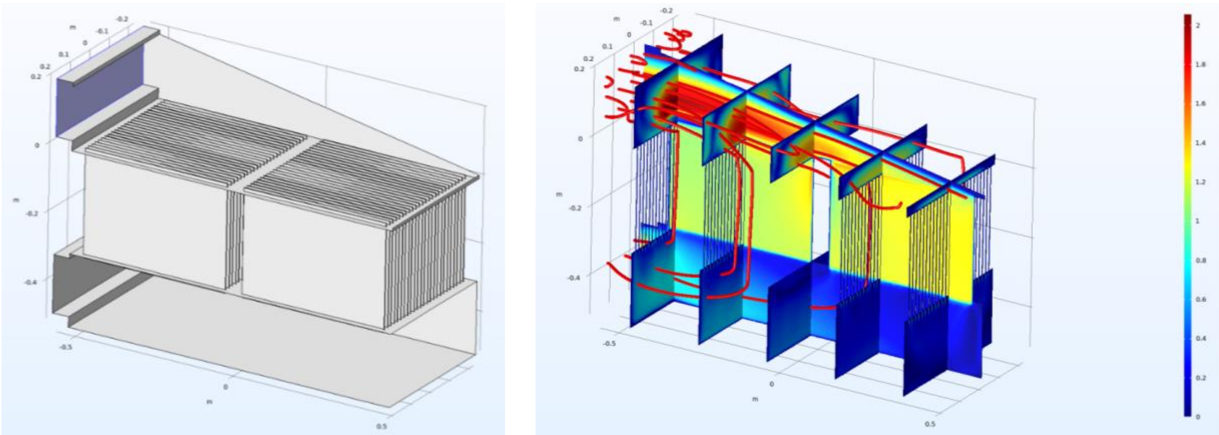


Figure 10: Simplified CAD representation of the full 3D system along with velocity field from simulation.

To allow for parametric studies and simulation-based optimization an approximate two-dimensional planar model was derived. The model was based on assuming an out-of-plane velocity distribution and analytically integrating to obtain a flow resistance term from the out-of-plane viscous resistance, where the friction coefficient is given by $\alpha = \frac{10\mu}{s^2}$ where $\mu$ is the dynamic viscosity and $s$ is the spacing between the plates. This resistance term is similar to that from flow through a porous media, which can be seen as a physical analogy of the multiple spacings through the stacks.

Using the simplified planar model, it was possible to run multiple parameter studies to investigate the effect of the guide wall in the inlet domain on the distribution of flow between the two stacks. Figure  shows the velocity field for the initial design, as well as the geometric variables to be changed in the parameter study. The conclusion of the study was that the guide wall should connect directly to the inlet to avoid recirculation affecting both the pressure drop and thermal performance. The final recommended design is shown in Figure 12 along with the flow distribution for the modified design.

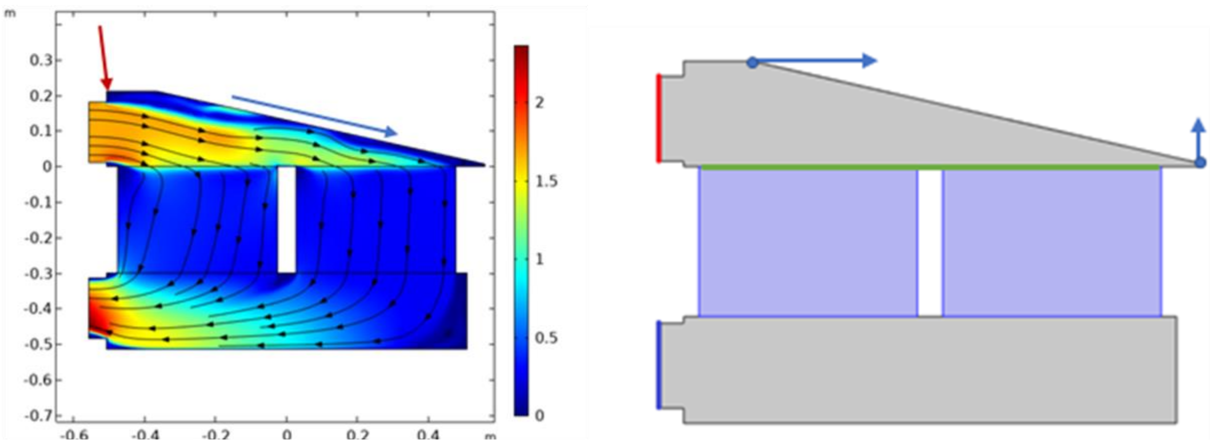



Figure 11: (left) Velocity field for initial design; (right) design changes for parametric study.

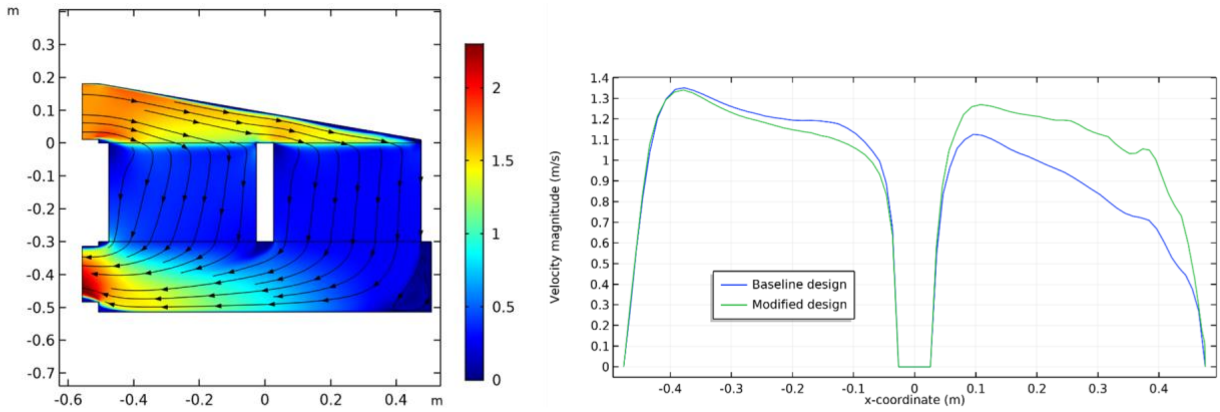


Figure 12: (left) Velocity field for modified design; (right) flow distribution for baseline and modified design.

The climate module is adjusted to fit the ceiling mounted VEX308´s design and production. The bodywork and hatch have the same dimensions as the VEX308. The challenge regarding doing service on the quite heavy PCM stacks, has been addressed by mounting the PCM stacks in a rail system that via a thread rod and an electric screwdriver can be gently brought down underneath the climate module.

The construction of the climate module is performed with large rectangular ducting and dampers. This with low differential pressure. Modulating motor dampers has been placed in the main duct on the inlet to the VEX308 and on the inlet and outlet to the PCM stacks. It is then possible to control whether you want full airflow the PCM stacks or partial airflow according to the cooling demand. In addition, an on/off damper and an extra ventilator is placed so the regeneration process can be activated in the nights.

The final design of the climate module can be seen in Figure 13 without the VEX308 air handling unit. The figure shows test setup for optical measurement of the internal air flow distribution, which gives detailed information of the velocity magnitude and direction.

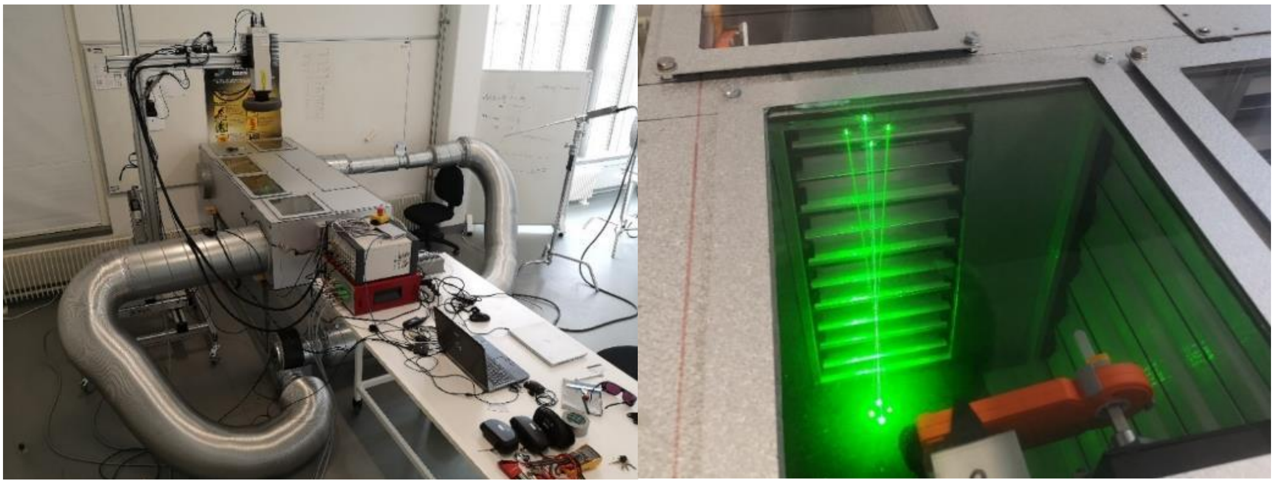
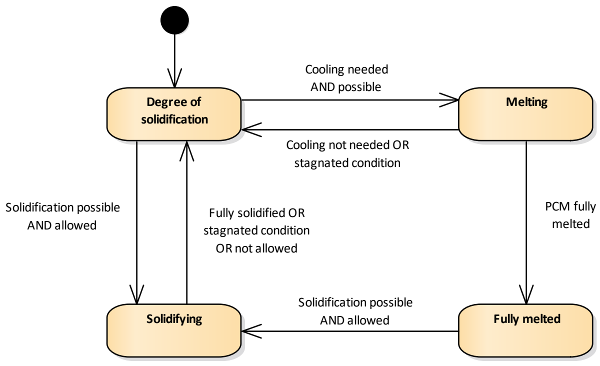


Figure 13: Full view of the LDA measurement setup and a close-up of ongoing measurements

**WP5: Controller**

WP5 investigated the necessary developments in control strategy for a PCM based system. Based on the model from WP2 and standard rule-based control (RBC), the control strategy used in the VEX308, was integrated into the simulation model. This was to further validate the WP2 model, and to find issues that might show up in the later experimental prototype.



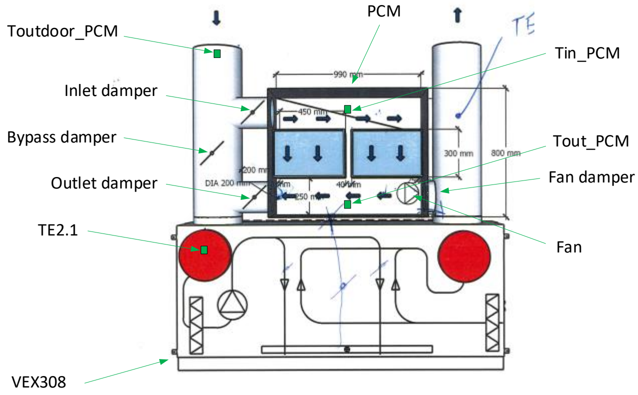




Figure 14. Left: schematic of the melting/solidification logic derived based on the standard rulebased control. Right: VEX308 with additional climate module and control components (sensors and, fans and dampers).

Figure 14 shows the control logic and sensor/fan/damper overview in the prototype. Analysis of the PCM state has been conducted and the logic is included in the standard controller. Investigation on how many sensors is needed for the product, and how many should be used in the prototype to give better experimental data was conducted. The extra sensors are used to find further dynamics that the reduced set may not clearly show. Additionally, they help make a better estimate on charge level in the PCM plates.

Work have been done to develop a model-based control algorithm and implementation for optimizing the conventional rule-based control strategy. The work integrates the PCM based ventilation cooling system with a building zone model and study the feasibility and overall performance of model predictive control (MPC) on such a system. To achieve this, a surrogate model of the PCM ventilation unit model was developed based on the experimental work in WP2. Here the PCM model is integrated with a calibrated grey-box office zone model as a system emulator. The simulation results of the whole system are performed under real occupancy and climate conditions. A full MPC framework controlling supply airflow rate of the PCM-based ventilation cooling system has been developed and tested on the emulator under summer weather conditions. The performance of the entire system is compared to a conventional system employing rule-based control (RBC) approach. Results show that PCM-based ventilation cooling system allows to mitigate indoor zone thermal discomfort. MPC can achieve less energy consumption, but it does not necessarily result in less thermal discomfort as compared to RBC.

Currently the MPC approach is being developed further using a mixed integer approach which is more relevant as it lends itself to automated and optimized identification of the operation model and thereby optimal usage of the PCM charge. This will lead to optimized operation, based on a wide range of data on building latency, outdoor temperature, use patterns etc., making it possible to use building latency, free cooling and the PCM module in combination to optimize energy efficiency and reduce PCM capacity needs

**WP6: Prototyping and tests**

The purpose of WP6 was to develop and test the PCM-based heat storage module (climate module) for ventilation systems, integrating components from prior WPs. The final version of the module utilizes two stacks of PCM plates in parallel as heat storage medium. The climate module has been tested as a standalone unit at the Danish Technological Institute (DTI) and the design has been improved iteratively across three series of tests spanning the duration of the project. Different pressure and temperature measurements have been recorded. It was shown that the module respects the design constraints for its integration with the VEX308. The module also shows great potential as a heat storage unit for the different operating conditions investigated.

The 2nd iteration of the module was manufactured in May-June 2020 and shipped to DTI, where the 2nd series of tests took place starting in June 2020. The test results were delivered by DTI in August 2020. Results from the second series of tests have been compiled and summarized in a technical report and summarized at a WP6 meeting in September 2020. It was shown that there was a temperature loss between the inlet of the two stacks that resulted in poor utilization of the second stack. It was also shown that there was a potential flow imbalance between the stacks, which again could lead to an uneven use of the stacks. WP6 team worked on ideas on how to improve the climate module based on the 2nd test results – four designs were suggested with incremental change that were aimed to address the shortcomings of the module.

The test matrices for the final (third) series of test were finished in October 2020. The final iteration of the module with all components necessary to investigate the four designs were received by DTI in November 2020. The final tests took place over the next few months. Due to some time constraints and technical difficulties during the tests, the test matrices have been reworked in collaboration between SDU and DTI in January 2021. The tests that were necessary to answer the initial research questions formulated for the final tests were prioritized. The final test data was delivered by DTI in early March 2021. Results from the final series of tests have been compiled and summarized in the technical report.

The 3 months extension for the project allowed additional results to be generated by WP6. Additional tests of the velocity field in the climate module were initiated caused by the uncertainty in the dynamics pressure test based on pitot tubes. This measurement is based on optical LDA-technology (Laser Doppler Anemometry) to capture 2D point measurement of air velocity and direction as also indicated in figure 13.

The three test reports and the LDA which are all very elaborate are attached in appendices for further detailed information.

**WP7: Project management and dissemination**

As mentioned, the project management was reasonably uncomplicated and WP7 project management led the project to finalize the goal of a functioning prototype of a PCM based ventilation unit. The development process and results of the project work is documented and disseminated in several internal reports and open publications as listed below and attached as separate appendix.

Due to the Covid pandemic there was not an opportunity for disseminating the project results in trade fairs, neither national, nor international.

List of presentations related to the project:

- Joe Alexandersen, *"Topography optimisation – a new method for flat plate heat exchangers?",* at internal research meeting, 17th of September 2020.

- Joe Alexandersen, *"Topography optimisation of parallel plate heat exchangers",* at the World Congress of Structural and Multidisciplinary Optimization 2021 (WCSMO14), 14th to 18th of June 2021.
- Viktor Ljungdahl, *"Experimental and numerical investigation of a PCM module for ventilation systems"*, at the 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems conference (ECOS 2020), June 29 - July 3, 2020, Osaka, Japan.

- Tao Yang,*"Object-oriented modeling and performance evaluation of a PCM-based ventilation system"*, at the 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environ-mental Impact of Energy Systems conference (ECOS 2020), June 29 - July 3, 2020, Osaka, Japan.
- Konstantin Filonenko, *"Modelica implementation of phase change material ventilation unit"*, at the 6th IEEE International Energy Conference (ENERGYCon), September 28 —October 1, 2020, Tunis, Tunisia.
- Viktor Ljungdahl, *"A PCM-based cooling solution for ventilation applications*", at the 1st Energy Informatics. Academy Asia Ph.D. Workshop, 28 May 2021, Beijing, China.
- Viktor Ljungdahl, *"Impact of Domain Discretization on the Accuracy of a 2D Model of PCM Module for Ventilation Application*, to be presented at the 8th European Thermal Sciences Conference (EUROTHERM2021), 20-23 September, 2021.
- Viktor Ljungdahl, *"Performance Evaluation of an Active Phase Change Material Cooling Application in Northern European Climate"*, to be presented at the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environ-mental Impact of Energy Systems conference (ECOS 2021), June 28 - July 2, 2021, Giardini Naxos, Italy.
- Tao Yang, *"Formulation and implementation of a model predictive control (MPC) strategy for a PCM-driven building ventilation cooling system",* to be presented at the Building simulation Conference 2021 (BS2021), September 1-3, 2021, Bruges, Belgium.

List of project Reports:

1. NeGeV WP 1 Report: Defining System, Application and Scoping of the Project.
2. NeGeV Proof of Concept Report.
3. Test Report #1: Test Report for Stand-alone Research Platform of the Climate Module
4. Test Report #2: Test Report for Prototype no. 1- for VEX308 integration
5. Test Report #3: Test Report for Design Optimization of Prototype no. 1 for VEX308 integration
6. Test report: An experimental study on charging and discharging characteristics of SP21 PCM.
7. LDA Report

List of publications:

1. Christian Veje, Muhyiddine Jradi, Ivar Lund, Thomas Hansen, Klavs Kamuk, Esther Kieseritzky, and Christian G Nicolaisen. NeGeV: Next Generation Energy efficient ventilation system using phase change materials. Energy Informatics, 2, 2019.
2. Viktor Ljungdahl, Muhyiddine Jradi, Esther Kieseritzky, Mads Rasmussen, Klavs Kamuk, Christian Veje, NeGeV: Phase Change Materials for Innovative Cooling Solutions, The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) Journal 2019, pp.42-47.
3. Ahmad Omar El-Kassem, An Experimental study and simulation of latent heat in phase change materials, SDU Master Thesis, (2019).
4. Anders Dyreborg Schmidt, Analysis and optimization of air flow in a rectangular channel for energy storage application, SDU Bachelor Thesis, (2020).
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Simulation and Environ-mental Impact of Energy Systems conference (ECOS 2020), June 29 - July 3, 2020, Osaka, Japan.

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7. Konstantin Filonenko, Viktor Ljungdahl, Tao Yang, Christian Veje, Modelica implementation of phase change material ventilation unit, Proceedings of the 6th IEEE International Energy Conference (ENERGYCon), September 28 —October 1, 2020, Tunis, Tunisia.
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10. Viktor Ljungdahl, Muhyiddine Jradi, Christian Veje, Jonathan Dallaire, Performance Evaluation of an Active Phase Change Material Cooling Application in Northern European Climate, Proceedings of the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environ-mental Impact of Energy Systems conference (ECOS 2021), June 28 - July 2, 2021, Giardini Naxos, Italy.
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13. Viktor Ljungdahl, Muhyiddine Jradi, Christian Veje Utilizing Phase Change Material for Increasing Data Center and High-Performance Computing Energy Efficiency, submitted to Applied Thermal Engineering Journal, 2021.
14. Hafiz Muhammad Adeel Hassan, Ivar Lund, Inorganic PCMs Applications in Passive Cooling of Buildings - A Review, Accepted for publication in the proceedings of the 8th European Thermal Sciences Conference (EUROTHERM2021), 20-23 September, 2021.

Further publications in preparation:

15. Joe Alexandersen, Revisiting the origin to bridge a gap between topology and topography optimisation of fluid flow problems, under preparation, Structural and Multidisciplinary Optimization.
16. Joe Alexandersen, Topography optimisation of parallel plate heat exchangers", under preparation, International Journal of Heat and Mass Transfer.
17. Hafiz Muhammad Adeel Hassan, Ivar Lund, Christian Veje, Mads Peter Hansen, An experimental study to investigate the effect of gap size and air flow rate on the performance of phase change material based thermal energy storage system, Energy Conversion and Management.

18. Ivar Lund, Martin Nørgaard, Hafiz Muhammad Adeel Hassan, Analysis of the effect of phase separation on melting and solidification of PCM encapsulated in aluminium boxes
19. Ivar Lund, Jesper Bjernemose, Hafiz Muhammad Adeel Hassan, Experimental and numerical analysis of flow uniformity at the inlet to a PCM based heat exchanger
20. Joe Alexandersen, Hafiz Muhammad Adeel Hassan, Ivar Lund, A reduced-dimensional planar model for parallel plate heat exchangers: comparison to full three-dimensional results
21. Martin Winther-Gaasvig, Mads Høi Rasmussen, Ivar Lund, Hafiz Muhammad Adeel Hassan, Design and Optimization of air-PCM Heat Exchangers

At least three more journal papers are planned and will use the test results from DTI in test report #1-3 as foundation (specific paper title and journal to be determined).

# 6. Utilisation of project results

The results developed in the project will be utilized by both the commercial partners and SDU. From SDU side there are several unanswered questions that still need to be dealt with and the solution of many of these will reach into the commercial product development side of future work.

From a technical aspect further development and in situ demonstration of the optimal control of the system needs to be conducted. Likewise further optimization of the airflow and pressure drops leading to thermal maldistribution merits more development to harvest the full potential of the PCM. In addition, there are many research aspects that still need proper publication and dissemination as also indicated in the list of articles in preparation. The project has spurred many interesting problems of optimization of heat transfer, especially in relation to the corrugated PCM plates and by stacking thereof. Also, further work on techno-economical evaluation based on the energy system modeling approach will generate more research publications alongside publication of the experimental work on both testing and the LDA work.

Commercially, when the remaining technical details are overcome, the further development of prototypes for regional climate zones for widening the marked area are needed to establish a marked and business case for commercialization. Exhausto will be the partner in this as they are the end product manufacturer, but also the two other commercial partners Bitzer and Rubitherm will be key as subcontractors for the further development and commercialization of the product.

The project has not at this point led to direct increase in turnover or employment. However, pending the decision on go/no-go for a final commercial project development phase, the results will see direct commercial utilization in line with the expectations of the original application. In this project the PCM technology and the climate module has been dedicated designed for a smaller decentral HVAC solution for applications in ex. learning environment, offices, and meeting rooms. This suits very well the capacity of the PCM materials available at present. The full-scale climate module demonstrates the proof of concept and will form the base of the commercial product development projects This project will need to develop a complete family of climate modules fitting the product family of the Air Handling Units. The go/no-go decision depends on a further validation of the commercial business case and the market investigation. While the project shows clearly, that the demanded dayli cooling capacity can be fulfilled in most cases, it also shows, that present expectations on precision in the indoor climate experience needs a new perception. The accepted indoor temperature tolerance needs to change to an understanding that the Zero-Emission technology delivers higher short term temperature changes during the day.

Two PhD students, Mr. Viktor Ljungdahl and Mr. Tao Yang were directly involved in the NeGeV project WP2 work with many of the findings and deliverables achieved under the project work feeding into their overall PhD activity plans and deliverables.

Viktor Ljungdahl has been part of the project family since day 1 and has taken part in completing the Proof of Concept Report. His inclusion in the project is natural as his PhD is entitled 'Modelling design and assessment of innovative phase change material-based HVAC systems'. His contribution in the project is very well highlighted as he is included in most publications reported under WP2 activities and findings dissemination. In terms of teaching, Viktor has been involved and aiding in multiple courses at SDU Energy Technology Program.

In addition, PhD student Tao Yang has been partly involved in the work under WP2 and WP5, mainly focusing on the component modeling of PCM using Modelica tool and implementing MPC techniques to optimally control the system performance. His PhD project is entitled 'Analysis and application of model predictive control in energy systems and the activities under NeGeV WP2 were in line with the overall activities and deliverables of his PhD.

One Ph.D. student, Hafiz Adeel Hassan, has been part of WP4 and selected research results obtained in connection with the Ph.D. project has been taught to the students in master courses in Advanced Fluid Mechanics and Computational Fluid Mechanics. The PhD student also supervised one bachelor thesis project dealing with simulation of pressure loss in the NeGeV developed climate module and presented his PhD work at the SDU-Mechanical Research Seminar.

# 7. Project conclusion and perspective

The main conclusions drawn from the modeling work were:

- It was shown that the PCM based cooling solution was able to provide improved levels of thermal comfort compared to night ventilation.
- The optimal phase change temperature with minimum thermal comfort violations was attained at a melting temperature of 23.8°C.
- Utilizing 250 kg of PCM with the optimal phase change temperature was able to reduce thermal comfort violations to below 1°Ch.
- The use of additional PCM stacks was found to lower efficiency of the PCM module.
- The efficiency loss can be counteracted by higher flow rates that are able to extract more energy from the later stacks.
- The peak cooling capacity was found to increase with number of stacks.
- Optimizing the volume flow rate and PCM melting temperature, the cooling/kg PCM and the peak cooling capacity of the module is increased by 38.4 % and 71.1%, respectively.
- It was shown that the developed model predicts well the system performance with an average deviation of less than 2% for the PCM temperature and less than 4% for the air temperature.

The main conclusions drawn from the mechanical development work were:

- Development of a sensor system to measure the internal temperature distribution in a CSM plate to evaluate the melting and solidification zones gave knowledge of the time for fully melting and solidification in 2D.
- Optical Laser Doppler Anemometry methods for air velocity magnitude and -direction at the entrance of the CSM stacks gave detailed information of the velocity profile and the inlet mass flow in each stack.
- Using the simplified planar model, it was possible to run multiple parameter studies to investigate the effect of the guide wall position and -angle in the inlet domain on the distribution of flow inlet between the two stacks.
- By use of flow conditioning perforated plate and wedge-shaped pressure chamber (guide wall) for pressure loss compensation it was possible to obtain uniform air inlet flow.
- Development of a stand-alone platform of the climate module with one CSM stack for initial experimental study of the functionality and to validate a CFD simulation of the air inlet uniformity, pressure loss and heat transfer.
- A compact climate module adjusted to fit the ceiling mounted VEX308´s design and production with 2 parallel stacks of CSM plates with 1,5 mm gap sizes were developed, designed, and manufactured. The system was implemented with a service function for the CSM plates

The main conclusions drawn from the DTI testing results were:

- The first design investigated showed that pressure drop for both configurations (1.5mm and 3mm distance between the plates) is well within the range of the VEX 308 system. The wedge-shaped region for the inlet chamber is suitable for pressure loss compensation. A distance of 1.5 mm between the plates is recommended, as it offers faster heating and cooling rates and provides more energy storage potential.
- The second design (2 stacks of PCM plates in parallel) using 1.5 mm gap between the plates also showed to be within the range of the VEX 308 system in terms of pressure drop. The data suggests that there could be a flow imbalance between the two stacks, which leads to an uneven utilization of the stacks for energy storage. Dynamic pressure measurements proved to be inaccurate to estimate the air flow rate passing through each stack. A significant temperature difference was observed between the inlet of stack 1 and stack 2. It is recommended to insulate the back of the guiding plate to minimize this in future iterations, as well as to further investigate the flow distribution between the stacks.
- The final tests showed that adding insulation behind the guiding plate seems to have resolved the issue of decreasing temperature between the inlet of stack 1 and stack 2, therefore improving the relative utilization of the stacks for energy storage. The results also showed that it is possible to control the flow fractions between the stacks by using flow conditioning, such as perforated plate, grills and dampers.

In summary, the project concludes that the application of room ventilation based on PCM can provide a cost-effective and scalable solution to provide thermal comfort at a highly reduced energy consumption as compared to conventional DX systems. Based on modeling work of the system dynamics and controls, the project also concludes that optimal operation control (MPC) can be implemented for further energy savings and ultimately integration to a flexibility aggregator contributing to demand side management in a future sector coupled energy marked.

The future steps to be taken is partly technical, partly commercial. The further development and in situ demonstration of the optimal control of the system needs to be conducted and further optimization of the airflow and pressure drops leading to thermal maldistribution merits more development to harvest the full potential of the PCM.

Commercially, Exhausto is currently deciding on a go/no-go for further project development to mature the prototype into a commercial product. A few remaining technical details remains to be overcome and then, the further development of products for different regional climate zones for widening the marked area are needed. The decision is not only depending on the technical results and the go/no-go for starting the product development project at the commercial partner Exhausto, is very much depending on the maturity and acceptance in the market. During the project period further market inquiries has been completed with focus on the Danish and the German market and applications. The transition from traditional cooling technologies to more environmentally friendly alternatives, is moving very slow, even though the F-Gas directive is pushing very hard on phasing the traditional refrigerants out. Being a technological first mover always requires extra marketing, communication, and training in the markets. But the construction business is still preferring technologies, that has proven stable reliability over many years, and gives the best economical advantage. This preference will not change, and therefore is the NeGeV project team facing an enhanced challenge on demonstration and validation of the new PCM technology. The PCM material has been intensively studied, concepts of the climate module have been simulated, laboratory test have successfully verified the concept and a full-scale prototype of the climate module with PCM has been designed and manufactured and also tested. To satisfy the and eliminate the reluctance of the market, we will need to conduct several full-scale installations with test of performance and validation of efficiency. The next needed steps will therefore be to find live and operative buildings and projects, that can serve as full scale demonstrations and also be show rooms for excellent indoor quality.

# 8. Appendices

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