Final report

1. Project details

Project title	iCeiling – Intelligent køle- og varmeloft med energilagering
File no.	64 018-0612
Name of the funding scheme	EUDP
Project managing company / institution	JS Ventilation
CVR number (central business register)	39 49 54 14
Project partners	Teknologisk Institut, Neogrid & Aalborg Universitet
Submission date	30 June 2021

2. Summary

Summary (engelsk):

The project has developed "iCeiling": A ventilation ceiling with draft-free cooling and heating supplied by a decentralised heat-pump. Furthermore, the system includes a thermal energy storage and intelligent controller ensuring a good and energy efficient indoor climate and energy flexibility, increasing the utilisation of fluctuating renewable energy. iCeiling implements data collection for operational monitoring and diagnostics for use in services. The main activities have included technology development, system optimization and demonstration, resulting in proven solutions, dimensioning tool and design guidelines. iCeiling is a competitive and flexible alternative to traditional central heating, ventilation and air conditioning (HVAC) solutions. The market includes new and refurbished office buildings, hospitals and schools, mainly in the Nordic countries, the EU, and climate zones with significant needs for energy efficient cooling as Dubai.

Summary (dansk):

Projektet har udviklet ”iCeiling”: Et ventilationsloft med trækfri køling og opvarmning leveret af en decentral varmepumpe. Desuden indeholder systemet termisk energilagring og intelligent styring, der sikrer et godt energieffektivt indeklima og en energifleksibilitet, der øger udnyttelsen af fluktuerende vedvarende energi. iCeiling indeholder dataopsamling til driftsovervågning og diagnosticering af driftsfejl. Hovedaktiviteterne har omfattet teknologiudvikling, systemoptimering og demonstration, der har resulteret i en veldokumenterede løsning, dimensioneringsværktøj og projekteringsvejledning. Loftet er et konkurrencedygtigt fleksibelt alternativ til traditionelle centrale HVAC-løsninger. Markedet er kontorbyggerier, hospitaler, skoler og institutioner primært i de nordiske lande og EU. Hertil klimazoner med særligt kølebehov og markant større installationsmæssige udfordringer som f.eks. Dubai.

3. Project objectives

The objective was to develop an intelligent, controlled cooling and heating ceiling with heat pump and energy storage. iCeiling can replace traditional ventilation, cooling and heating systems, optimise indoor climate, and meet requirements for energy efficiency and energy flexibility. iCeiling is suitable for new and existing buildings, including office buildings, hospitals and schools. The solution is targeting the Nordic market, the German market and markets with significant needs for energy efficient cooling.

In order to ensure competitiveness compared to traditional installations, two targets were set up:

1. Construction costs should be 10-20% lower than alternatives providing the same indoor climate
2. Operating costs should be at least 20% lower than alternatives providing the same indoor climate

Furthermore, focus has been on production costs, effective operation, performance and reliability.

The ceiling delivers cooling, heating and ventilation and can therefore replace the traditional installations for HVAC. The ceiling is duct-free and therefore simple to install. In the installation process conflicts with other installations are reduced which gives reduced work processes. This gives a total reduced workload on the installation side and the ceiling is therefore very competitive to traditional HVAC products.

The technology is expected to be competitive from year 1 after project completion.

4. Project implementation

During the project we have had to overcome several challenges:

- Testing of the prototypes turned out to take a lot longer than anticipated. The first prototype turned out to have several limitations. After optimizing the control of the prototype to comply with the set comfort requirements and overcoming the limitations, the way it was necessary to operate the heat pump in a way that gave rise to concern about the service life, the manufacturer shares this concern. This eventually resulted in postponing the project deadline by almost half a year.
- The final prototype was scheduled to be installed and tested in a school. Unfortunately, the ongoing pandemic resulted in closed schools. The uncertainty regarding when and whether they would open again resulted in the decision to discard the school demonstration. Instead, the system was tested in DTI's Energy Flex Office with volunteers stationed in the office to evaluate the indoor environment.
- The price of the PCM elements is still a great risk determining whether a PCM storage is viable. The key to unlock its full potential is reliant on flexible energy usage. PCM could enable flexible energy usage, however the current energy market price structure does not promote the flexibility.

5. Project results

5.1 Concept development

The developed solution can cover a range of different applications. Below the table shows some of the basic requirements for different applications. In the case of hospitals, operation rooms and bed wards should be differentiated, the first being covered in the table below while the latter having much reduced requirements.

	Schools		Hospitals		Offices	
Requirements						
Indoor environment						
CO2	Acc. to BR18.	< 1000 ppm			Acc. to BR18.	< 1000 ppm
Room airtightness						
Draught						
Ventilation						
Energy consumption	SEL	< 2100 J/m3			SEL	< 2100 J/m3
Heat recovery	Acc. to BR18 and EU1253/2014.	73%	Acc. to BR18 and EU1253/2014. For run-around coils, otherwise 73%.	68%	Acc. to BR18 and EU1253/2014.	73%
Volume flow	731 m3/h based on an occupancy of 29 and a ventilation rate adequate of indoor environment class B acc. EN1752	1300 m3/h	Continuous flow. >1200 m3/h fresh air.	3000 m^3/h		
Filter		F7		H13		
Heat pump						
COP	Acc. To BR18 when used for heating in conjunction with heat recovery.	>3,6			Acc. To BR18 when used for heating in conjunction with heat recovery.	>3,6
Heating capacity		1,0 kW		0,5 kW		
Cooling capacity		5,4 kW		5,0 kW		
Downtime	None				None	
Sensors	RH, temperature (and CO2).				RH, temperature (and CO2).	
Noise	Acc. to BR18. 40-45 dB above the ceiling.	< 30 dB	Acc. to BR18. 40-45 dB above the ceiling. Perhaps operation rooms have different requirements.	< 30 dB	Acc. to BR18. 40-45 dB above the ceiling.	< 35 dB
BMS						
Communication						
Interface						

5.1.1 Acoustics and noise considerations

A good indoor climate has a huge influence on persons efficiency and work quality. The indoor climate is influenced by a complex mixture of physical, psychological and social factors. The implementation of a ventilation system may add beneficial as well as the opposite to the indoor climate.

While ventilation will improve the air quality and thermal environment, it often has a negative impact on the acoustical environment.

The noise from the system should be at a sufficiently low level, without any hissing, low frequency rumble and other detectable noises. If the noises disturb and introduce a stressful environment there is a risk of manual intervention like shutting off, reducing speed, blocking air-valves etc. which may be a crucial factor for the success of the ventilation. All components in the system should be chosen and implemented with minimal noise.

To be able to work with undisturbed concentrated, sound levels as low as 30-35 dB(A) is required, and for some persons even lower. For working in groups with aural exchange of knowledge and immediate information levels up to 45-50 dB(A) may be acceptable.

The acoustics in the room will influence the sound level caused by the ventilation installation, as well as the sounds from human activities. Here the sound absorption of surfaces like walls, ceiling, floor and furniture determine the level as well as the sound distribution, together with possible acoustic room resonances and ‘flutter echoes’ disturbing the speech intelligibility etc.

The iCeiling solution uses a perforated ceiling system that can help dampening noise and improve the rooms acoustical properties of the room.

Remarks for choosing and implementing air ventilation components

Ventilation unit:

It may be placed either outside the ventilated room or ‘above the ceiling:

Placed in separate room the vibrations to supports and ducts, and the sound emitted from the surfaces of the unit may be no problem in the ventilated room. The technique room or vertical shaft should be air-tight and with heavy/stiff supporting walls etc. Also, the inner surfaces should be covered with sound absorption or the free space could have some ‘sound absorbing mats (baffles) for reducing the air borne sound.

Mounted above the ceiling e.g., the cavity between ceiling and the deck, the unit should only be elastically mounted up to the floor above. No connections to the relatively light and low damped metal plates and support rails. If possible close to a wall for the most massive (heavy and stiff) support to the vibration isolators. Also, the emission from the outer surfaces of the unit should be as low as possible either by choosing a low noise cabinet version or / and mounting a surrounding and low-leak box around it. This may inherit easy and periodic exchange of air-filters.

Ducts will transmit the airborne noise and also structure borne vibrations from the ventilation unit fans as well as noise from the airflow in the duct and the air valves in it. Also, it may transmit airborne noise from one room to another if the same unit is supplying more than one room. Always use mufflers to prevent this.

The airborne noise transmission must be reduced by absorption sound attenuators places as close to the sound source as possible. It may be above the ceiling, but then directly at the openings in the walls for eliminating possible ‘short cuts’ from the noisy side of the attenuator to the space above the ceiling. Remember to mount attenuators on the inlet openings supplying the air to the open space above the ceiling, and not only on the suction ducts.

The structure-borne noise (vibrations) from unit to duct must be eliminated by elastic short flexible duct connectors, which sometimes also must be covered by some acoustic damping material or the inside airborne noise will transmit out of the duct.

As for **all ductwork** it is important to ensure enough space to the ducts for large dimensions (low air speed and low pressure loss, soft bends for low turbulence and thus less low frequency noise, and graduate changes of dimensions when splitting up in several ducts. Also, the use of two valves instead of just one valve for the whole range of air flow needs may reduce the total noise because dividing the needed pressure loss reduces the total sound generation.

The finish of the ductwork is important: ensure that no leaks are present, that no holes for ‘flow/pressure testing’ are left without a plug afterward, ensure that screws and sharp edges/ slits are not present in the air flow. This may eliminate hissing, tonal noises and unsteady flow, which can be difficult to find and repair at a later stage.

The **compressor in the heat pump** may give special problems, due to the typical low frequent tonal noise and vibrations. If this is installer in the ceiling cavity it is important to use sufficient vibration isolation and sound absorbing/enclosing measures.

The Heat Storage unit (**PCM)** should not add noise to the duct noise, but if the ductwork to and from this unit is restricting airflow due to sharp bending, abrupt changes of dimensions etc. this may be a problem.

5.2 Development of the unit

Ventilation systems with integrated reversible heat pump in the current market is challenged by the fact that during the winter periods, icing may occur in the unit. To remedy this problem, the control in the ventilation unit starts a regeneration process. However, while the regeneration process is ongoing, the ventilation unit cannot provide the desired inlet temperature. As a result, the room temperature in the ventilated rooms changes and the indoor environment cannot be maintained.

A solution with a ventilation unit combined with a reversible heat pump is often discarded if the conditions for the indoor climate cannot be met. With the iCeiling project, the purpose was to develop a ventilation unit with integrated reversible heat pump, which with the right design, system structure and control can maintain the indoor environment conditions required in a given building.

In addition, it will be explored whether it is possible to build up an energy storage, using the passive storage by PCM material to collect heating capacity, which can be released when needed.

The iCeiling project also examines whether it is possible to control the release of the stored heating power while the ventilation system is in the regeneration process in order for the indoor environment to be maintained continuously.

5.2.1 System structure

The ventilation unit that has been built for the project, is a traditional ventilation unit with built-in reversable heat pump. On traditional heat pump systems, a compressor is built in, which is controlled by on/off or by step control. In the project there is a compressor with built in frequency control, which allows a stepless regulation and thus a more precise regulation.

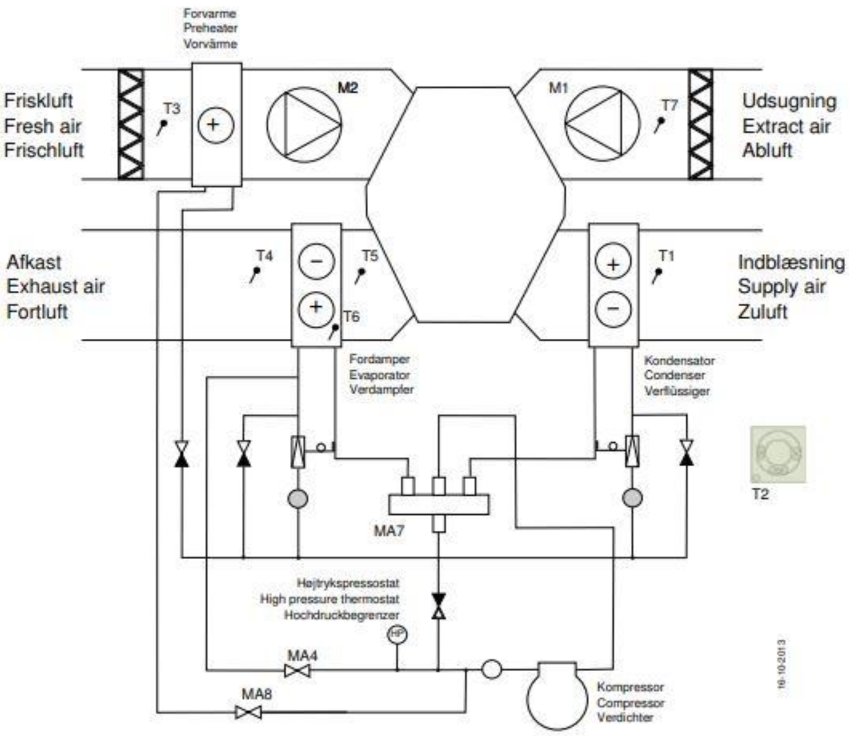


Figure 1: Picture of ventilation unit structure

PCM elements are used to store heating capacity. The size and quantity used in the system structure was determined by trials and analyses. The PCM elements was built into a device that allowed to adjust the number of PCM elements during the different tests of the system.

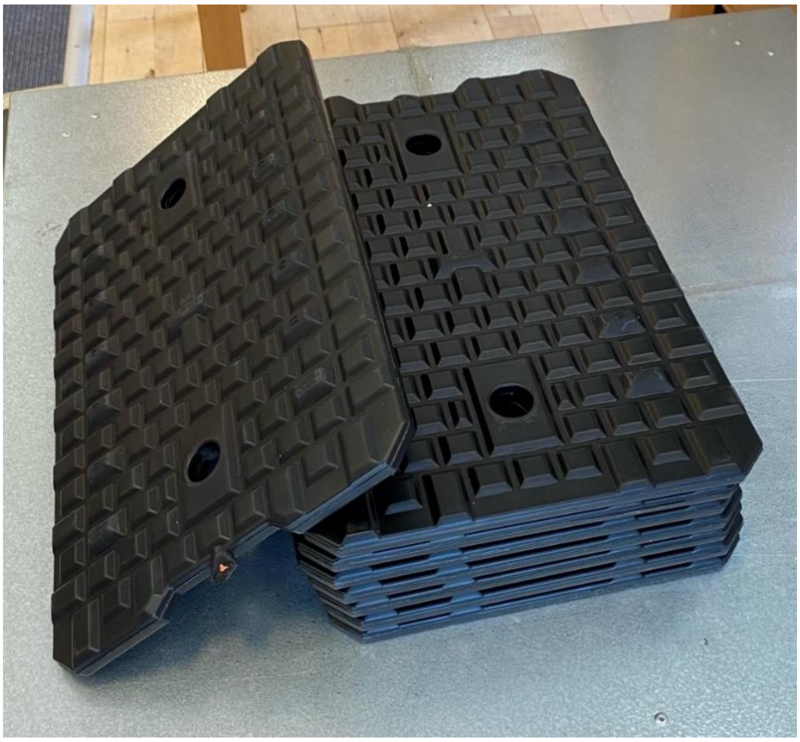


Figure 2: Picture of PCM elements

The ductwork was constructed in such a way that there was full control over the air flows. It is possible to control how much air is passed through the PCM storage when either charging or discharging, bypass the PCM storage or heat pump completely.

In order to regulate the air volumes in the inlet and exhaust ducts, ultralink control dampers are built in. The control damper technology is based on ultrasound and measures accurate air volume and temperature in ventilation systems.

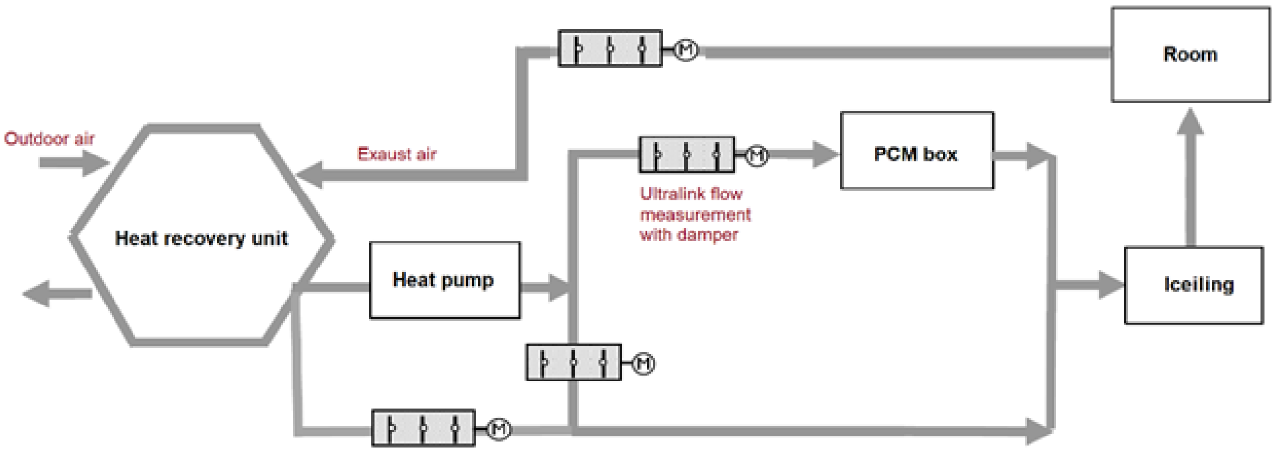


Figure 3: System structure

The system is designed to be an integrated part of the Cool Ceiling family. The ceiling is a suspended ceiling system consisting of steel cassettes 625 x 625 mm with built-in inlet and exhaust air diffusers. The cavity above the suspended ceiling functions as a large pressure chamber that leads the inlet air to the inlet diffusers. There are no inlet ducts above the suspended ceiling. The Cool Ceiling climate ceiling is suitable for both heating and cooling, with great effect without providing drafts in the room.

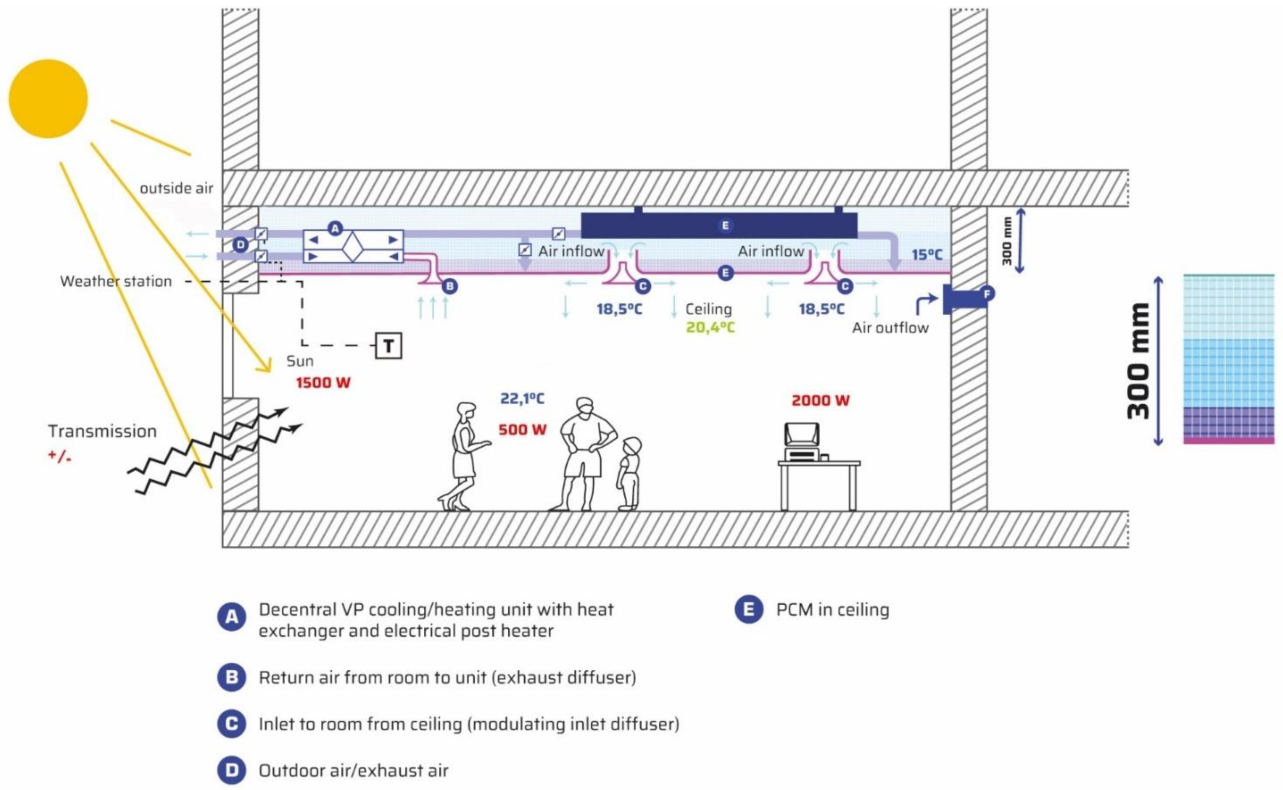


Figure 4: Principle building of the test room

The room was set up as an office where people in the room participated as test subjects.

5.3 Development of PCM storage integrated with heat pump system

The implementing of the PCM storage to the heat pump system was tested by both experiment and numerical studies. The experiments were done in the Energy Flex Office (EFO) at DTI. A pre-test was done for the room, including a blower door test. The results of the pre-test were used to build and test the EnergyPlus model. In the experimental study the PCM storage was built and tested. The EnergyPlus model with PCM storage was verified by the experimental data. It was used to develop the energy flexibility control of the heat pump system for the electricity peak hour shifting.

5.3.1 The pre-test of the energy flexibility office

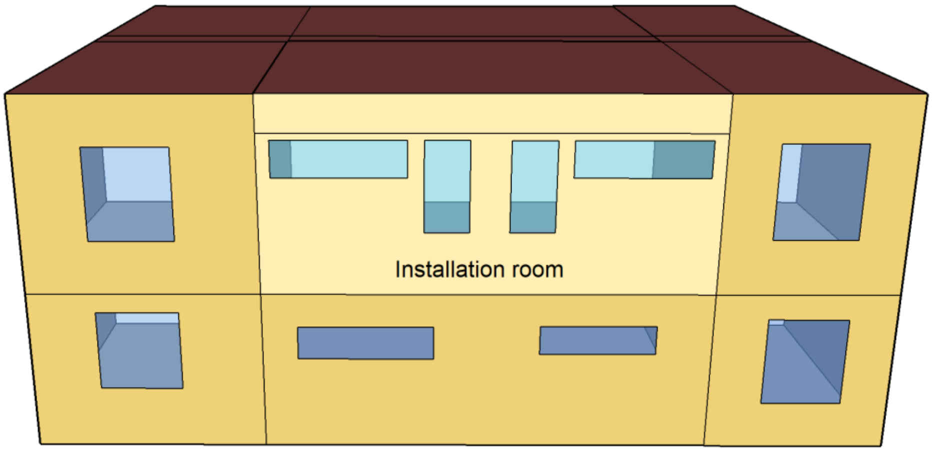


Figure 5: The test room for installations.

A 1:1 scaled EnergyPlus model was built for the installation room in EFO lab at DTI. The constructions of the room and ceiling are the same as the EFO facility.

The heat load experiment was done in 14.11.2019. The experimental results are used to compare with the modeling results. The measured outdoor air temperature and solar radiation rate are set as input in the model, which are shown in Figure 6 and Figure 7 respectively.

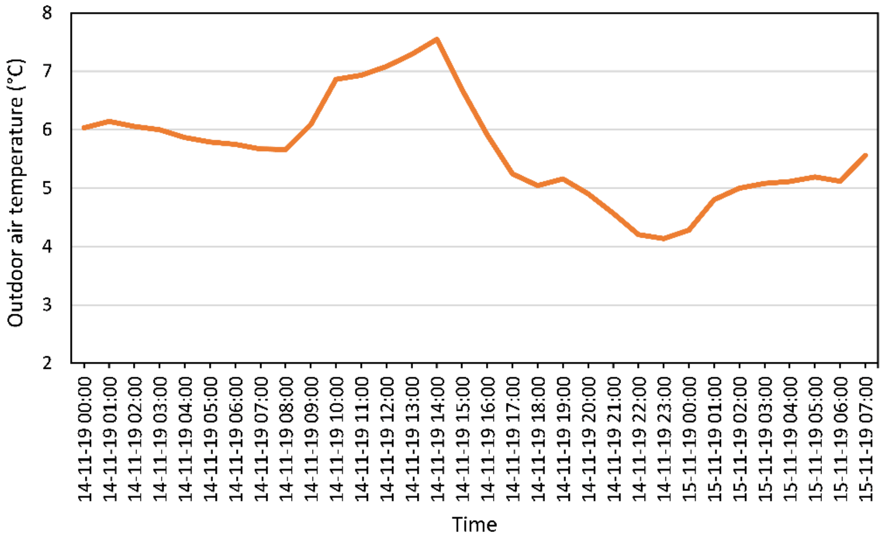


Figure 6: The measured outdoor air dry-bulb temperature.

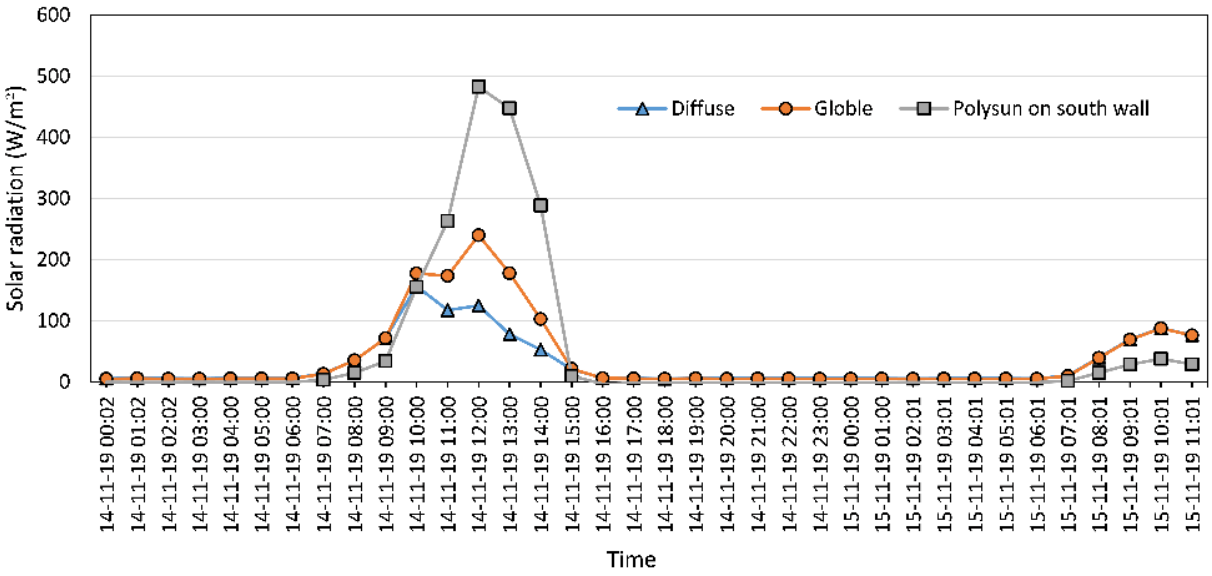


Figure 7: The measured outdoor solar radiation, including the diffuse solar radiation, global solar radiation and south wall received solar radiation.

During the experiment, a heater was located in the center of the room. It decreases gradually after turning the heater off, and is assumed to reach 0 W at 21:00. Figure 8 compares the room indoor air temperature of the simulation results to the heat load testing experiment.

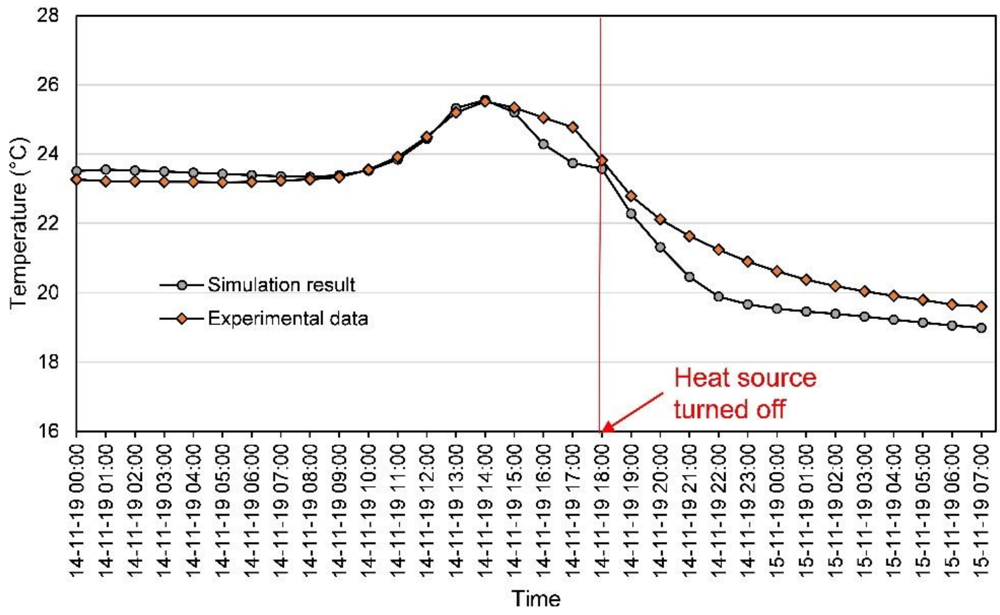


Figure 8: The indoor air temperature from both simulation and experiment.

5.3.2 The development of the PCM storage

The PCM chosen for heat storage is ATS 30 from AXIOTHERM®. It has a melting range of 28-33°C, and a freezing range of 29-32 °C. The latent heat capacity of the PCM is 220 kJ/kg. The thermal properties of the PCM are listed in Table 1.

Table 1: The PCM properties [1].

	Unit	Value
Melting range	°C	28-33
Freezing range	°C	29-32
Latent heat (23 – 38°C)	kJ/kg	220
Specific heat	kJ/kg·K	2
Density (liquid)	kg/L	1,3
Thermal conductivity	W/(m·K)	0,6
Volume expansion	%	<6
Flashpoint	°C	Non-flammable

The heat capacity of the PCM is shown in **Error! Reference source not found.**10, including the heat capacity of the PCM in melting process and freezing process. The melting point of the PCM is 32°C and the freezing point is 29°C. The data is from [1].

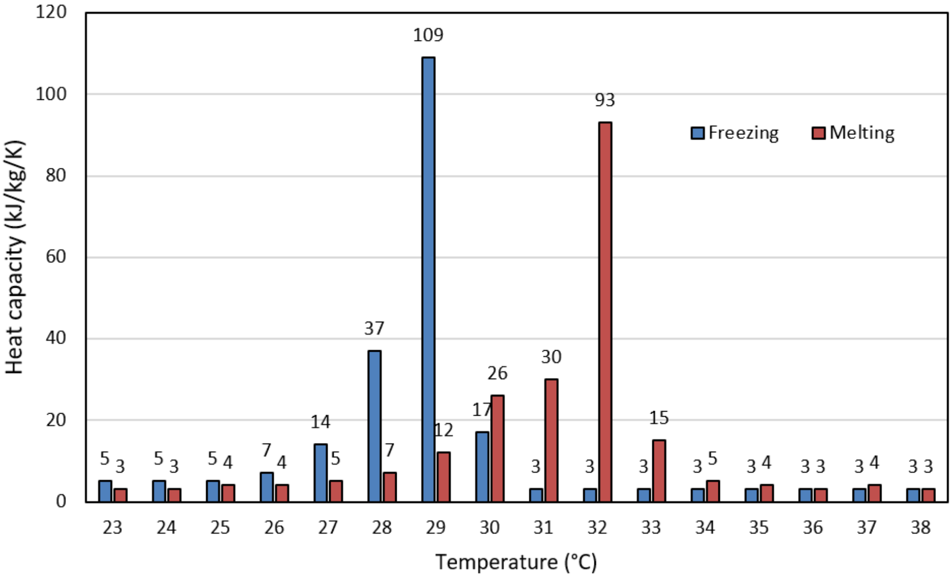


Figure 9: The heat capacity of the chosen PCM.

The PCM is encapsulated in plastic plates with 10 mm thickness. The size and volume of the PCM plates are shown in Table 2. The heat transfer surface of each PCM plate is 0.185 m^2. The PCM plates are stacked together in an isolated box, which is shown in Figure 10.

Table 2: The properties of the PCM encapsulated in plastic plates.

	Value
Size	340 mm×220 mm×10 mm
Heat transfer surface	0.185 m^2
Volume	500 ml
Weight	660g
Heat transfer surface / kWh	4.8 m^2
Volume flow / kWh	30-60 m^3/h

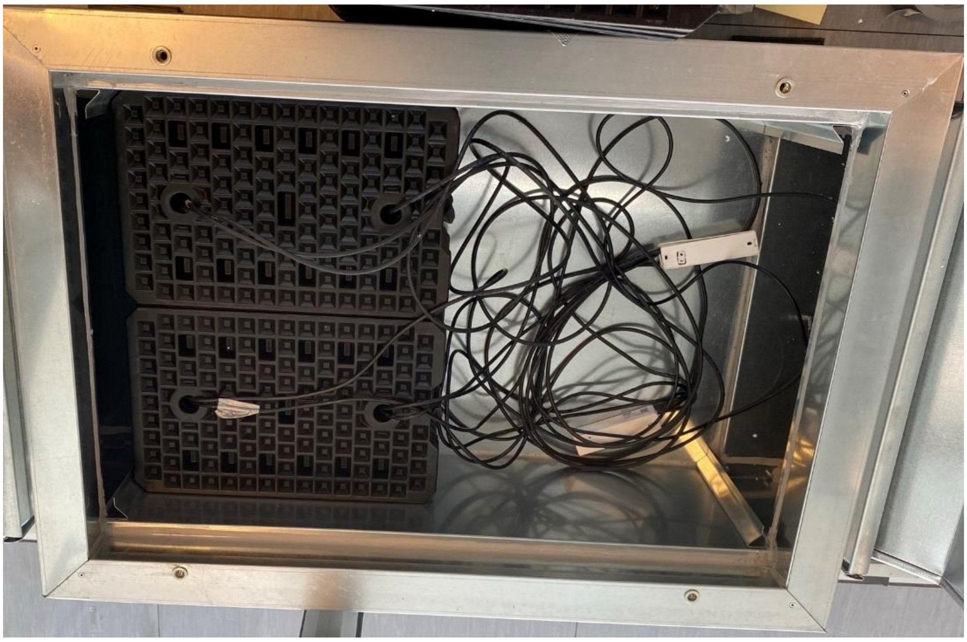
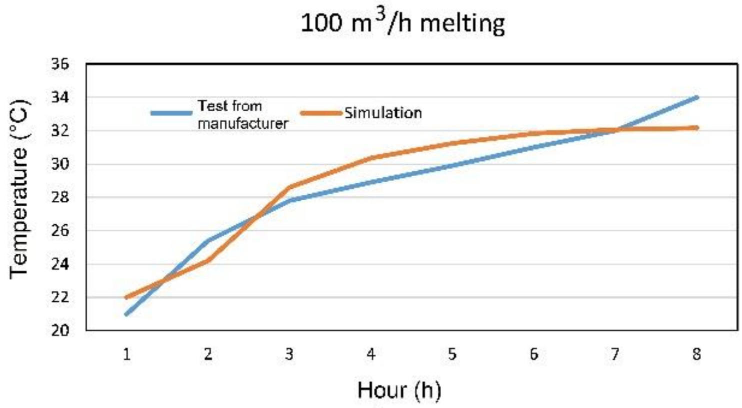


Figure 10: The design of PCM storage and added temperature sensors.

The heat store/release processes of the PCM are compared between the model results and the test data provided by the manufacturer in https://www.axiotherm.de/en/produkte/heatstaxx%C2%AE-air/ for both melting processes (Figure 11) and freezing processes (Figure 12) with different flow rates. The test is done with 52 pieces of PCM plates. The model results show good coincidence to the test data.



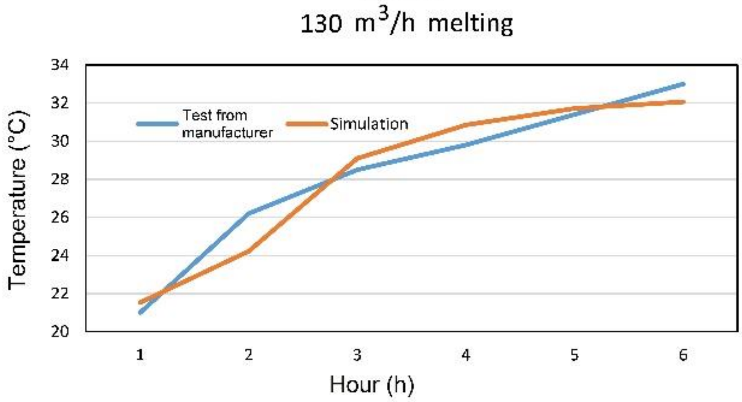


Figure 11: Comparison of the model results and data from manufacture: the outlet air temperature in melting processes.

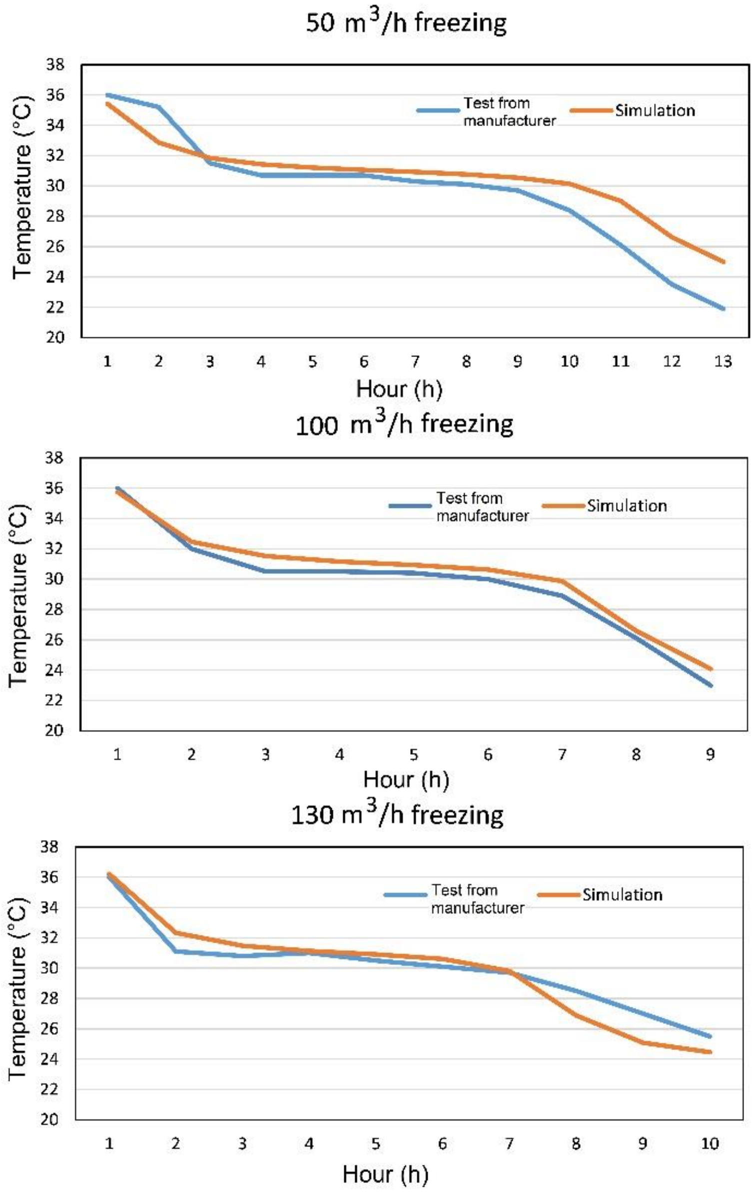


Figure 12: Comparison of the model results and data from manufacture: the outlet air temperature in freezing processes.

5.3.3 The experimental study of the PCM for energy storage and supply air temperature control

The PCM box is built in the heat pump system for energy storage and supply air temperature control. The experiment is set up in EFO at DTI. The system setup is shown in Figure 13 and Figure 3. The PCM box is an insulated box with stacked PCM plates, as shown in **Error! Reference source not found.**. The experiment tests 3 different PCM amounts: 52 pieces of PCM plates, 36 pieces of PCM plates and 20 pieces of PCM plates.

Figure 13: The setup of PCM integrated heat pump system in energy flexibility lab [2].

The temperature sensors used to measure the temperature in the PC box and other system nodes are temperature external AMR-Wireless M-BUS with a resolution of 0.05°C. Figure 14 shows the temperature sensor locations in the PCM box. The sensors labeled with 1, 2, 3 are placed between the layer 3 and 4 of the PCM plates.

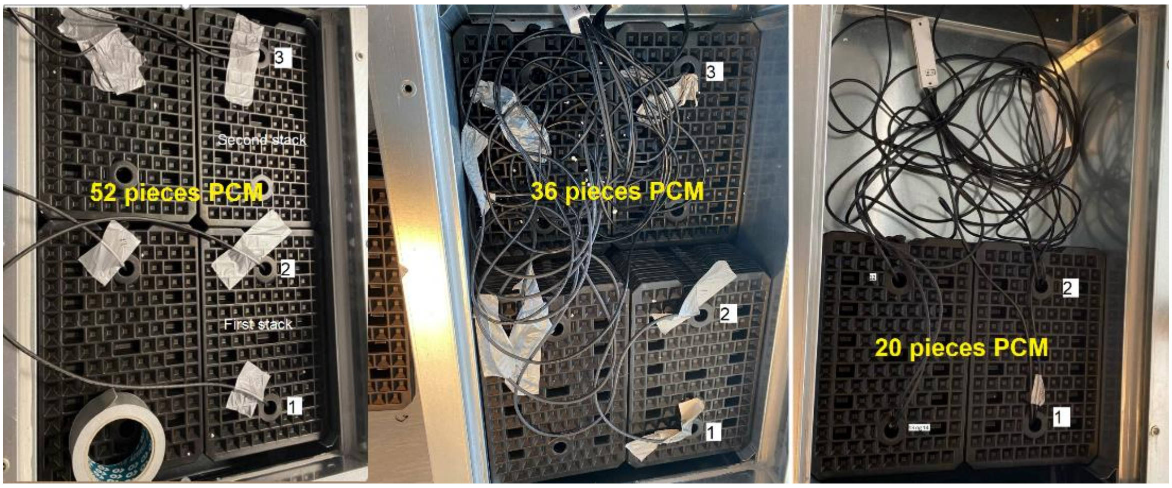


Figure 14: The temperature sensor locations in the PCM storage.

The challenge of experimental testing of the PCM storage is that it is complicated and time consuming. The basic test of the heat transfer mechanisms in the PCM storage is doable in the lab. However, the system control of the heat pump system with PCM storage is hard to realize with current setup, because the control of the ventilation air flow rate in the system nodes need to have more dedicated control than Ultralink, preferably with separate fan installations in the system nodes instead of one exhaust fan for the whole room.

One possible solution to continue this work is testing the system control of the heat pump integrated with PCM storge in the building simulation software EnergyPlus. EnergyPlus is a well-developed building energy simulation software developed by U.S. Department of Energy's (DOE) Building Technologies Office (BTO). It is long been used by engineers, architects and researchers to simulate the building energy performance and indoor thermal comfort of different building systems and applications.

5.3.4 The numerical study of PCM storage integrates with heat pump system for grid peak hours shifting

Based on the experimental study, the PCM box with 36 pieces of PCM plates has a fast response time to be charged and discharged, and the outlet air temperature is high in a quite long period in the discharge process. Thus, the medium sized PCM box is chosen for grid peak hour shifting. The idea of using the PCM storage for peak hour shifting is that the PCM stores the energy when the electricity price is low and releases the energy to the heating system when the electricity price is low. The electricity price in Denmark in the year of 2019 is shown in Figure 15. The medium price limit is the 2nd quartile of the last two weeks' electricity price. The hourly electricity price is considered to be high if it is higher than the medium price limit; and low if it is lower than the medium price limit.

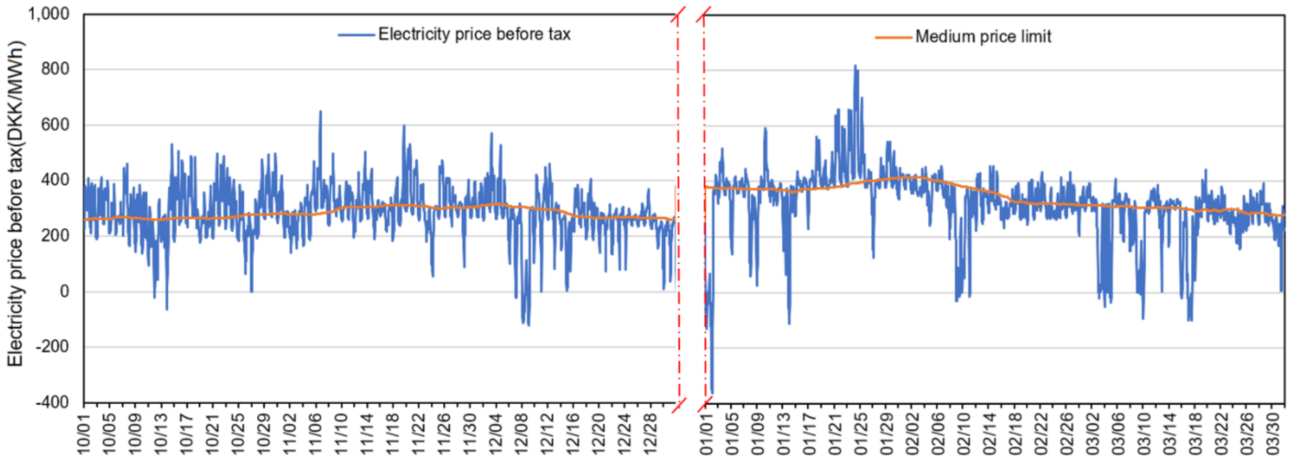
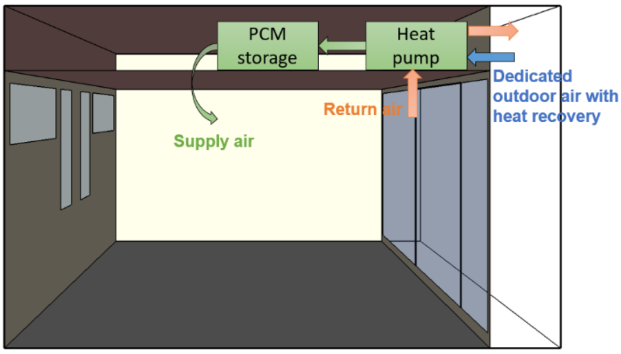
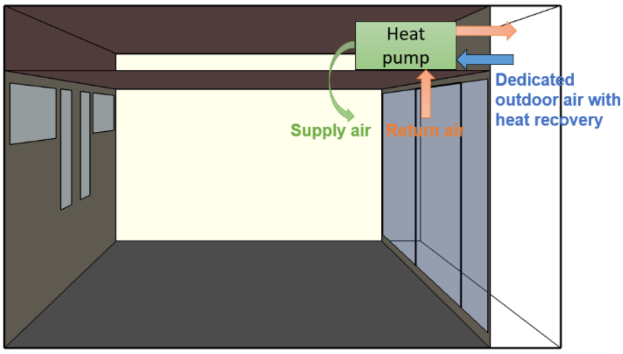


Figure 15: The electricity price (SPOT) before tax in 2019 Denmark [2].

A numerical model of PCM integrated heat pump system is built in EnergyPlus. The system configuration is shown in Figure 16(a). When the electricity price is lower than the middle price limit, the heat pump provides hot air to the PCM storage through the hotbox, which is a virtual zone simulate the ventilation ducts. Meanwhile the PCM is charged with heat. When the electricity price is higher than the middle price limit, the heat pump is shut off, and the PCM provide heat to the ventilation. The heat pump provides auxiliary air to the room if the room thermal comfort cannot be guaranteed by the PCM. As a reference, the heat pump without PCM storage is simulated, as seen in Figure 16(b). In this case, the room heating setpoint is 22°C if the electricity price is high; and 24°C if the electricity price is low.



a. Heat pump integrate with PCM storage.



b. Reference case: heat pump without PCM storage.

Figure 16: a.The PCM integrate with heat pump system for electricity price control compares to b. The heat pump system without PCM for electricity price control.

1. Axiotherm PCM - products | Axiotherm GmbH - Innovative thermal storage systems Available online: https://www.axiotherm.de/en/produkte/axiotherm-pcm/ (accessed on May 20, 2021).

2. Hu, Y.; Heiselberg, P.K.; Drivsholm, C.; Vogler-Finck, P.J.C.; Kronby, K. Experimental and numerical study of PCM storage integrated with HVAC system for energy flexibility. *Renew. Energy*. (submitted)[i]

5.4 Development of the controller

In this project, the intelligent controller has different dimensions:

1- Online communication and data collection between the iCeiling system and the cloud
2- Predictive control of the system, where 2 use-cases were considered in the project:
    a. Stable supply temperature and flow, despite heat-pump regeneration, using the PCM storage
    b. Flexible energy usage, responding to dynamic price signals
3- Dynamic balancing of supply and exhaust fans

This section presents the learnings from the control development phase, while the results in the demonstration are presented later in the document.

5.4.1 Online data collection and control from system to cloud

The backbone of the controller consists in a 2-way communication between the equipment on site (heat-pump, dampers and IoT indoor climate sensors) and a cloud-based intelligent controller. At the same time, the cloud controller gets access to data from weather forecasts as well as upcoming day-ahead electricity prices.

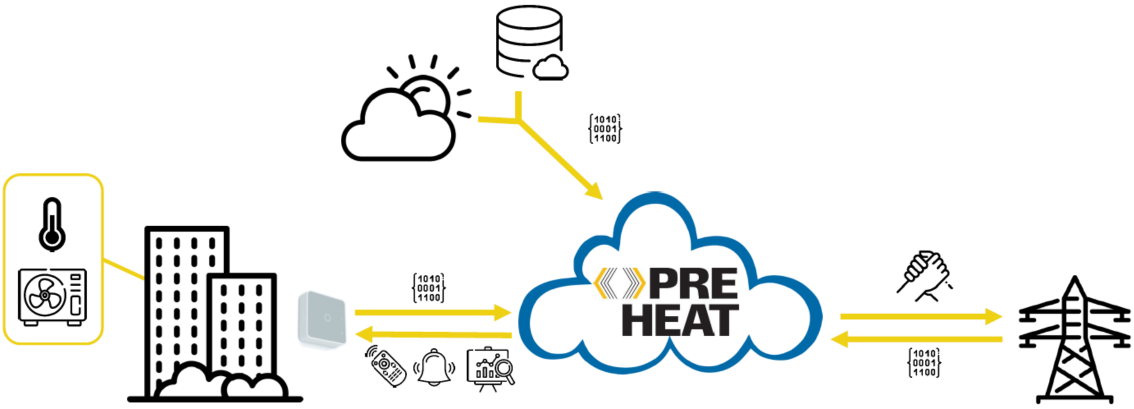


Figure 17: Concept drawing of Neogrid's cloud-based control and 2-way communication integrating weather service, third party and energy system data with local building sensor data.

Locally in the building, the gateway communicates with the heat-pumps and dampers using the Modbus protocol on RS485 and receives data from the IoT indoor-climate sensors over wireless Mbus. With the dampers and the heat-pump/AHU, the data flow is a 2-way one: measurements are collected by the gateway and new setpoints are written to the systems where relevant.

Then the gateway communicates with the cloud over an encrypted MQTT channel. Once in the cloud, the data is stored and processed in the context of extra data such as weather data to allow dynamic modelling, and prices to allow optimization.

5.4.2 Dynamic control of the ventilation

5.4.2.1 Dynamical model identification

Dynamical state space linear models were identified on the data, based upon a so-called grey-box representation of the dynamics of the ventilation system and the room's thermal conditions. The room's thermal dynamics were modelled with a RC-network with a single state (for the indoor temperature) and direct coupling to the neighbouring rooms and ambient (both with a single thermal resistance) and a simple solar gain description. The heat-pump and heat recovery dynamics were described using simple first order approximations of their behaviour. Parameters were fitted using standard optimisation methods and the CasADi[1] framework for Python.

Dynamical model identification has been a comparatively simple process, given the detail of the data available. In particular, the high resolution of the data (5 minutes or lower), fast dynamics of the ventilation system and availability of flow measurements (from the Lindab Ultralink dampers) facilitated the identification of its dynamics. The room's thermal dynamics were less straightforward to identify, although the wide dynamics of the indoor temperature and reduced noise (as the room was unoccupied most of the time) made it easier than what would actually happen in an occupied building.

However, the differences between system dynamics in heating and cooling mode has been a challenge when reaching the demonstration stage which started towards the end of the heating season and finished well into the cooling season.

[1] www.casadi.org

5.4.2.2 Securing a stable supply temperature

A first use-case for the solution aimed at providing a stable supply temperature despite regeneration in the heat-pump. In order to achieve this, the regeneration must be predicted in advance and the air channelled through the PCM when the event occurs.

The project has been challenged by the difficulty of predicting the regeneration of the heat-pump in both heating and cooling situations, as well as the internal logic of the heat-pump that automatically reduced the air flow at regeneration. Solving these challenges has not been possible in time to be able to provide a full demonstration before the end of the heating season. However, the regeneration has been simulated by switching off the heat-pump in an equivalent period and observing the dynamic of the supply temperature.

5.4.2.3 Reacting to dynamic price signals (simple flow optimisation)

Initially, a simplified formulation of the control problem was investigated, where optimisation was solely carried out on the flow (while temperature regulation was left to extract regulation to the desired room temperature).

The optimisation was formulated as a constrained optimisation problem where air flow is adjusted between a lower value (V_min) and a higher value (V_max), while keeping an average value (V_avg) over a given time window (of length N).

The problem is formulated as an optimal control problem of the air flow (V) given a price (p).

$$\min \sum_{k=0}^{k=N} p[k] \times V[k]^3$$

Under constraints:

$$\frac{1}{2N+1} \sum_{k=-N}^{k=N} V[k] = V_{avg}$$

$$V_{min} \leq V[k] \leq V_{max}, \forall k \in [0 - N]$$

5.4.2.4 Complex model predictive controller

Based upon the learnings of the simple optimised controller and the dynamical models identified on the data, a more advanced predictive controller was developed. This time, both the air flow and the supply temperature were controlled, providing significantly higher potential for energy flexibility and indoor climate regulation.

The optimisation was again implemented in Python using the CasADi framework, which is able to handle non-linear dynamics and optimisation. A major challenge with respect to this advanced predictive controller has in fact been the non-linearity of the optimisation problem and the state dynamics (due to the airflow and temperature optimization, together with the bypass). Overcoming it has required significant effort and a number of adjustments on the optimisation formulation (including a break-down in a sub-optimal 2-step optimization) to get adequate convergence with the solvers used. However, the control achieved on this level in cooling conditions was only able to minimise energy demand, and further work would be required to adequately solve the full price optimisation. As a further consequence of this, it has not been possible to explicitly integrate the PCM box in the optimisation, due to a further significant complexity introduced by a non-linear behaviour of this PCM), so that further work is also required on this level.

5.4.3 Balancing of the supply and exhaust ventilation flows

A dynamic compensation of the extract flow with respect to the supply flow was implemented in order to ensure balancing of the ventilation system.

This balancing was based upon a model of the flow characteristic of the supply and exhaust fan, which was fitted on the data from the Ultralink dampers on the supply and extract channels. Given a fan speed on the supply side, the corresponding air flow was computed and then converted back in an exhaust fan speed using these characteristics.

Another possibility would have been to use the Ultralink damper on the extract for dynamic adjustment. However, this is not an energy efficient approach compared to direct control of the extract fan, which is why it was not investigated in more details in the demonstration phase.

5.4.4 Challenges encountered in the control design

As often in the implementation of a higher-level control layer, the in-built regulation logic of the installation has been challenging. In particular, the automatic regeneration of the heat-pump and coupling to the supply fan speed, as well as the software limitations to supply temperature setpoints (to 30°C in heating mode, when 35°C was expected due to building standards) have been major bottlenecks.

Interacting with the heat-pump has been a point of complexity too. Originally, the documentation of the Modbus registers of the system was available and deemed sufficient, but the implementation of higher-level control highlighted that use-cases for the control signals and parameters were often unclear and communication with the manufacturer was required (both Nilan and Genvex provided the partners with great support when needed). Here, a lesson for future projects would be to involve the manufacturer of the critical equipment in the consortium, as the support-related load for them can be quite extensive and make it hard for them to provide input and operate adjustments on the system, despite their willingness to engage with their users and support them in using their technology.

Another major challenge in the control design development was the strong difference between the operating conditions in heating and cooling mode, which has meant that the logic developed and demonstrated based upon the learnings of the heating season would no longer apply in the late phase of the demonstration which was already in the cooling season.

Lastly, the non-linear optimisation problem structure and numerical solving of it has proved significantly more tedious than expected, resulting in further work required in order to achieve the initial vision.

5.5 Dimensioning tool

In the project there have been developed a dimensioning tool for the PCM storage. The PCM module has two important features in relation to the iCeiling EUDP project:

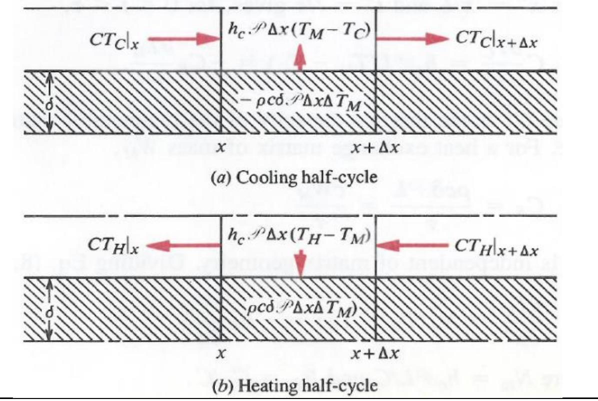
- When the heat pump in the ventilation system stops to defrost the evaporator, the supply air temperature must be able to be maintained for a short time within certain specified tolerances. In this case, the specific heat capacity of the PCM module is primarily utilized by small change in material temperature.
- When utilizing electrical flexibility, the supply air temperature must be able to be maintained for a longer period within certain stated tolerances. In this case, the phase change energy of the PCM module is primarily utilized at a selected melting temperature of about 31°C.

The calculation tool will primarily use the following input from the user:

- Maximum air flow through PCM module expressed in m^3/s
- Length of defrost period expressed in seconds
- Length of period when utilizing electrical flexibility expressed in hours

The physics can be characterized as dynamic, which involves setting up a basis corresponding to regenerative heat exchange as opposed to the stationary recuperative heat exchange. The temperature in the PCM module is a function of location and time. The controlling equations are therefore partial differential equations, which can usually only be solved numerically.

Anthony F Mills has in the book "Heat Transfer" laid out a numerical basis, which is shown in the following:



$$C\frac{\partial T_C}{\partial x^*} = h_c\mathscr{P}L(T_M - T_C) = -C_R\frac{\partial T_M}{\partial t^*}$$

$$\frac{\partial T_C}{\partial x^*} = N_{tu}(T_M - T_C) = -R_R\frac{\partial T_M}{\partial t^*}$$

Figure 18: Numerical basis

$X^* = x/L$, $t^* = t/\tau$ and $0 < t < \tau$

$C = q_v \cdot \rho_{air} \cdot c_{p\_air}$ {air}

$C_R = c_p \cdot m/\tau$ {PCM}

$R_R = C_R/C$

$N_{tu} = (U \cdot A)/C$

Temperature variations in the PCM material itself on the shortest dimension (δ) are not taken into account, as this will make the calculation significantly more complex.

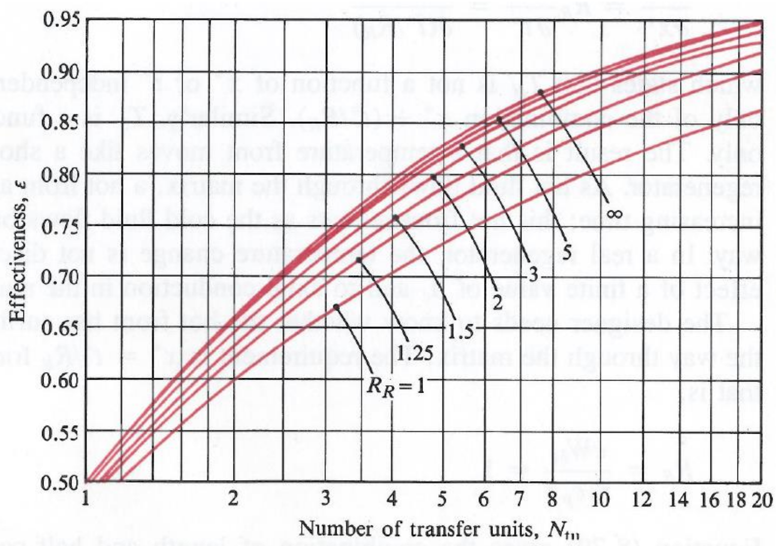


Figure 19: Result of the numerical calculations

$\varepsilon = (\langle T_{c,\,out}\rangle - T_{c,\,in})/(T_{h,\,in} - T_{c,\,in})$

Example: $R_R = 5$, $N_{tu} = 10$, $T_{c,\,in} = 25$ ˚C, $T_{h,\,in} = 35$˚C → $\langle T_{c,\,out} \rangle \approx 34$ ˚C (Average temperature in the period).

PCM elements from the German company klara energy systems have been chosen due to their great flexibility. The PCM elements are specially designed for airflow. When stacking elements, there are spaces for air passage. In addition, the data specifications are also sufficiently comprehensive for the development of calculation tools.

The program is based on a B · H · D: 3 · X · 1 matrix of elements, i.e., the height of the stack is the only optional parameter. It gives a width of 3 · 0.22 = 0.66 meters and a depth of at least 0.34 meters depending on the need for extra space for air distribution. A depth of only one element is for the sake of pressure loss. Above the iCeiling ceiling, there is plenty of space in width and in height. The selected width of 0.66 meters can be increased if necessary.

	A	B	C	D	E	F	G	H	I	J	K	L
7												
8		Luftstrøm	250	[m^3/h]	69,4	[liter/s]	0,069	[m^3/s]				
9												
10		PCM, ATS31	31	[°C]								
11		Bredde	0,66	[m]					{3 elementer i bredden}			
12		Dybde	0,34	[m]					{1 element i dybden}			
13		Højde	0,35	[m]								
14		Volumen	0,079	[m^3]	78,5	[liter]						
15		Massefylde	782	[kg/m^3]					{11,7/(0,34·0,22·0,2) = 782 }			
16		Smeltevarme	315	[kJ/liter]	14322	[kJ]	4,0	[kWh]	{ATS 31, klara energy systems, Germany}			
17		Varmekapacitet	2000	[J/(kg·K)]								
18		A_face	0,23	[m^2]								
19		V_face	0,30	[m/s]								
20		h_luftspalte	5	[mm]	0,005	[m]						
21		A_luftspalte	0,087	[m^2]					{15 elementer fylder 20 cm}			
22		V_luftspalte	0,80	[m/s]					{15 elementer vejer 11,7 kg}			
23		A_PCM	14,6	[m^2]								
24		Vægt_PCM	61,4	[kg]								
25												
26		C_luft	83,8	[W/K]								
27		c_PCM	122837	[J/K]								
28												
29		h_c	35	[W/(m^2·K)]								
30		f·Re	82	[ ]	Re	531	[ ]	f	0,15	[ ]		
31		Δp	2,0	[Pa]								
32		Ntu	6,1	[ ]								
33												
34		Afrimningstid	60	[s]								
35		C_PCM	2047,3	[W/K]								
36												
37		R_R = C_PCM/C_luft	24,4	[ ]								
38		ε_aflæsning	0,85	[ ]					{aflæsning i diagram til højre}			
39		T_luft_ind	27	[°C]								
40		T_pcm	39	[°C]								
41		<T_luft_ud>	37,2	[°C]								
42												
43		El_fleksibilitet										
44												
45		T_ind	17	[°C]								
46		Δτ	3,4	[timer]								

Figure 20

In this example, the average outlet temperature can be maintained at 37.2˚C for the selected period of 60 seconds. With a greater tolerance, the PCM module can maintain the outlet temperature for about 3.4 hours.

The calculation tool is an extension to the existing calculation tool for the cool ceiling ventilation system. Originally this tool was developed as a part of Elforsk project 348-032. A guide for the tool is located in appendix 8.4.

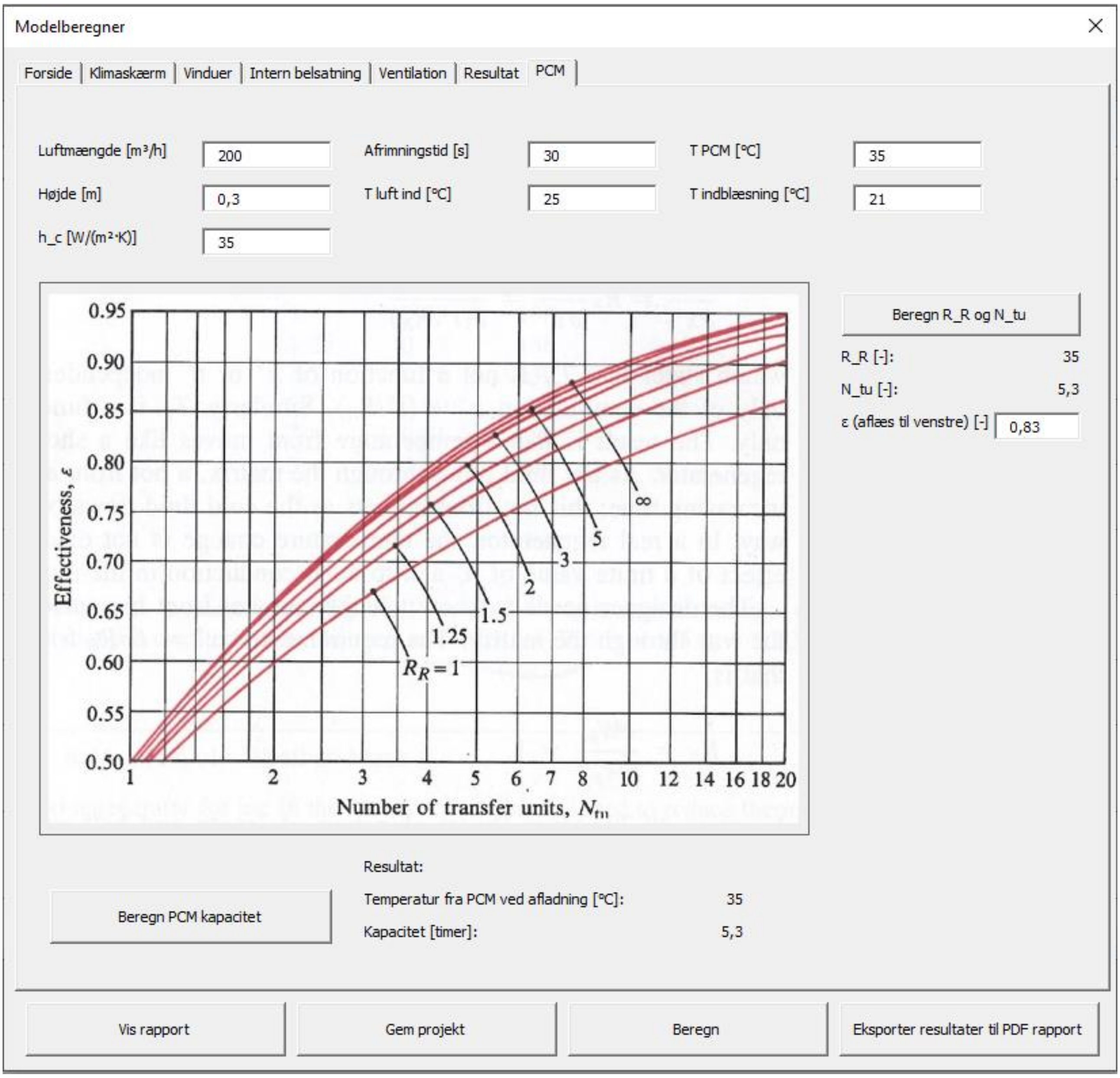


Figure 21: Implementation of the dimensioning tool in the already existing tool.

5.6 Test results

All the prototypes of developed in the project have been demonstrated at DTI's facility Energy Flex Office (EFO). As described in the implementation chapter unfortunately it was not possible to test at Damhusengens skole due to the ongoing pandemic. Therefore, all results presented in this chapter is generated in EFO.

5.6.1 PCM

5.6.1.1 The experimental results of the PCM for energy storage and supply air temperature control

Figure 22 shows the air temperature in the PCM storage with 52 pieces of PCM plates. The PCM 1, 2 and 3 corresponding to the sensor locations shown in Figure 14. The PCM is charged with around 40°C inlet air from 9:15 to 14:15, and discharged with 20°C from 14:15 to 17:15. It is seen that PCM 1 melts and freezes first, which is closer to the inlet of the PCM box. PCM 3 melts and freezes last, and its temperature is closer to the outlet air temperature. Based on the outlet air temperature, the total charge period of the PCM box with 52 pieces of PCM plates is 210 minutes, from 10:30- 14:00; the total discharge period of the PCM box is 160 minutes, from 14:40- 17:20.

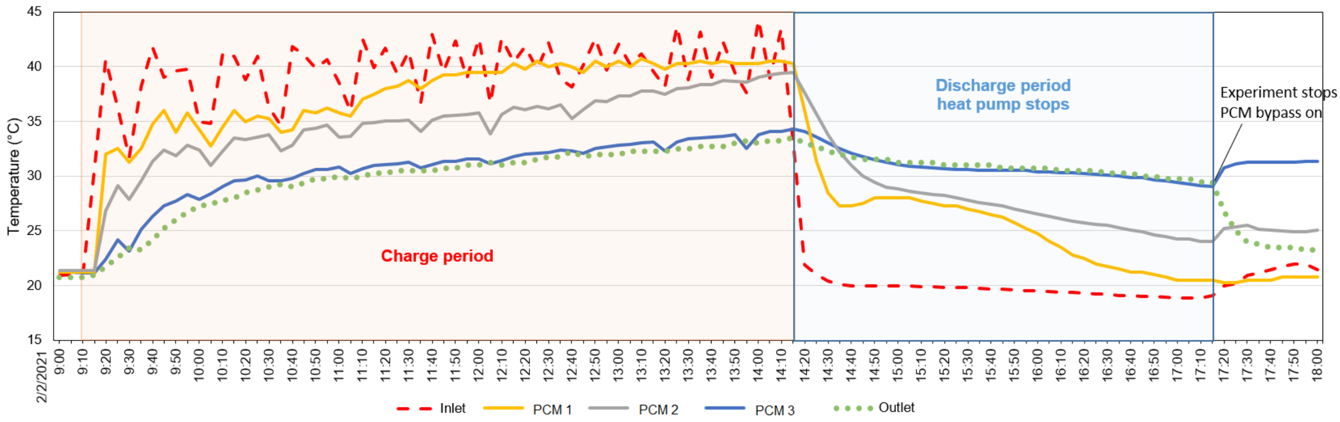


Figure 22: The air temperature in the PCM storage with 52 pieces plates [2].

Figure 23 shows the air temperature in the PCM storage with 36 pieces of PCM plates. The temperature inside the PCM storage shows similar trends as with 52 pieces of PCM, with the PCM in the first stack (PCM 1) melt and freeze first, and the second stack (PCM 3) melts and freezes slowest. The total charge period of the PCM storage calculated based on the outlet air temperature characteristic is 98 minutes, from 10:36- 12:14. The total discharge period of the PCM storage calculated based on the outlet air temperature characteristic is 148 minutes, from 14:57-17:25.

The discharge time of PCM storage with 36 pieces PCM plates is not much shorter than 52 pieces PCM plates showing in, because that the discharge air from the heat pump is less cold in this test. The inlet air temperature during the discharge period is between 20-25°C, while with 52 pieces PCM plates, the inlet air temperature during the discharge period is around 20 °C.

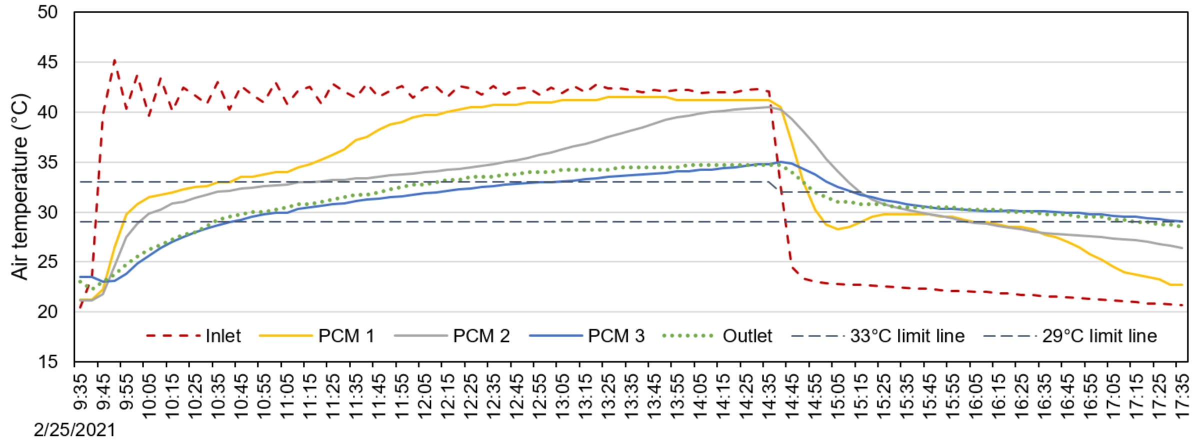


Figure 23: The air temperature in the PCM storage with 36 pieces plates.

With 20 pieces of PCM plates, the air temperature in the PCM storage shown in Figure 24 shows similar trends as with 52 and 36 pieces PCM plates, where PCM 1 melts and freezes faster than PCM 2. However, the temperature difference in the PCM storage is not so big. The PCM along the storage can be active quite fast at the same time. The total charge period of the PCM storage calculated based on the outlet air temperature characteristic is 75 minutes, from 14:10- 15:25. The total discharge period of the PCM storage calculated based on the outlet air temperature characteristic is 90 minutes, from 17:10-18:40. Storage with 20 pieces PCM plates has a lower outlet air temperature during the PCM latent heat releasing period (around 28°C) compares to 52 pieces PCM plates (around 30.5°C) and 36 pieces PCM plates (around 30°C).

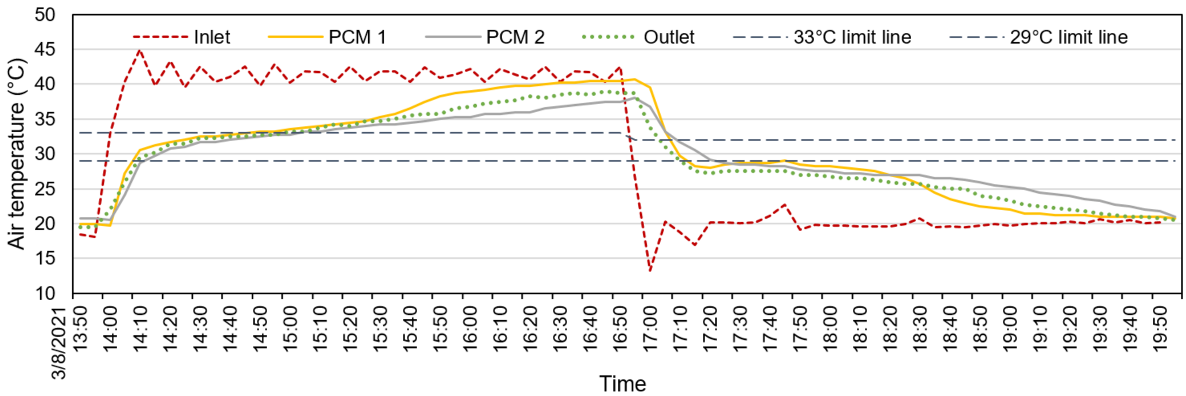


Figure 24: The air temperature in the PCM storage with 20 pieces plates.

Table 3 summarizes the charge and discharge time of PCM storage with different PCM amounts based on the outlet air characteristic of the PCM storage. It shows that the fewer PCM plates, the shorter the charging/discharging period, except for the discharge time of 36 pieces PCM, due to the relatively high-temperature air provided by the heat pump during the discharge period. With 20 pieces PCM plates, the storage has a long discharge time, but the outlet air temperature is much lower than with 36 pieces and 52 pieces PCM plates.

Table 3: The charge and discharge time of PCM storage with different PCM amounts.

PCM storage size	Charge time (minutes)	Discharge time (minutes)
52 pieces PCM plates	210	160
36 pieces PCM plates	98	148
20 pieces PCM plates	75	90

5.6.1.2 The numerical results of PCM storage integrates with heat pump system for grid peak hours shifting

The simulation results of the two cases are shown in Figure 25. It is seen that when the electricity price is low, the system with PCM has a higher hourly electricity consumption; when the electricity price is high, the system with PCM has a lower electricity consumption.

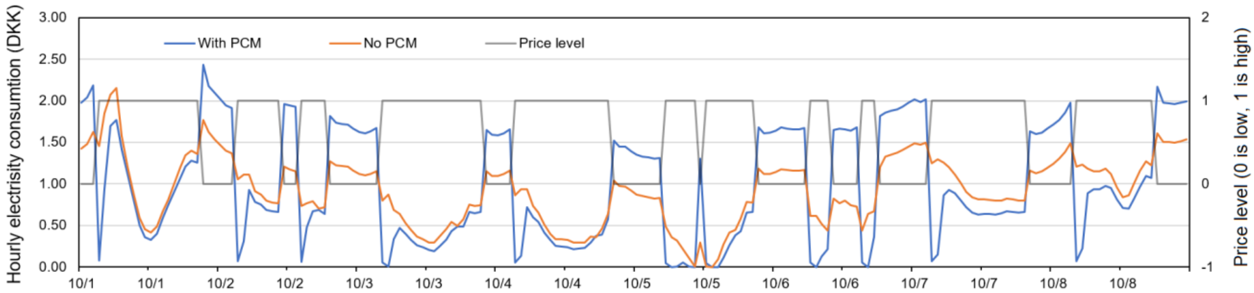


Figure 25: The hourly electricity consumption of PCM integrate with heat pump compares with no PCM [2].

The energy consumption if the two systems and the energy saving potential of the PCM integrates with heat pump system are summarized in Table 4. With the PCM storage, the system can save 6.7% electricity consumption compared to without PCM; the energy cost saving is 6.9%. The relatively low energy cost saving is due to the high tax of the electricity transmission and cost, even though the PCM consumes less energy when the electricity price is high.

Table 4: The energy consumption and energy cost of the heat pump system with PCM and the energy improvement with PCM [2].

	No PCM	PCM	Improvement with PCM
Consumption (MWh)	7.31	6.82	6.7%
Cost (DKK)	14447.40	13445.00	6.9%
Thermal comfort percentage (%)	89.66	89.03	-0.7%

1. Axiotherm PCM - products | Axiotherm GmbH - Innovative thermal storage systems Available online: https://www.axiotherm.de/en/produkte/axiotherm-pcm/ (accessed on May 20, 2021).

2. Hu, Y.; Heiselberg, P.K.; Drivsholm, C.; Vogler-Finck, P.J.C.; Kronby, K. Experimental and numerical study of PCM storage integrated with HVAC system for energy flexibility. *Renew. Energy*. (submitted)

5.6.2 Provision of a stable supply temperature

The provision of a stable supply temperature was evaluated in an experiment in heating conditions with a reduced amount of PCM (10 pieces). The air handling unit was running at full flow when the heat-pump was active, while its system automatically reduced the flow to 40% whenever regeneration was activated (which should be avoided in the final product). Fluctuations in the supply air temperature would therefore be higher in reality when operating at full flow.

An extra temperature logger (with a faster dynamic) was added in the ceiling cavity in these experiments, as there was a concern that the IoT sensors initially used were not sensitive enough for air flow measurements with fast temperature changes.

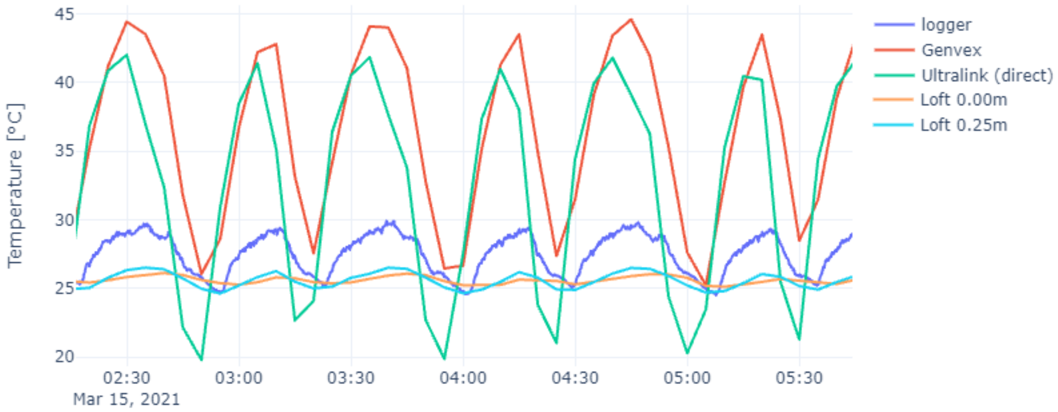


Figure 26: Fluctuations of the supply air temperature at different levels in the system in heating mode, without use of the PCM

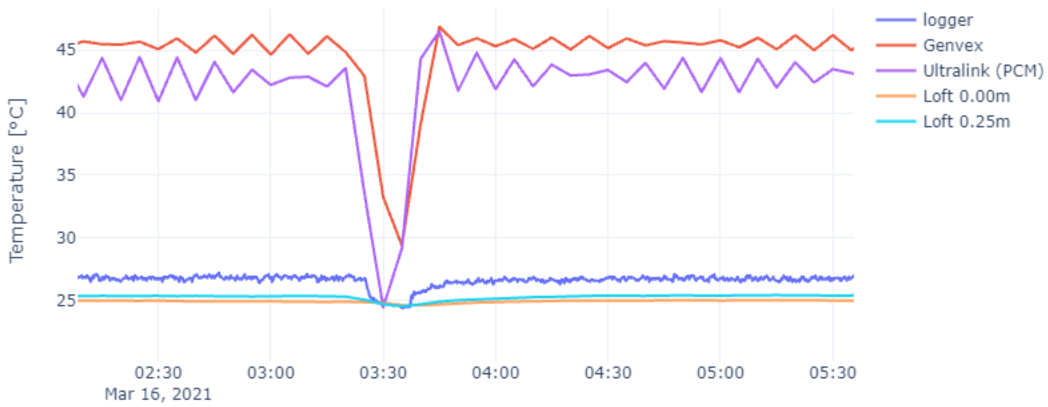


Figure 27: Fluctuations of the supply air temperature at different levels in the system in heating mode, without use of the PCM (10 pieces of PCM)

The conclusion of this demonstration was fourfold:

- First, the IoT sensors used were insufficiently reacting to changes in the supply airflow temperature to be usable adequately in a future system (as illustrated in the figures above where the “Loft” lines correspond to IoT sensors and “logger” to the added sensor).
- Second, the temperature sensors of the Ultralink had a high precision for airflow temperature measurements and moving the Ultralink of the PCM channel to after the PCM box could have provided us with a better overview of the PCM’s impact on the airflow temperature.
- Third, the duct system and ceiling cavity seemed to already provide significant dampening of the supply air temperature fluctuations. It is however not guaranteed that a similar installation in another building would provide the same dampening.
- Lastly, the PCM (although in smaller amounts) had a significant dampening effect on the supply air temperature (the observed temperature drop was about 2 °C compared to 5 °C without PCM).

5.6.3 Air flow control in the system

A characterisation of the fans of the AHU was carried out in the operative range (50 to 100% of nominal speed), which also aimed at evaluating the impact of channelling the air in different ways using the Ultralink dampers. The characterisation was both made in terms of inlet and extract flows, as well as pressure drop between the AHU (prior to the heat-pump) and the ceiling cavity. Here, 4 configurations were tried:

- Directly to the ceiling ("direct")
- Fully bypassing the heat-pump and PCM box ("bypass")
- Full flow through the PCM box with 10 pieces of PCM ("PCM-10")
- Full flow through the PCM box with 20 pieces of PCM ("PCM-20")

The results of these characterisation experiments are provided below.

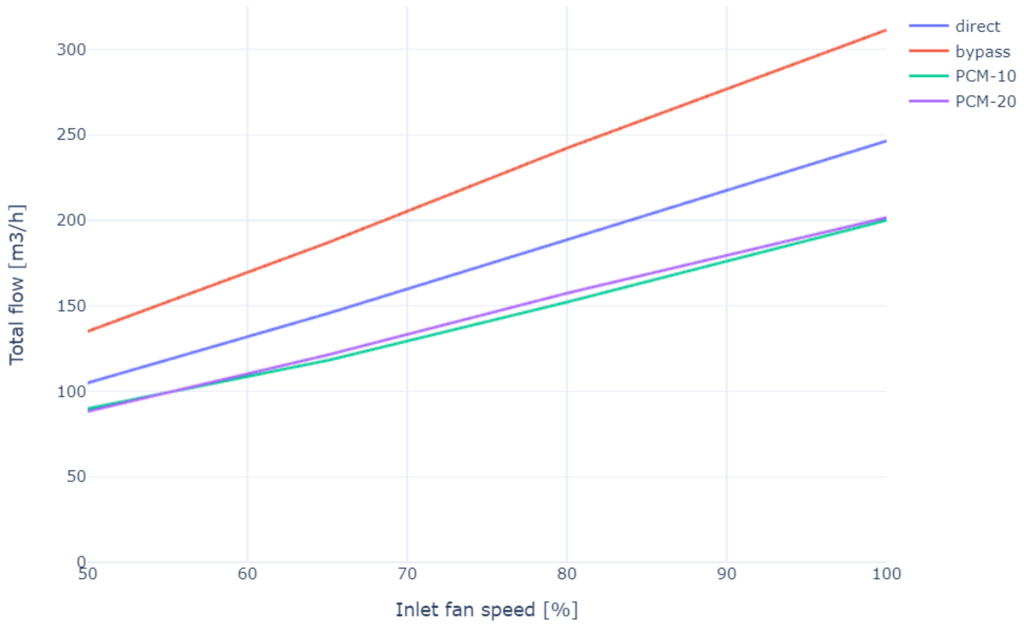


Figure 28: Air flow delivered by the supply fan as a function of its speed and the channel used.

In comparison, the extract fan characteristic was nearly independent of the channel used, with an airflow of 150 m3/h at 50% of nominal speed, and 320 m3/h at 100% (close to the "bypass" characteristic in the figure).

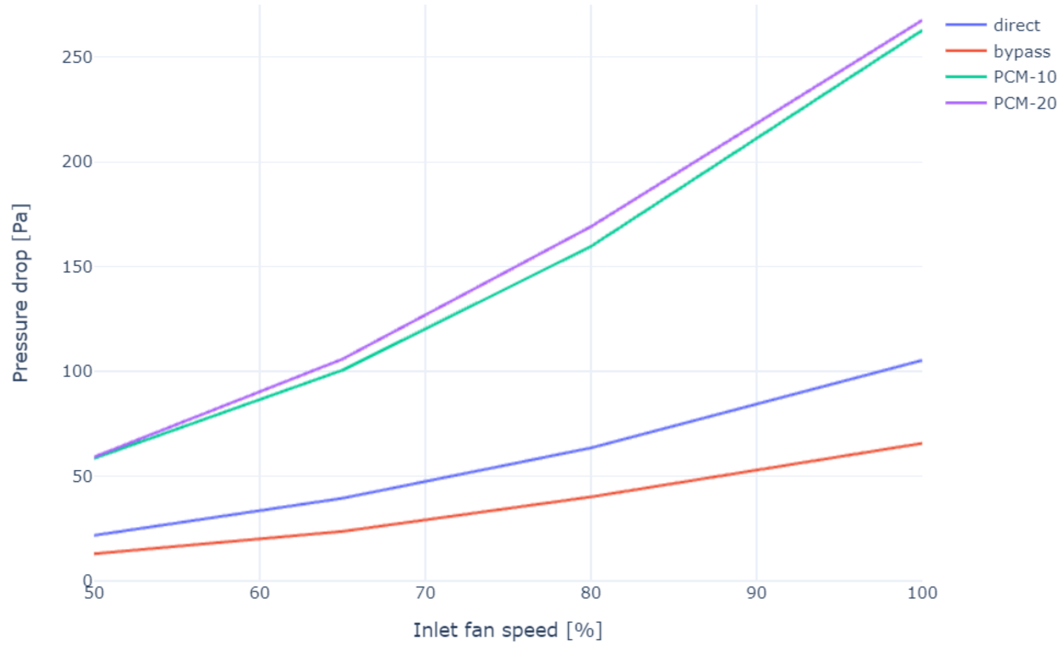


Figure 29: Pressure loss between air handling unit and ceiling cavity, as a function of fan speed and channel used

This characterization highlighted an impact of the channeling that was much higher than expected. In particular, the pressure loss across the PCM box reduced the available flow for PCM loading more than expected. When operating parallelly on bypass and heat-pump channels (e.g. for PCM loading), the difference in pressure loss prevented the flow from splitting according to expectations while providing a sufficient flow in the PCM channel.

These observations therefore raised the question of integrating an active ventilation element (i.e. fan) in the channels in a new design of the system, rather than relying on a single fan on the intake side (integrated in the air handling unit) and passive elements to direct the flow.

5.6.4 Balancing of air flows between supply and extract

A flow balancing experiment was carried out, where the reference setpoint to the extract fan was adjusted depending on the reference to the supply fan speed. The supply fan speed was also modulated according to a dynamic schedule to try whether the compensation would apply equally well in different flow ranges.

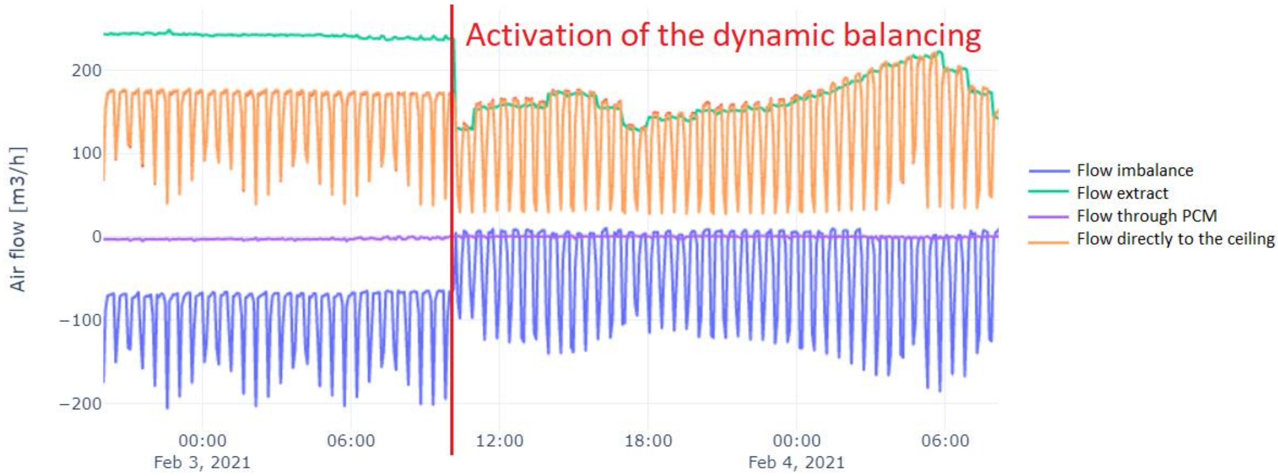


Figure 30: Performance of supply/extract balancing (the blue line is the flow imbalance between supply and exhaust) in a heating situation.

As illustrated on the above figure, the flow balancing was able to drastically reduce the offset in the imbalance flow in normal operating conditions. However, the air-handling unit (AHU) has in-built logic to reduce flow when regenerating (in heating mode) and provide full flow when cooling (in cooling mode) for which there is no simple forecast possible. Therefore, whenever these situations arise, the flow imbalance becomes temporarily much stronger. This was however not possible to react these imbalances with a cloud-based setup, and a more realistic solution would either be to add a logic on the local controller on site (which has a significantly shorter reaction time) or get an update of the heat-pump which fully disables flow reduction during regeneration.

Further fine tuning reducing the residual offset could be achieved by controlling the opening of the Ultralink damper on the extract side, although this was not investigated here due to the overall good performance of the balancing out of the regeneration periods. In the context of this project, an imbalance of up to 10% was the limit on acceptable imbalance.

In cooling mode, the flow balancing was not possible given the internal logic of the system, which forces both supply and extract fan to operate at full speed. An update of the AHU's logic would therefore also be required there in order to support overriding of the extract fan speed.

5.6.5 Predictive controller of the ventilation system

Two versions of the predictive controller were implemented. A first one consisted in a simple flow optimization, where the aim was to maintain a given average flow over a time window, while modulating the instant flow according to variations of the electricity price. Then a more complex one was later implemented

In the first experiment, the optimization delivered flow setpoint variations consistent with the spot price variations, as presented below. The average flow was also held in the vicinity of the reference (75%) over longer period, although deviations were observed around this setpoint.

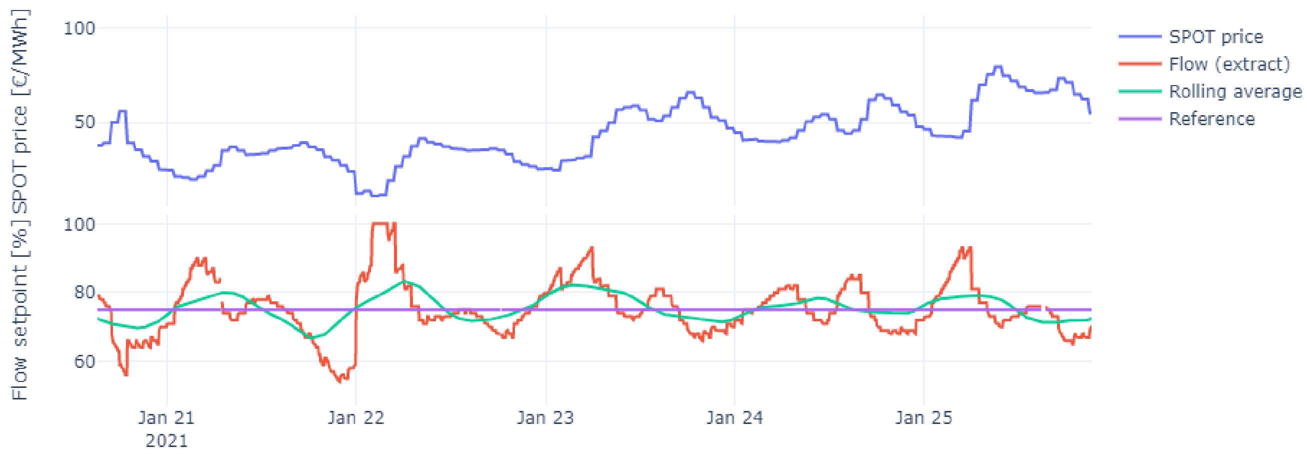


Figure 31: Variations of the controlled air flow (extract shown here) according to a price optimization on the real system

This demonstrated the possibility of controlling the air handling unit according to an optimal controller of the flow based upon a dynamic power price.

Then, a more complex implementation of a model predictive controller was carried out. As mentioned previously, the algorithm of the predictive controller had to be adapted and the optimization split in two (one for the flow, one for the thermal dynamics) in order to obtain the right convergence in the solver, due to the non-linearity of the problem. This control was run on a series of days, with the objective to maintain the temperature within a range and minimize energy demand. The resulting room temperature is shown below for a period of the experiment (in cooling conditions).

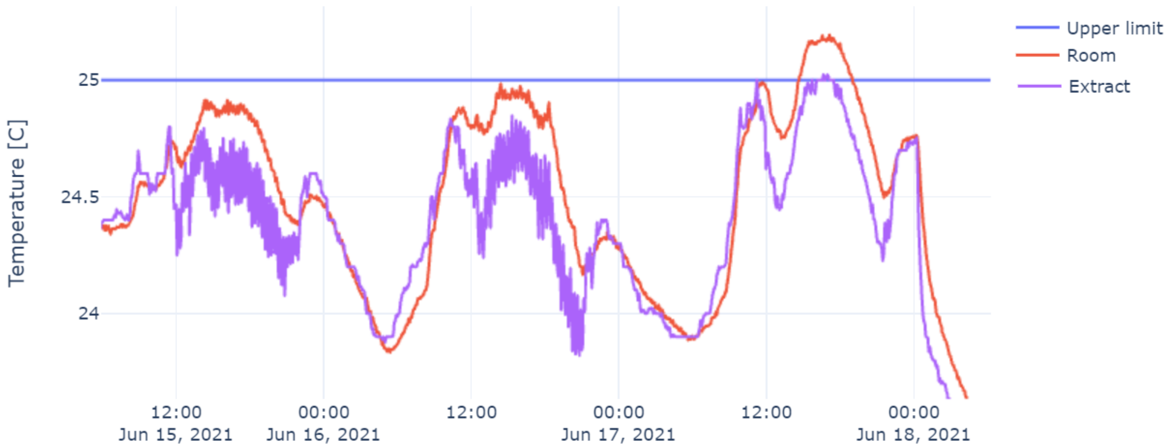


Figure 32: Room temperature during the advanced MPC operation in cooling conditions (with a desired upper bound of 25°C).

This shows the ability for the controller to maintain the temperature within the desired range (with a short small violation) as long as the heat-pump capacity was sufficient to provide the required cooling. In part of the experiment, the ambient temperature has been unusually high (reached above 30C), which was more than the cooling capacity could handle with the usual extract temperature regulation. In order to handle these extreme events, the prediction horizon of the controller was later adjusted to 24h.

In the experiment, significant discrepancies between the temperature from the weather forecast and the local ambient temperature (measured as the inlet temperature of the ventilation) were observed, as illustrated below.

This indicates that there might be value in an ongoing correction to the weather forecast in order to improve the model accuracy. However, this is a rather complex issue, since the local measurement might also be inaccurate or not representative (e.g. due to local effects from the building along the intake channel or solar radiation), so that this aspect was not investigated further in the demonstration.

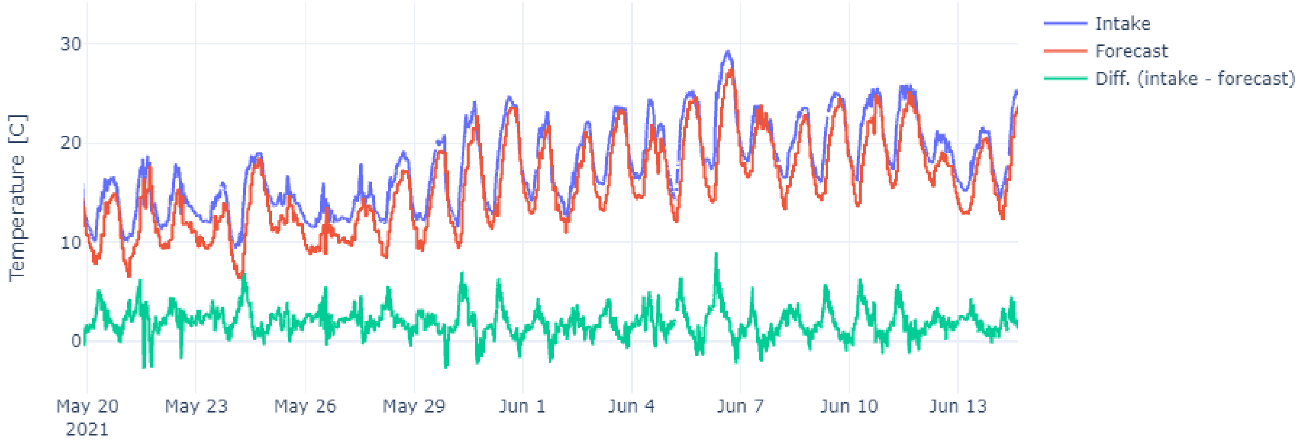


Figure 33: Discrepancies between a local ambient temperature measurement and a weather forecast (from www.yr.no).

5.6.6 User evaluation

As a part of the experiments in EFO, we equipped the test room with a complete office setting and placed two test persons to work there for a prolonged period. The figure below shows the two primary indicators for the indoor environment. The CO_2 levels where very low, - they never exceeded 600 ppm. This suggests that it would even be possible to reduce the fresh air supply if thermal conditions allow. The indoor temperature was held between 23-27 °C. Some of the days were very hot, and the unit was working at maximum capacity.

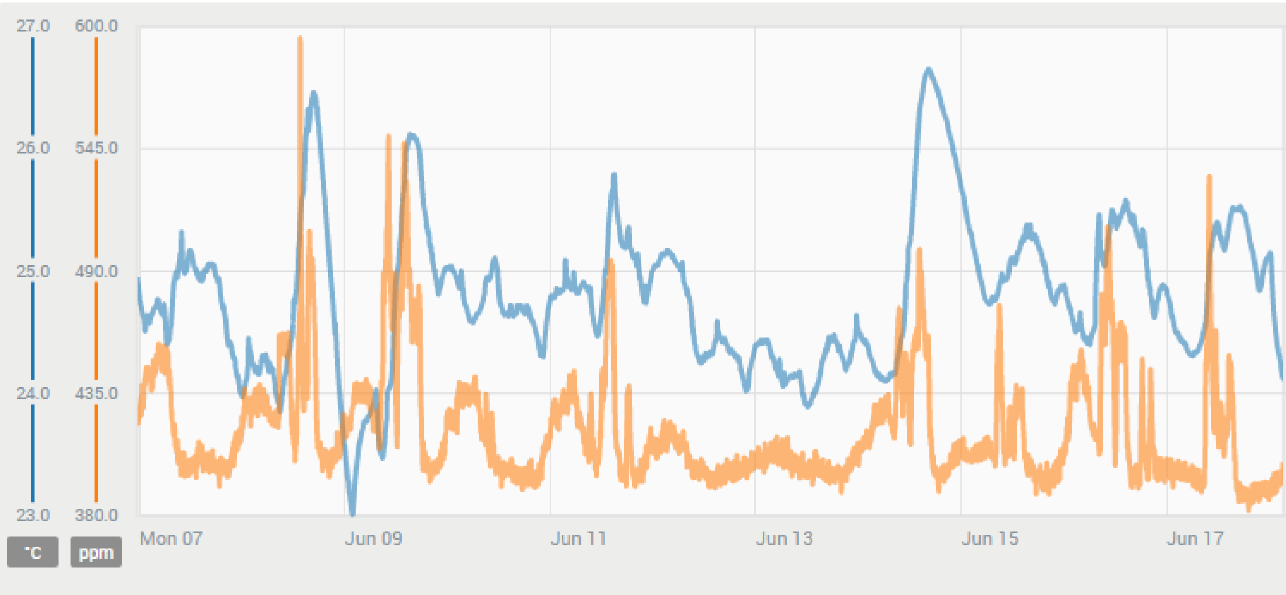


Figure 34: Temperature (blue) and CO_2 (orange) levels during the user test.

The evaluation of the test subjects is based on interviews. Even though both participants were interviewed seperately the interviews showed that they had very simmilar experiences. The interviews can be summerized to:

- The participants had no expectations going into the experiment.
- The fact that they were physically separated from the rest of their team turned out to be a hinderance for their daily functions, but also allowed them to work more concentrated without interruptions.
- They did not notice any changes in the perceived indoor environment due to changes in the control scheme.
- The temperature was very pleasant in the morning, some days the temperature got warmer than they preferred. However, even on the hotter days the temperature was much better than their normal offices.
- They were not compelled to open the windows at any time.
- They were able to control the external solar shading. They had it disabled until the room got too warm.
- They both thought the air quality was great.
- The noise from the unit was too much.

Overall, the evaluation was very good, the participants even asked if they could continue to use the facility at from time to time. The issue with too much noise should be solved by applying the principles described in chapter 5.1.

5.7 Dissemination

5.7.1 Presentations

Ventilation day

It was planned for the project to be showcased at the 2020 edition of the “Ventilation day” and “Indoor climate day” at DTI. Unfortunately, both events were cancelled due to COVID-19. Instead, the project ended up being one of the main attractions at the event “Digital energy days” at DTI. Here the participants got to experience the live demonstration of the iCeiling installation, while getting a presentation of the technology. The “Digital energy days” was held at September 15th with 65 attendees. The plan is that results of the iCeiling project will be presented at the “Indoor climate day” event at DTI on October 26th 2021.

Energiforum Danmark – Nyt fra ventilationsfronten

The project was presented by DTI at the online event “Nyt fra ventilationsfronten” held by Energiforum Danmark. Here the focus was how solutions like the one developed in the project plays a huge role in our ability to succeed in the future energy market, where energy generation will be renewable and we need to adapt our consumption to the production rather than the opposite. The event was held at 06-05-2021 with 29 participants.

VELTEK membership meeting

The project was presented by DTI at a VELTEK membership meeting. The subject of the meeting was intelligent building controls and data driven management of buildings. The event was held at 26-11-2020 with approximately 20 participants.

AI and Sustainable energy track at the Applied Machine Learning Days

The project use case was presented by Neogrid at the Applied Machine Learning Days (https://appliedmldays.org/events/amld-epfl-2021/tracks/ai-sustainable-energy) in a track on “AI and sustainable energy” on April 26th 2021, an international online event organised by EPFL in Switzerland. The talk was attended by 16 people in different countries and the recorded video has later been published on the Youtube channel of the event, which has 1.9k followers across the world.

5.7.2 Articles

Two articles have been published in the HVAC magazine. The first article is focusing on the general concepts of the project, the article are set to feature in the September edition. The second HVAC article have the intelligent controller in focus and is scheduled to feature in the October edition.

AAU scientific article

This paper presents both experimental and numerical studies of PCM storage integrated with HVAC system. The experimental study characterizes the heat transfer process of the PCM storage and indicates the suitable size of the PCM storage for energy flexibility; the experimentally verified numerical model studies the energy flexibility of the HVAC system without and with PCM to shift the peak hour loads of the grid.

Hu, Y.; Heiselberg, P.K.; Drivsholm, C.; Vogler-Finck, P.J.C.; Kronby, K. Experimental and numerical study of PCM storage integrated with HVAC system for energy flexibility. Renew. Energy. (submitted)

6. Utilisation of project results

One of the reasons why the project iCeiling has been initiated, is the increased interest in technical ventilation solutions on the Danish market, with requirements for stable indoor climate, great flexibility, sustainability, energy efficiency and high reliability. The market has been seeking technical ventilation solutions with the desire for a decentralized ventilation solution, where a ventilation unit with integrated heating and cooling can be installed locally.

The goal was to be able to install a ventilation unit with built-in cooling/heat pump, where it is possible to maintain the desired indoor climate throughout the operating time.

Using this solution gains the benefit of minimizing space consuming equipment and significantly reducing the flow of space consuming ventilation ducts on building floors. Smaller duct dimensions can be used and thus it is easier to dispose of the space in relation to the other installations. This solution releases several square meters for a more usable purpose.

In addition, a decentralized solution will solve the requirement of high function reliability and flexibility. If a decentralized unit is defect, it is only locally that the desired indoor climate is not achieved, whereas a central solution will mean that a defect unit will result in a larger part of a building not being able to maintain the requirement for the desired indoor climate. A decentralized ventilation unit can quickly be replaced, so that the building can get back to operation faster.

The individual units can maintain a stricter requirement for flexible indoor climate in the individual premises. By adding a PCM-solution, it is possible to store heating capacity, which can be released at other times.

The challenge on the Danish market has been to find a ventilation unit built with integrated cooling/heat pump, which can maintain the desired indoor climate throughout the operating time. There are periods when the cooling/heat pump must regenerate, resulting in shutdown and thus deviations on the desired inlet temperature. With the developed ventilation unit and the affiliated PCM-module, it is now possible to meet the requirement for a stable inlet temperature.

It is also ensured that the need for flexibility when installing small ventilation units to meet local indoor climate requirements is present. Reliability is high and it is possible to quickly replace a broken device and thus limit interference. Sustainability is the focus, as the decentralised solution reduces the technical installation to smaller units, which also provides significant savings in the scope of installation.

By combining a decentralized solution coupled with the Cool Ceiling climate ceiling, a minimum of technical installations is required. The advantage of the cool ceiling, which is a suspended system ceiling built up in steel cassettes with integrated inlet fixtures and the possibility of installing exhaust fixtures, is that no inlet air ducts should be carried over to the individual inlet fixtures. The cavity above the steel ceiling ensures that the inlet air is fed to the inlet fixtures.

Both subcooled air and heated air can be blown in over the ceiling. This allows the overall technical solution to both heat and cool a room, - without requiring other technical installations. There is no need for pipes from a central heating system or central cooling system. It is all integrated in the decentralized ventilation unit.

With a decentralized ventilation system with built-in cooling/heat pump, which is installed locally, in conjunction with the installation of the cool ceiling, it is a simple turnkey solution, with a minimum of technical installations that maintain a desired indoor climate.

At the same time, it is possible to install the PCM-solution over the suspended cool ceiling, so storage of cooling or heat energy will be possible for release for desired periods of time.

The technical setup chosen in the project is a solution that ventilation wise covers a traditional care ward in a hospital. The reason why a hospital care ward has been chosen as a dimensional basis, is that construction of new hospitals is on-going as many of the existing hospitals are to be renovated. When renovating or re-building care wads in hospitals, a decentralized ventilation model will be an attractive solution.

In institutions such as schools and the like, the decentralized solution will also have its merits. Here it will also be possible to integrate the decentralized unit into, for example, a cabinet solution.

Overall, a decentralized solution will be optimal in buildings where there is limited space for the installation of ducts and other technical installations. This offers great opportunities in the renovation of the building stock, where the challenge is often lack of space and where it is often a challenge to find space for the larger technical installations and central units.

Often it is also challenging to make room for the outdoor installations. With the iCeiling model there are no outdoor installations.

In buildings with rooms such as meeting and conference rooms, where a large heat load can occur locally in the building, the decentralised model will be an optimal solution.

In new constructions it is possible to think a decentralized solution into the overall design. Here it is possible to optimize the ventilation technical solutions and thus limit the space to the technical installations. This means space is saved for a more useful purpose.

The iCeiling model meets the new climate agreement, which focuses on the use of green energy rather than fossil fuels.

One obstacle for the PCM module is the price. At the current price point, the solution is not viable. Either the price of PCM material needs to come down or the price structure of the energy market needs to change significantly to make energy flexibility more profitable.

Besides the product developed in the project JS Ventilation sees Neogrid as a possible business partner going forward. Neogrid are able to provide extra value to the solutions JS Ventilation already offers. By partnering up with Neogrid JS Ventilation would be able to differentiate them self from the competition and Neogrid would get easier and faster access to the market.

The project has allowed Neogrid to further sharpen data collection and control toolchain, which leads to more robustness on the whole of its product range (as the communication toolchain used in the project is the common backbone). Furthermore, its PreHEAT platform has already benefited from the projects as dynamical electricity price signals are now integrated into it, and ventilation-related control and monitoring services on the platform are under way. Although the current version of the iCeiling controller is not fully market-ready in a scalable manner at this stage, many of the features developed for monitoring of ventilation systems are transferable to other existing market segments (residential and office buildings) where Neogrid is currently experimenting with market introduction.

Furthermore, the project has led to a further project application by Neogrid and Teknologisk Institut (together with IDA Ingeniørforeningen and Pro Bygningsautomatik) to the ELFORSK program (under the name “Smart Ready Building Control”) where the focus will be on data-driven optimisation of indoor climate into a complex office building with ventilation systems. In this project JS Ventilation is represented by their Cool Ceiling system that is installed on the premise.

The project has gained the vision of Aalborg University about the modelling of implementing PCM to the building HVAC system and its operation performance. The data and analysis from both the experiment and the modelling work is publishing in scientific journals, which is being peer-viewed by the expert in the field and the results can improve the vision of PCM implementing in building systems for the scientific field. The knowledge gained form this project can be used for teaching activities in AAU, knowledge sharing between projects, as well as inspiring new research ideas.

7. Project conclusion and perspective

The test results of the PCM integrated with heat pump system showed the high potential of using PCM for energy storage and grid peak hour shifting. The optimized amount of PCM in the storage is 36 pieces of PCM plates, for a fast response to the warm inlet air during the charge period, and a long discharge period to release heat to the ventilation. The modeling of the energy flexibility of the PCM shows that in spite of the capability of the PCM to store heat when the electricity price is low, and release heat when the electricity price is high, the total electricity cost saving is not so significant due to the high tax and transmission of electricity in Denmark. With the electricity price control, the system with PCM can save around 7% of the total electricity bill during one winter season. Considering the relatively high price in the current market, it is challenging to use PCM for electricity energy storage in Denmark. But it can be beneficial for some other countries where the tax of the electricity is not so high.

Another interesting finding is that when the PCM is installed, the supply air temperature to the room is more stabled. Therefore, it is beneficial for some special places to include the PCM in the HVAC system, when the stable and predictive supply air is required, such as a hospital room. The PCM storage is able to provide at least half hour high-temperature inlet air, which can be used to guarantee a good indoor thermal comfort when the heat pump is defrosting.

Online connection and remote control of the ventilation system (air handling unit and heat-pump) was demonstrated in a robust manner, as expected. The initially envisioned intelligent controller on top of the existing controller has however been very challenging due to the low-level regulation logic of the system, non-linearity of the behavior and optimization, as well as the strong variations between heating and cooling operation. However, value delivery from online control was demonstrated in the course of the project and resulted in a number of smaller solutions that can be exploited in a broader variety of ventilation-related contexts.

The user evaluation showed confirmed that the developed product was able to provide a good indoor environment.

Furthermore, the tests showed that the duct system and ceiling cavity seemed to already provide significant dampening of the supply air temperature fluctuations. It is however not guaranteed that a similar installation in another building would provide the same dampening.

8. Appendices

8.1 Article – Renewable Energy

Experimental and numerical study of PCM storage integrated with HVAC system for energy flexibility

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Abstract

This paper presents both experimental and numerical studies of PCM storage integrated with HVAC system. The experiments study the temperature change in the PCM storage during the charge and discharge period, the impact of the PCM amount on the charge and discharge rates of the PCM storage, and the impact of the discharge air temperature and airflow rate on the discharge rate. The main conclusions are that the storage with more PCM can store more heat and provide high and stable outlet air temperature, but have a relatively long charge/discharge period with the risk that some part of the PCM plates cannot be activated; while the storage with less PCM has a faster action time and none-delayed activation of all PCM, but provides a lower outlet air temperature, especially when the airflow rate is high or discharge temperature is low. Next, a model of the PCM storage integrated with HVAC system is built with EnergyPlus and validated by experimental data. Based on the experimental analysis, a medium-sized PCM storage is chosen for numerical work to study the energy flexibility of the system without PCM and with PCM. The study found out that the HVAC heating setpoint control based on the electricity price without PCM storage has limited cost-saving potential due to the high electricity transmission and tax cost. The PCM storage integrated with HVAC system can save the energy cost by 7 % while obtaining a similar indoor thermal comfort level compared to the HVAC heating setpoint control without PCM storage.

Keywords: Heat pump, PCM storage, Heat storage, Peak hours shifting, Electricity price control, Energy flexibility

1. Introduction

Phase change material (PCM) as thermal energy storage (TES) has been used in various building applications recently. It changes its phase at a certain temperature or temperature range, and simultaneously absorbs or releases a large amount of latent heat. Due to its high latent storage/release ability during its phase transition period, the material is used for building or solar energy storage. It can also be used for cooling applications, to act as a heat sink during a summer night, and remove the excess heat in the building during the day. Besides, it can be added to wallboard or other building construction as thermal buffer or insolation, because that its temperature stays stable for a relatively long period during the phase transition process.

The PCM applications can be mainly sorted into passive systems and active systems. PCM passive systems including PCM in building constructions, wallboard, ceiling, floor, furniture, blinds[1], etc. do not require any additional mechanical means for the PCM to be activated[2], thus it is easy to implement. PCM active systems require additional energy input to operate the system, but they are usually more effective than the passive systems in regards to the indoor environmental comfort and building energy saving, such as heat exchanger[3], thermal energy storage, solar collector, ventilated window, air conditioning system, ventilation ceiling panel[4], ceiling storage with water pips[5], floor[6], ventilation façade[7]. In those studies, the active systems are all been tested effective for either energy saving or indoor thermal comfort improvement. Another advantage of the active systems is that they can be controlled based on the desired indoor conditions with a quick system response, which on the other hand a passive system cannot achieve.

The main measures to decrease the HVAC heating and cooling energy demand are to apply PCM to ventilation and HVAC system for cooling or heating purposes. For cooling purposes, the PCM system is always operating in combination with night ventilation. Since 2000, Turnpenny et al[8][9]. has already built and tested the PCM thermal energy storage for night cooling application, and they concluded that the system has more energy saving compared to conventional air conditioning system and cooled beams. Similarly, Hed et al.[10] developed a PCM air heat exchanger for the night cooling system, by cooling down the PCM during the night with night ventilation, and using the low-temperature PCM to cool the indoor air during the day. Sun et. al. [11] tested a PCM thermal storage made by PCM slabs with 28 mm thickness in a wind tunnel experiment setup with different charging/discharging rates and airflow rates, and they had the conclusion that the energy charging speed of the PCM is increasing along with the increase of the airflow rate, but the increasing speed decreases when the ventilation is higher than 5 m/s. Zeinelabdein et al. [12] have studied a similar PCM thermal storage with PCM plates and its effectiveness of night cooling and had the conclusion that the compact design of the TES, which means a narrow gap between the PCM plates can save 15% of the charging time.

For heating purposes, the PCM is normally used as solar energy storage or thermal energy storage. For such systems, the configuration design, airflow rate, control strategies, etc. are the key design parameters. Since 1990. Farid et al.[13] has developed a model to predict an electric heater made by PCM slabs to store heat provided by off-peak electricity. They concluded that the heat transfer between the air and PCM should be improved by increasing turbulence to the ventilation. Navarro et al.[14] has developed and studied the PCM incorporation in a concrete core slab as a thermal energy storage system to be used for both heating and cooling purposes. They added a PV panel for the winter heating function. The conclusion was that the system shows good potential to save heating and cooling energy, but the control strategy optimization is required to achieve high effectiveness. Vakilaltojjar et al.[15] developed a similar PCM storage made by PCM plates for solar heating and energy-efficient space heating and cooling applications. They had the conclusion that the PCM plates and air gap between the PCM plates should be smaller within the system allowed pressure drop range.

PCM as TES is a good candidate for implementing energy flexibility to the building[16][17][18]. Energy flexibility of the building is becoming more important due to the increasing electricity produced by renewable surces[19]. The concept of an energy flexibility building is that the building has high latent storage density and smart grid, smart control for different parameters[20]. PCM storage integrated with electricity control in buildings has the potential to shift the peak hour loads of the grid and improve the building energy flexibility.

Even though there are a lot of studies applying the PCM TES for building heating, cooling, and off-peak power shifting, most of them are only the study of the PCM TES (how to say itself, alone). There are seldom experimental studies considering the PCM TES and the building HVAC and ventilation as a whole system, which has a big impact on not only the energy saving by the TES itself but also the indoor thermal comfort.

This study proposed a PCM integrated HVAC system for building energy flexibility, which is presented in Section 2. In Section 3, the mechanism of the heat transfer in the PCM storage is studied by experimentally examine the air temperature in a PCM storage. The PCM storage is designed with different PCM plates arranged in different stacks in the insolated box and integrated with a heat pump system. The study was carried out by analyzing the temperature in the PCM storage during the charge and discharge period, the impact of the PCM amount on the charge and discharge rates of the PCM storage. Based on the experimental study, the design optimization of the PCM storage is suggested based on different application purposes of the PCM storage. Follow on, the numerical study of the optimized PCM storage integrated HVAC system is presented in Section 4. The model is verified by the experimental data and used to exam the energy flexibility potential of the system without PCM and with PCM.

2. System concept

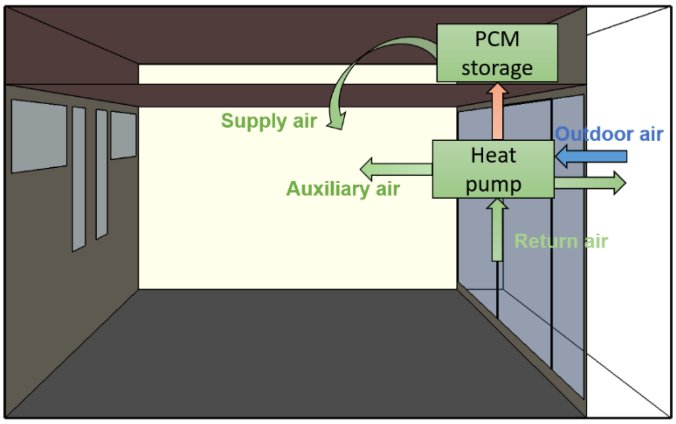


Figure 1. The system configuration of the PCM storage integrated with heat pump.

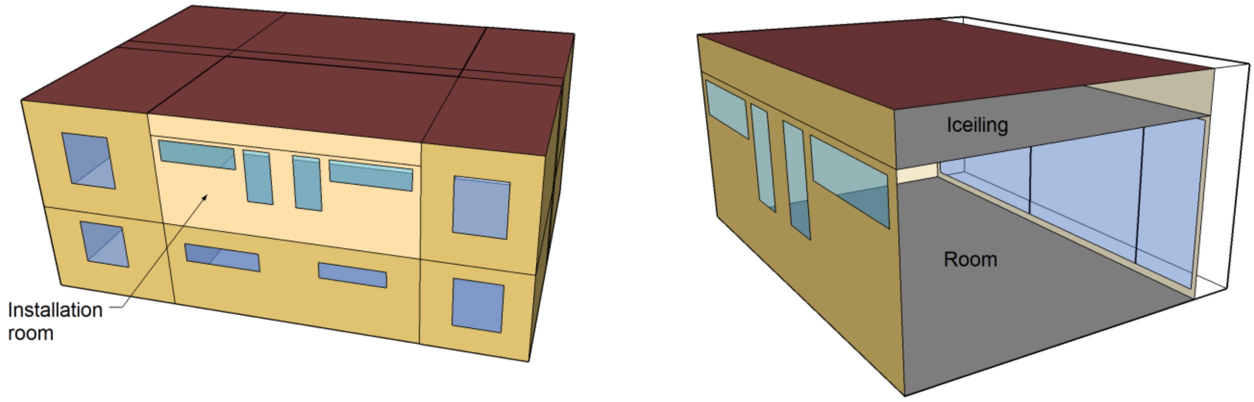
The configuration of the PCM storage integrated with heat pump system includes the PCM storage, the heat pump and the ventilation ducts, as shown in Figure 1. The PCM is used to shift peak hours in the grid, which requires control based on electricity price. When the electricity price is low, the PCM stores the energy from the warm air provided by the heat pump. When the electricity price is high, the heat pump is turned off, and the PCM releases the heat to the ventilation air. The heat pump is turned on and supply auxiliary air when the PCM cannot provide enough heat to the room during the high electricity price period.

The system can be used for another function to guarantee a stable supply-air temperature during the heat pump defrost period. During the heat pump functioning period, the PCM is charged by the warm air from the heat pump. During the heat pump defrost period, the heat pump is shut down, and the PCM is used to heat the supply air.

3. Experimental study

3.1 Experimental setup

The setup is in the Energy flexibility lab in DTI. One office room consists of a room and a ceiling cavity for diffuse ventilation is selected as an installation room. The room has 4 windows facing south with external shading. A ceiling penal with 4 diffusers divides the office room into the ceiling part and the room part.



a. Installation room in the lab.

b. Details of the installation room.

Figure 2. The installation room for the experimental setup.

The integration of the PCM into the heat pump system is illustrated in Figure 3. The room air is extracted with a fan through the heat recovery unit to the outdoor. Ventilation air can bypass both the heat pump and the PCM storage from the heat recovery unit to the ceiling cavity (iceiling).

The system can be controlled in 3 modes:

1. PCM charge/discharge mode, where the dampers 1 and 2 are turned off, and the ventilation air is passing from the outdoor through the heat recovery unit, the heat pump, the PCM storage and iceiling to the room;

2. PCM bypass mode, where the outdoor air is passing through the heat recovery unit, heat pump and damper 2 to the iceiling, when extra heating is needed in the room;

3. Heat pump bypass mode, where the outdoor air is passing through the heat recovery unit and damper 1 to the room, when the room is too warm.

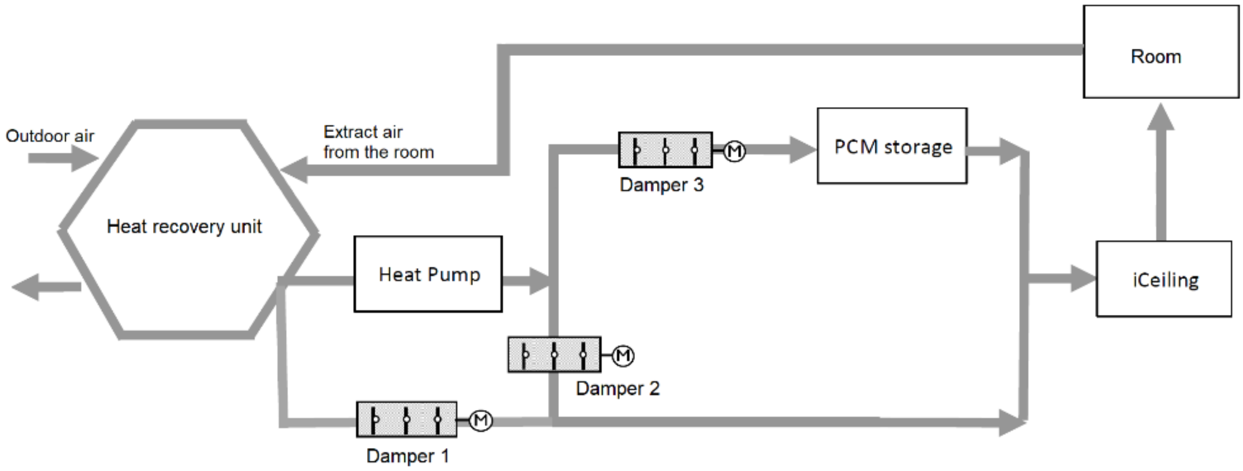


Figure 3. Integrate PCM into heat pump air system.

Figure 4 shows the setup of this ventilation system in the lab. The ventilation operation is controlled by adjusting the dampers with valves and the extract fan speed. The air temperate and speed through the damper are measured by the ultrasonic sensor technology provided by UltraLink. The damper can change its positions to adjust the flow.

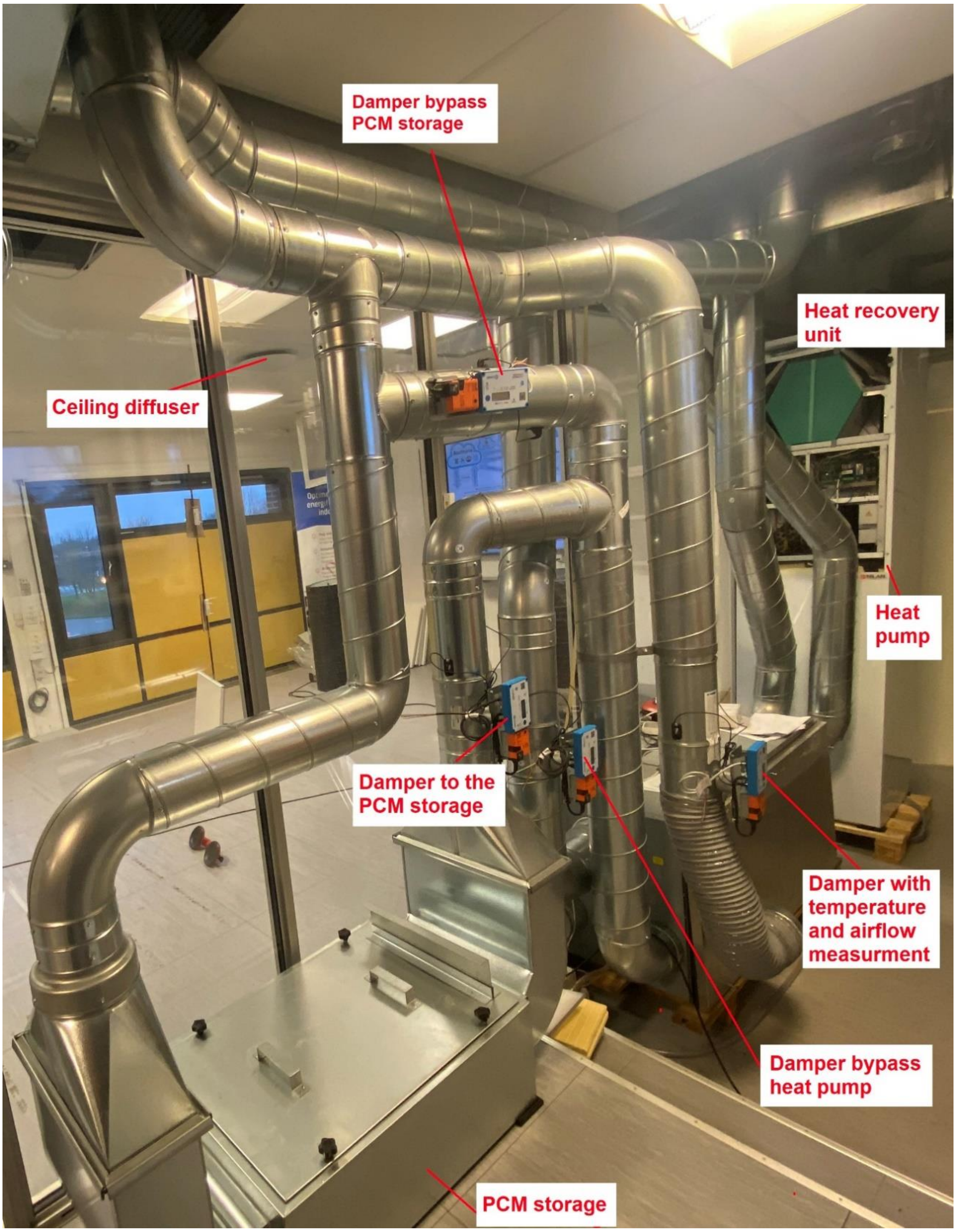


Figure 4. System setup in the lab.

The PCM used in the PCM storage is ATS 30, which has a melting/freezing point of around 31°C. Table 1 lists the thermal properties of the PCM ATS 30. It has a melting range of 28°C-33°C, and a freezing range of 27°C-30°C, and a specific heat of 220 kJ/kg within the temperature range of 23 – 38°C, which corresponding to the latent heat of 190 kJ/kg. The heat capacity of the PCM is plotted in Figure 5. The PCM is macro-encapsulated in a plastic container with the size of 0.34 m × 0.22 m × 0.01 m. Each container contains 660 g PCM. The surface area of each container is 0.185 m^2.

Table 1. The thermal properties of the PCM ATS 30[21].

	Unit	Value
Melting temperature	°C	28-33
Freezing temperature	°C	29-32
Heat storage capacity (temperature range of 23 – 38°C)	kJ/kg	220
Specific heat capacity	kJ/kg·K	2
Density (liquid)	kg/l	1,3
Heat conductivity	W/(m·K)	0,6
Volume expansion	%	<6
Flashpoint	°C	Non-flammable

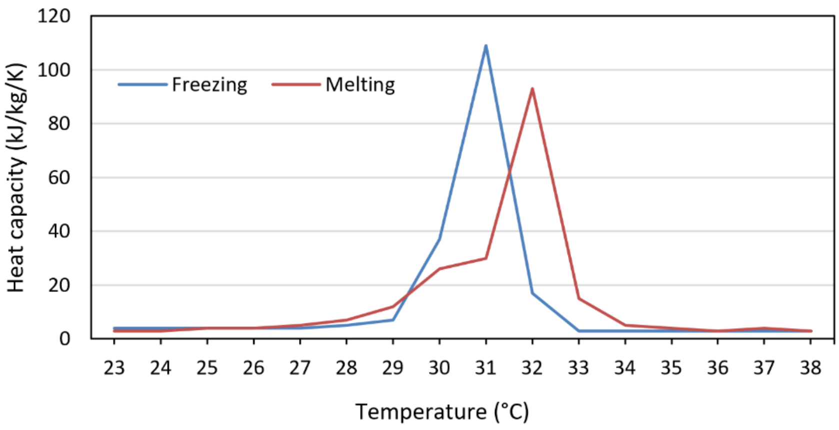


Figure 5. The heat capacity of the PCM[21].

One aim of this testing is to identify the right size of the PCM storage. 3 sets of PCM storage are tested in the experiment, with 52, 36, 20 pieces of PCM respectively, as shown in Figure 6. The temperature in the PCM storage is measured by temperature external AMR-Wireless M-BUS with a precision of 0.05°C. The sensors are put between layers 3 and 4, layers 10 and 11.

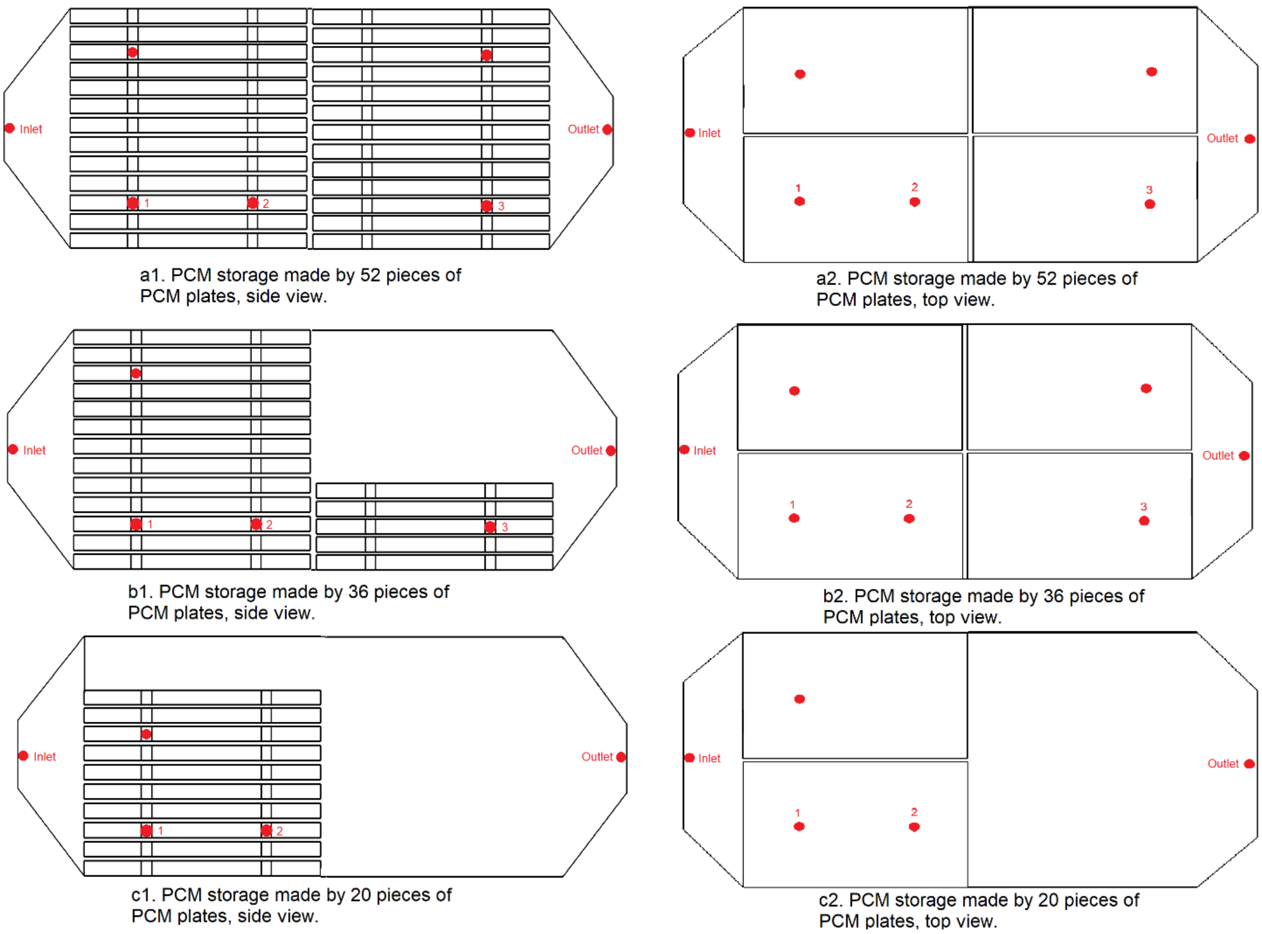


Figure 6. PCM temperature measurements. a. PCM storage made by 52 pieces PCM plates (a1. Side view; a2. Top view); b. PCM storage made by 36 pieces PCM plates (b1. Side view; b2. Top view); c. PCM storage made by 20 pieces of PCM plates (c1. Side view; c2. Top view).

3.2 Experiment Results

3.2.1 The temperature in the PCM storage

During the test, the PCM is charged with hot air from the heat pump, and discharged with the outdoor air or the cold air from the heat pump. The heat pump provides around 41°C 160 m^3/h-180 m^3/h hot air during the charging period. During the discharge period, different ventilation temperatures and airflow rates are tested for the 3 different PCM storages.

Figure 7 shows the air temperature in the PCM storage with 52 pieces of PCM plates. In the test, the PCM is charged with around 41°C 160 m^3/h-180 m^3/h hot air provided by heat pump, and discharged with around 20°C 200 m^3/h cold air from the heat pump. The PCM melting range is 29-33°C, and the freezing range is 29-32°C (where the latent heat of the PCM is dominant). The PCM 1, PCM 2, PCM 3 are the measured air temperature in the PCM box corresponding to the labels in Figure 6. The inlet air temperature of the PCM storage is measured in the damper from the heat pump to the PCM storage. The outlet of the PCM storage is located in the middle of the outlet duct from the PCM storage. The PCM storage is charged from 9:15 to 14:15, and discharged from 14:15-17:15. During the charging period, the PCM in the first stack melts first, resulting in the air temperature in the first stack PCM rising first (PCM 1 and PCM 2). The PCM in the second stack (PCM 3) starts charging around 10:10 and finishes around 13:25, resulting in a charging period of 195 minutes. The reason why it takes a longer time for the second stack of PCM to be charged is that even though the first stack PCM already finished charging latent heat, its temperature is still rising due to the charging of sensible heat, thus the heat amount provided to the second stack of PCM is much smaller. The total charge period of the PCM storage calculated based on the outlet air temperature characteristic is 210 minutes, from 10:30- 14:00.

During the discharging period, the PCM in the first stack freezes first, and the PCM in the second stack freezes later. During the latent heat-releasing period (where the air temperature in the PCM storage has a slower decreasing rate), the air temperature in PCM 1 is the lowest (around 28 °C), and the air temperature in PCM 3 is the highest (around 31 °C). The total discharge period of the PCM storage calculated based on the outlet air temperature characteristic is 160 minutes, from 14:40- 17:20.

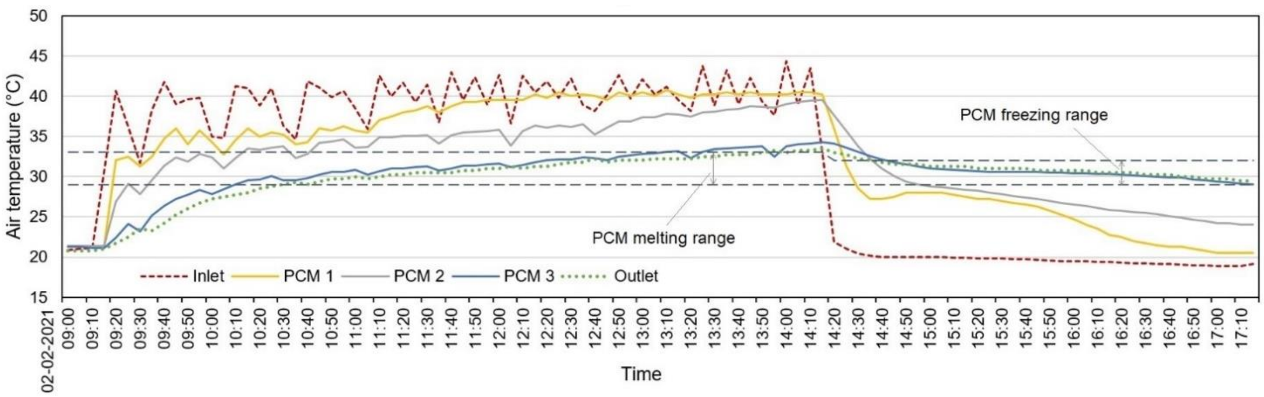


Figure 7. The air temperature in the PCM storage with 52 pieces plates.

3.2.2 Impact of PCM amount on the charge rate

For the charge of the PCM storage, 3 tests with 52, 36, and 20 pieces of PCM were done with charging temperature around 41°C and charging air flowrate 160 m^3/h -180 m^3/h provided by the heat pump. To make the 3 cases comparable, the temperature efficiencies of the PCM storage of the 3 cases are calculated and compared. The temperature effectiveness represents the heat exchange efficiency between the PCM and the air in the PCM storage and is calculated by Equation (1)[22]. The PCM temperature is the average temperature of positions 1, 2 and 3 (if applicable) in the PCM box measured in Figure 6.

$$Temperature\ effectiveness = \frac{T_{outlet} - T_{inlet}}{T_{PCM} - T_{inlet}} \tag{1}$$

Figure 8 shows the results of the PCM storage outlet air temperature and temperature effectiveness of the 3 tests. It is seen in Figure 8(a) that with 52 pieces of PCM plates, the charge time is longer than 3 hours (until the outlet temperature reaches 33 °C). The more the PCM plates, the smaller the temperature difference between the air and PCM temperature in the PCM storage, thus it takes a longer time to charge the PCM storage (the PCM initializes at a quite low temperature). With 20 pieces of PCM plates, the PCM can be charged in 75 minutes. With 32 pieces of PCM plates, the charge time is around 98 minutes, which is suitable for the application considering the long discharge period it provides (shown in Figure 9). The comparison of temperature effectiveness in Figure 8(b) shows that the more the PCM plates, the higher the temperature effectiveness of the PCM storage during the charge period.

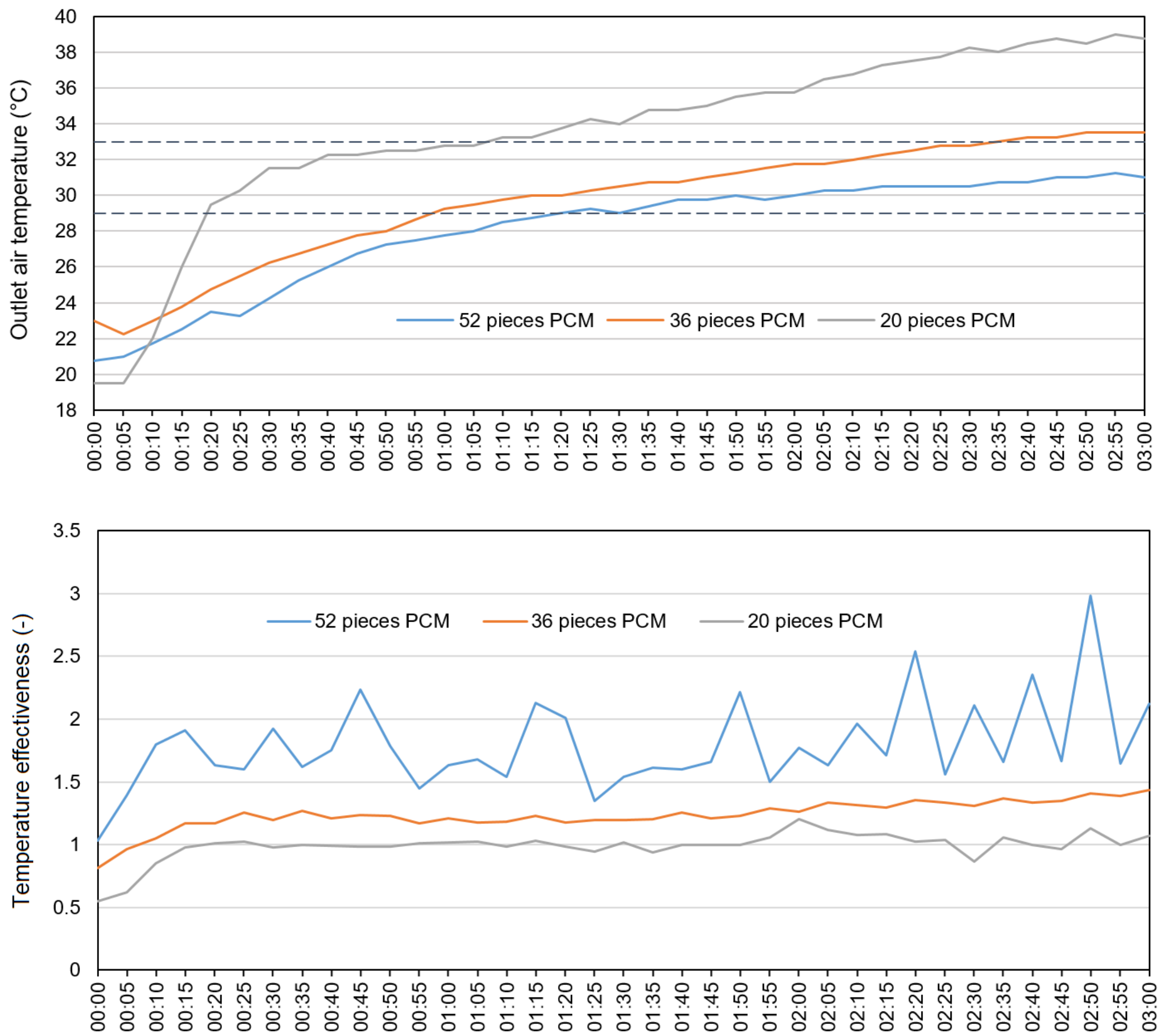


Figure 8. (a) Outlet air temperature and (b) temperature effectiveness of the PCM storage with different PCM amounts during the charging period.

With 20 pieces of PCM plates, the outlet air temperature of the PCM storage is higher than with 36 pieces PCM plates and 52 pieces PCM plates during the charging process, which means the PCM can active faster. With 52 pieces of PCM plates, even though the temperature effectiveness is highest, it takes much longer to charge the PCM, which could be a drawback for the PCM storage design.

3.2.3 Impact of PCM amount on the discharge rate

The impact of the PCM amount on the discharge rate is shown in Figure 9. The 20°C 200 m^3/h cold air is provided by the heat pump and ventilated through PCM storage. Figure 9(a) shows the outlet air temperature of the PCM storage with different PCM amounts. With 20 pieces of PCM plates, the discharge of the PCM takes place around 0:20-1:25; the outlet air temperature of the PCM storage is mostly around 26-27 °C when the phase change happens. With 36 pieces of PCM plates, the discharge of PCM happens around 0:30-2:05; the outlet air temperature of the PCM storage is around 29-31°C. While with 52 pieces of PCM plates, the discharge of PCM starts at 0:20 and ends after 3:00; the outlet air temperature of the PCM storage is around 29-32°C. The less PCM, the bigger difference between the air temperature and the PCM temperature in the PCM box. That is the reason that with 20 pieces of PCM plates, the outlet air temperature stabled at around 27.5°C when the PCM is releasing latent heat (0:18-0:50), which is lower than with 36 pieces of PCM plates (30°C) and 52 pieces of PCM plates (31°C). The comparison of temperature effectiveness in Figure 9(b) shows that the more the PCM plates, the higher the temperature effectiveness of the PCM storage during the discharge period.

With 20 pieces of PCM plates, the outlet air temperature of the PCM storage is lower and less stable than with 36 pieces of PCM plates and 52 pieces of PCM plates in the PCM discharge period, especially during the PCM phase change period, where the temperature effectiveness is also lower. This could be a drawback of the PCM application with a few PCM plates.

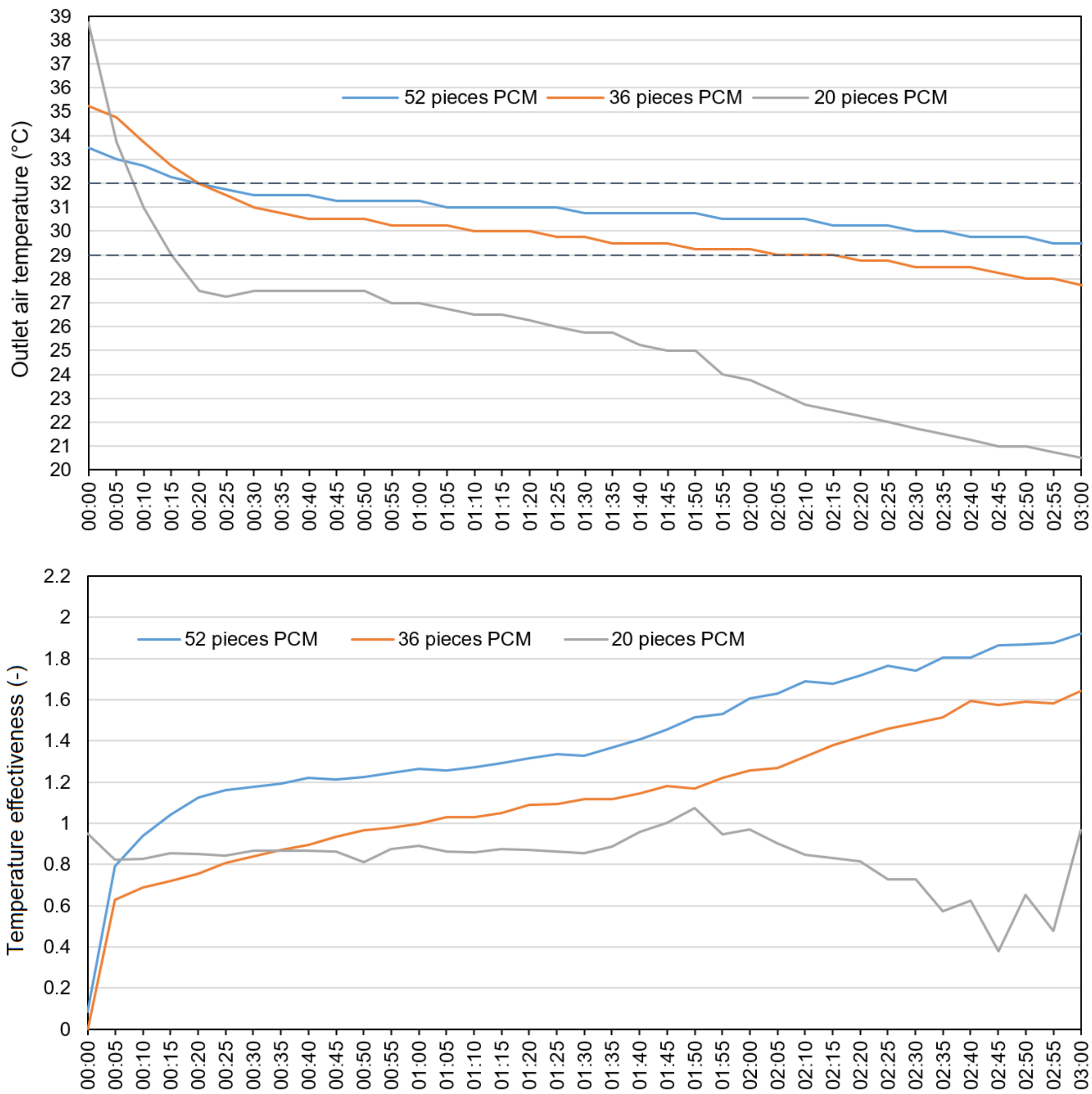


Figure 9. (a) Outlet air temperature and (b) temperature effectiveness of the PCM storage with different PCM amounts during discharge period, with 20°C discharge temperature.

3.2.4 Impact of discharge inlet air temperature on the discharge rate

The impact of the discharge air temperature on the discharge rate is studied by measuring the temperature in the PCM storage with 36 pieces of PCM plates under different inlet air temperatures. The ventilation rate for all the tested cases is around 200 m3/h. the inlet air temperature changes from 10°C to 21 °C. Figure 10(a) shows the measurement results of the outlet air temperature. It shows that the lower the discharge inlet air temperature, the faster it is to discharge the PCM. With lower discharge inlet air temperature, the temperature difference of the PCM and air in the PCM storage is bigger. Thus the air in the PCM storage has a lower temperature, which results in the lower outlet air temperature from the PCM box. However, the temperature efficiencies of the PCM storage for all the cases (Figure 10(b)) are similar during the phase change period.

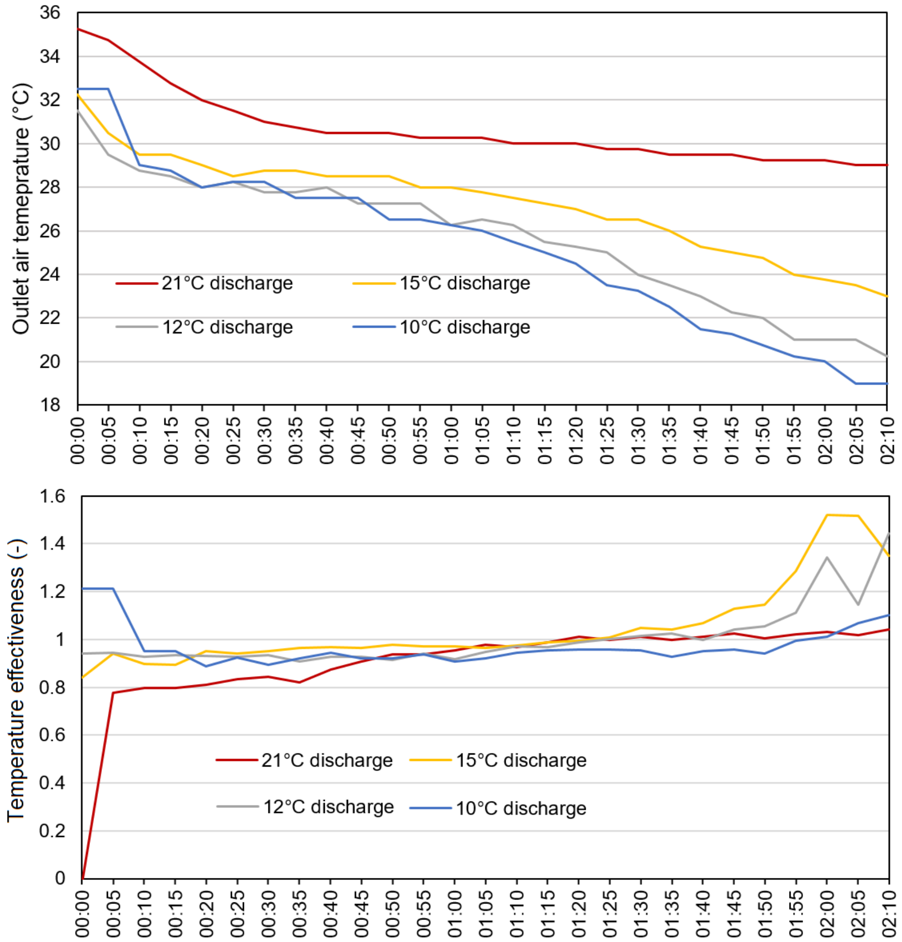


Figure 10. (a) Outlet air temperature and (b) temperature effectiveness of the PCM storage with different discharge inlet air temperatures.

3.2.5 Impact of discharge inlet air flowrate on the discharge rate

The impact of the discharge airflow rate on the discharge rate is studied by measuring the temperature in the PCM storage with 52 pieces of PCM plates under 15°C inlet air temperature. Two inlet airflow rates are measured: 190 m^3/h and 50 m^3/h, as shown in Figure 11(a). The lower the airflow rate, the smaller the difference between the PCM temperature and air temperature in the PCM storage. This results that the outlet air temperature of the PCM storage with 50 m^3/h airflow rate is higher than with 190 m^3/h airflow rate during the

PCM phase transition period. Figure 11 (b) shows that with a lower flow rate, the temperature effectiveness of the PCM storage is higher.

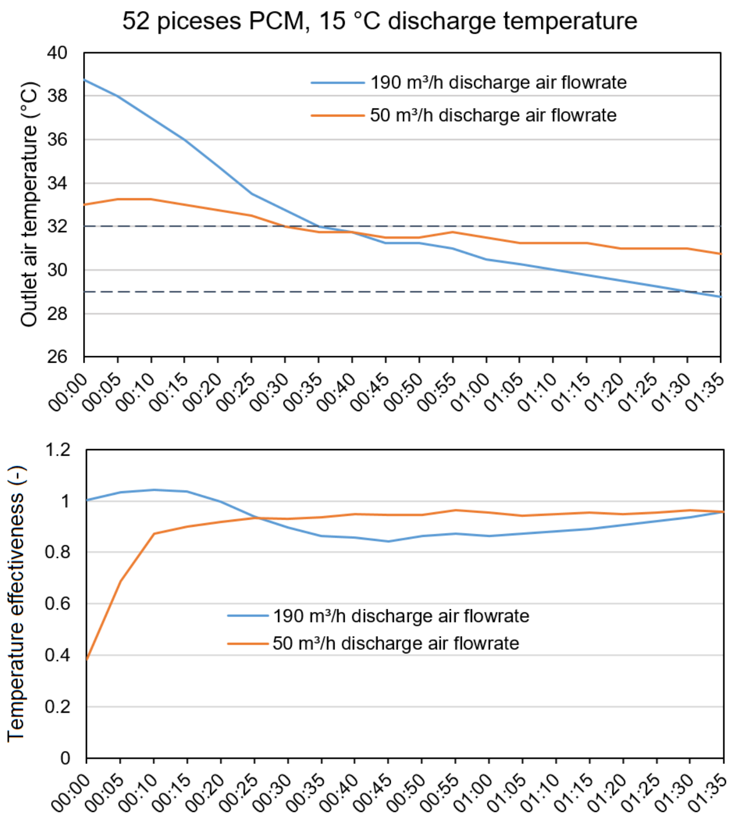


Figure 11. (a) Outlet air temperature and (b) temperature effectiveness of the PCM storage with different discharge inlet flowrates.

3.2.6 The selection of the PCM storage

With more PCM plates, the PCM can store more heat, thus provide a high and stable outlet air temperature during the discharge process. The temperature effectiveness of the PCM storage is also higher. However, it has the drawback of a long charge period and non-simultaneous activation of the PCM in the storage. With fewer PCM plates, the PCM can be charged and discharged faster, but the heat provided in the discharge period is less and in a shorter period, with a lower outlet air temperature and temperature effectiveness in the discharged process (compared to with more PCM plates). This disadvantage is even more outstanding when the discharged air temperature is lower or the discharged airflow rate is higher. The different solutions have different advantages and drawbacks, which makes it essential to choose the right solution for real applications.

The selection of the PCM storage should be based on the purpose of the PCM storage. If the PCM storage needs to be designed for fast response, for example, extra heat supply during the HVAC defrost period, the design of the PCM storage should be with fewer PCM plates. For PCM storage to shift peak hours in the grid, it requires the PCM to be charged/discharged fast, with high and stable outlet air temperature, especially during the discharge period. Medium-sized PCM storage could be the most beneficial one in this case. For the applications where the relatively long charge period can be guaranteed, for example, solar energy storage or plant heat recovery, the more PCM plates in the PCM storage can be a benefit.

4. Modeling energy flexibility

The limitations of the experimental study are that it is time-consuming and hard to make adjustments. Thus further analyses of the applicability of PCM storage integrated with HVAC system and its energy flexibility potential are conducted in the building simulation software EnergyPlus. The Energyplus model simulates the PCM using Conduct Finite Difference algorithm for heat balance modeling. The data from the manufacturer is used as material inputs.

4.1 Model validation

The model validation is done by applying the boundary conditions measured from the experiments to the numerical model, including the inlet air temperature and the airflow rate. The model output of PCM outlet air temperature is then compared to the experimental measurements. The error of the simulation results is calculated by Equation (2). The mean bias error (MBE)[23][24] shows the overall bias in the model by calculating the mean difference between the measured and simulated data, which is calculated by Equation (3). The MBE has the drawback that the negative bias can compensate the positive bias, thus a third index, which is Coefficient of Variation of Root-Mean Squared Error (CV(RMSE)) [23][24] is introduced in Equation (4). The CV(RMSE) defines how well the model fits with the experiment by calculating the offset errors between the simulation data and experiment data.

$$error = \frac{m_i - s_i}{m_i} \tag{2}$$

$$MBE(\%) = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N} m_i} \qquad (3)$$

$$CV(RMSE)(\%) = \frac{\sqrt{\sum_{i=1}^{N}(m_i - s_i)^2 / N}}{\sum_{i=1}^{N} m_i / N} \qquad (4)$$

Where m_i and s_i are the measurement data and the simulated data respectively, N is the total data in the calculated period.

Figure 12 shows the results of the model validation. It is shown that with 52 pieces of PCM plates and 36 pieces of PCM plates, the simulation results have less error than that with 20 pieces of PCM plates. The reason is that in the model, the surface convection coefficients are set as a fixed value for all the cases. However, the PCM storage with 20 pieces of PCM plates may have a smaller surface convection coefficient. Overall, the maximum hourly errors of all the 3 cases are below 15%. The average error of each case is below 5.1%.

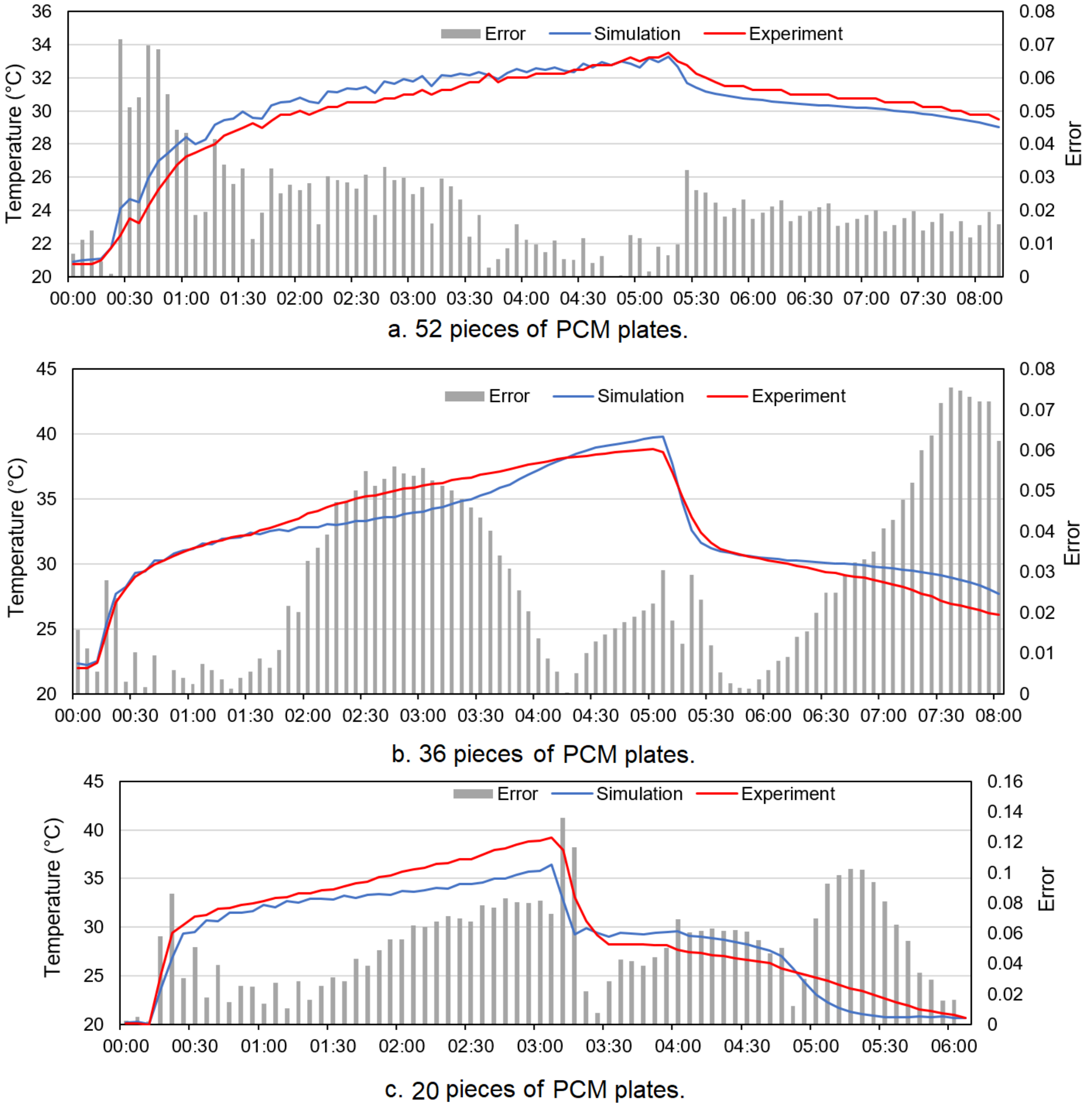


Figure 12. Model validation with different amounts of PCM plates. a. 52 pieces of PCM plates; b. 36 pieces of PCM plates; c. 20 pieces of PCM plates.

Table 2 lists the MBEs and the CV(RMSE)s of the model results compare to the measurement data with different sizes of PCM storage. The MBEs vary from 0.2 to 3.1, while the CV(RMSE)s vary from 2.4 to 6.2. The models with 52 pieces of PCM plates and 36 pieces of PCM plates have smaller MBEs and CV(RMSE)s than the model with 20 pieces of PCM plates. Overall, the model has a high accuracy compared to the measurement.

Table 2. The mean bias error (MBE) and Coefficient of Variation of Root-Mean Squared Error (CV(RMSE)) of the model compared to the measured data.

Number of PCM plates	52	36	20
MBE (%)	0.6	0.2	3.1
CV(RMSE) (%)	2.4	3.4	6.2

4.2 Energy flexibility of HVAC heating setpoint

The energy flexibility of the HVAC system with different heating setpoints without PCM is simulated and analyzed firstly. In this simulation, the electricity price is divided into 3 categories: low price level, where the electricity price is below the lowest quartile of the price in the last two weeks; high price level, where the electricity price is higher than the highest quartile of the price in the last two weeks; medium price level, where the electricity price is between the lowest quartile and the highest quartile of the electricity price in the last two weeks[25][19]. Figure 13 shows the electricity price in the winter of 2019 and the low and high electricity price limits.

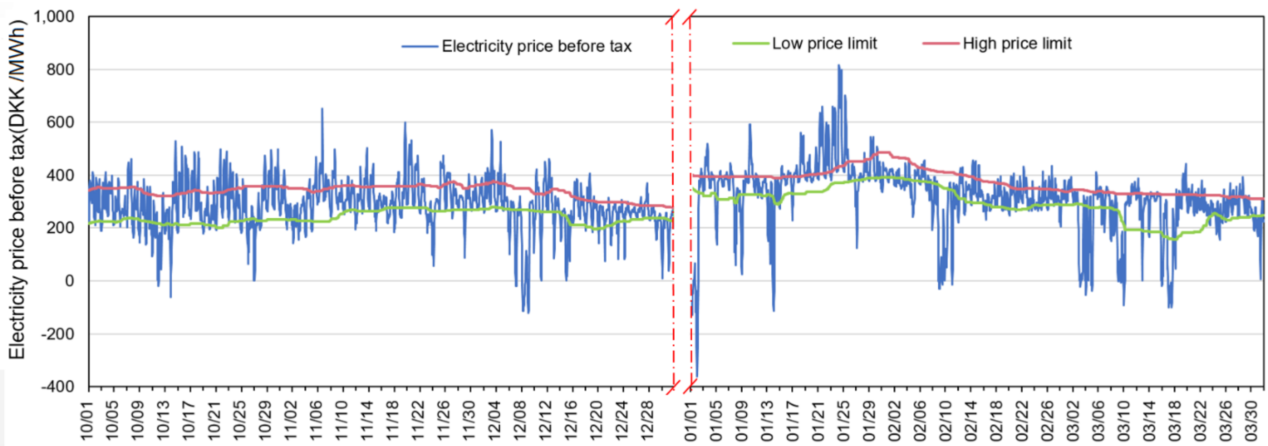


Figure 13. The electricity price before tax in 2019. Source from [26].

Different heating setpoints of the HVAC system based on the electricity price control are studied in this simulation, to analyze the cost-saving potential of the electricity price control. Table 3 shows the 6 cases with different heating setpoints for different electricity prices. As a reference case, case 1 has the setpoint of 24°C for all the electricity price levels. Cases 2 and 3 have the same medium price setpoint, but a high heating setpoint when the electricity price is low, and a low heating setpoint when the electricity price is high. The thermal comfort of all the cases should be similar so that the energy consumption of different cases could be comparable. The predicted percentage of dissatisfied (PPD) is used to calculate how much percentage people are feeling comfortable in different cases.

Table 3. The heating temperature setpoint of different cases for energy flexibility control.

	Case 1	Case 2	Case 3	Case 4	Case 5
High price setpoint	24	22	23	22	23
Medium price setpoint	24	24	24	24	24
Low price setpoint	24	26	25	24	24

The energy consumption and energy cost of different cases are calculated and compared. The energy cost

$$Energy\ cost = \int Q \cdot 2.77778 \cdot 0.0000001 \cdot \frac{Ep + E_{transmission+tax}}{1000}\, dt \text{ [DKK]}$$

Where *Ep* is the electricity price before tax [DKK/MWh], which is shown in Figure 13;

Q is the energy consumption of the HVAC system in [MWh];

$E_{transmission+tax}$ is the transmission and tax costs per kWh electricity:

$$E_{transmission+tax} = 0.224[\text{EUR / kWh}] = 1680[\text{DKK / MWh}]$$

The value of electricity transmission and tax $E_{transmission+tax}$ comes from the statistics from 2018[19]. It takes 80% of the electricity price in Denmark and does not variate during the year.

Figure 14 shows the energy consumption and energy costs of cases with different heating setpoints. Figure 15 shows the energy savings and energy cost savings of all cases compare to case 1. It is seen that compared to case 1, all the other cases can save energy use and energy cost, except case 3. Case 3 has a higher energy use than case 1, but the energy cost of case 3 is lower than case 1. It is because case 3 uses more energy when the electricity price is low, and less energy when the electricity price is high compared to case 1, so the energy cost is lower even though the energy use is higher than case 1.

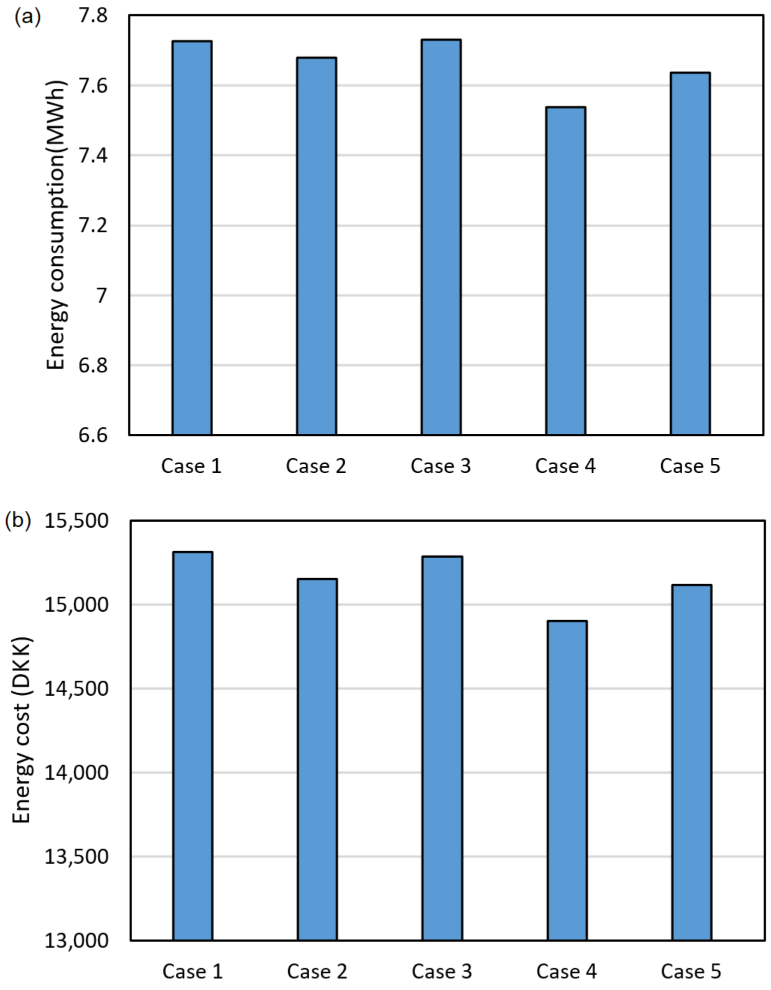


Figure 14. The heat pump energy use and energy cost of different cases for energy flexibility control.

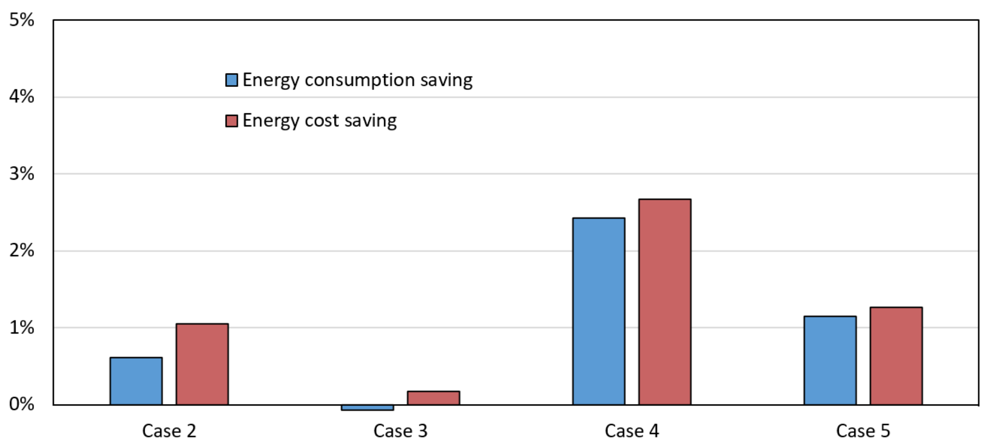


Figure 15. The energy and cost saving percentage of different cases with energy flexibility control compared to the reference case.

Another important parameter when comparing different setpoint controls is the thermal comfort of the room. It is calculated by how much percentage of people feel comfort under different cases. According to ASHRAE Standard[27], more than 80% of the people should be satisfied. The results of comfort percentage in Figure 16 shows that compared to case 1, all the other cases have similar thermal comfort percentages, especially for case 3 and case 5. For case 2 and case 4, the thermal comfort percentage drops 2%. For case 3 and case 5, the thermal comfort percentage drops 1%.

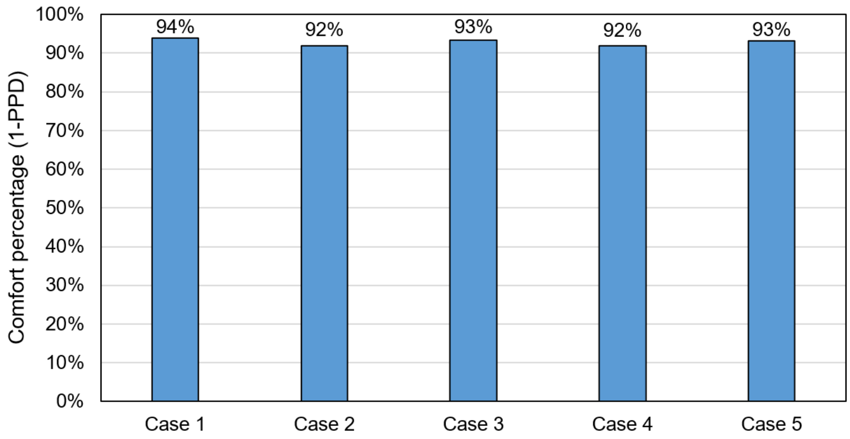


Figure 16. The thermal comfort percentage of the room with different heating setpoints in different cases.

The energy cost saving can be achieved by electricity price control. However, the cost saving percentages are not significant for all the studied cases, due to the high electricity transmission and tax cost.

4.3 Energy flexibility of the PCM storage integrated with HVAC system

The PCM storage integrated with HVAC system is simulated a bit differently than the system conception in section 2, to simplify the model in EnergyPlus. Figure 17(a) shows the model description of the heat pump integrated with PCM storage and electricity price control strategy. The PCM box is charged with 35 °C warm air from the heat pump through a virtual zone when the electricity price is low. The virtual zone is named hotbox, with adiabatic boundary conditions, to simulate the air distribution ducts from the heat pump to the PCM box in the real system. When the electricity price is high, then the heat pump stops charging the PCM. Instead, the PCM storage is used to heat the outdoor air before supply it to the room. During this process, the room temperature is guaranteed by an auxiliary power supply from the heat pump, in case the room air temperature drops below 22°C. The reference case, shown in Figure 17(b), includes a heat pump and an outdoor air system. The room temperature setpoint is 22°C when the electricity price is higher than the medium piece limit, and 24°C when the electricity price is lower than the medium price limit. The medium price limit here is defined as the first two quartiles of the last two weeks' electricity price, which is shown in Figure 18.

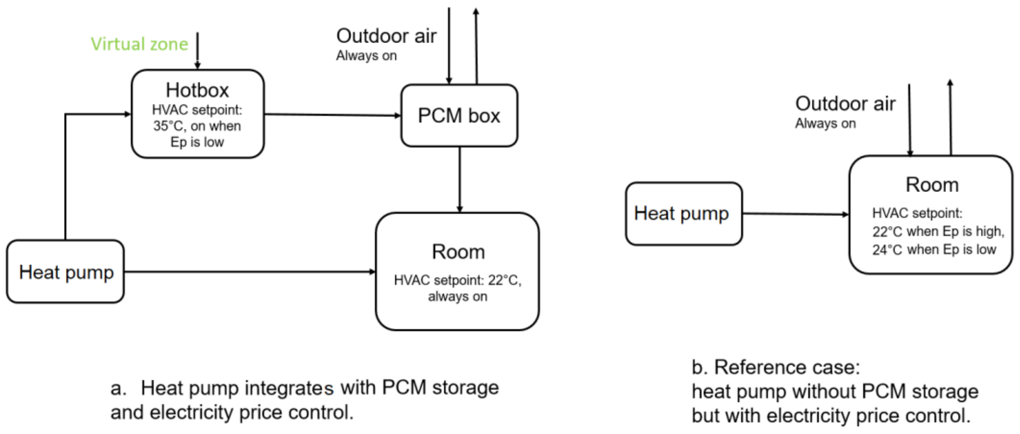


Figure 17. System description of the PCM integrated with a.HVAC system and b.reference case.

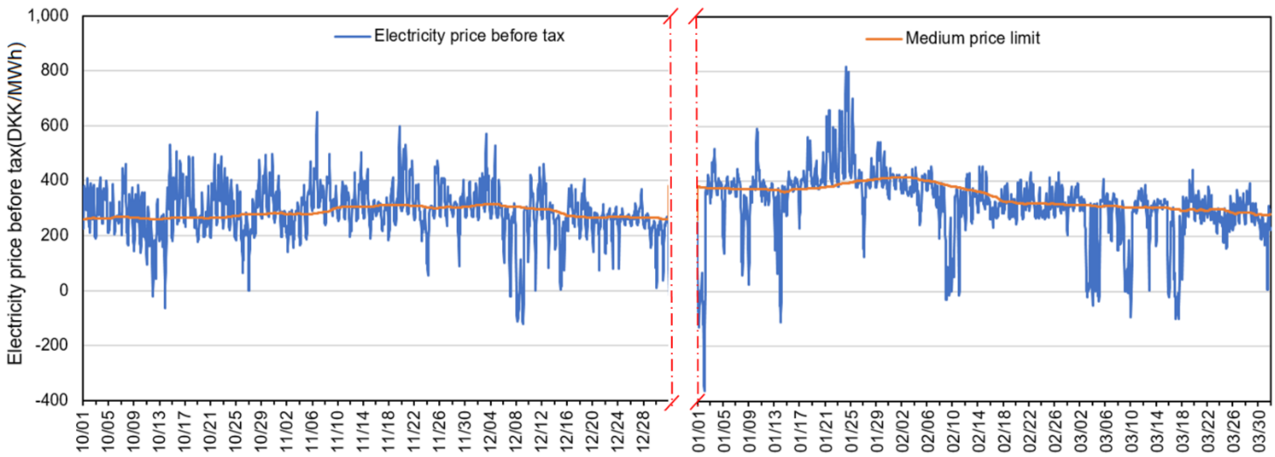


Figure 18. The medium price limit of the electricity price based on the last two weeks' electricity price.

Figure 19 shows the hourly electricity cost of the HVAC systems with PCM and without PCM. The price level is defined as 1 if the electricity price is higher than the medium price limit, and 0 if the electricity price is lower than the medium price limit. It is shown in Figure 19(b) that when the electricity price is low, the HVAC with PCM has more electricity consumption than the HVAC without PCM, due to the high-temperature air needed to charge the PCM; when the electricity price is high, the HVAC with PCM has less electricity consumption than the HVAC without PCM, because that the PCM releases heat to the ventilation.

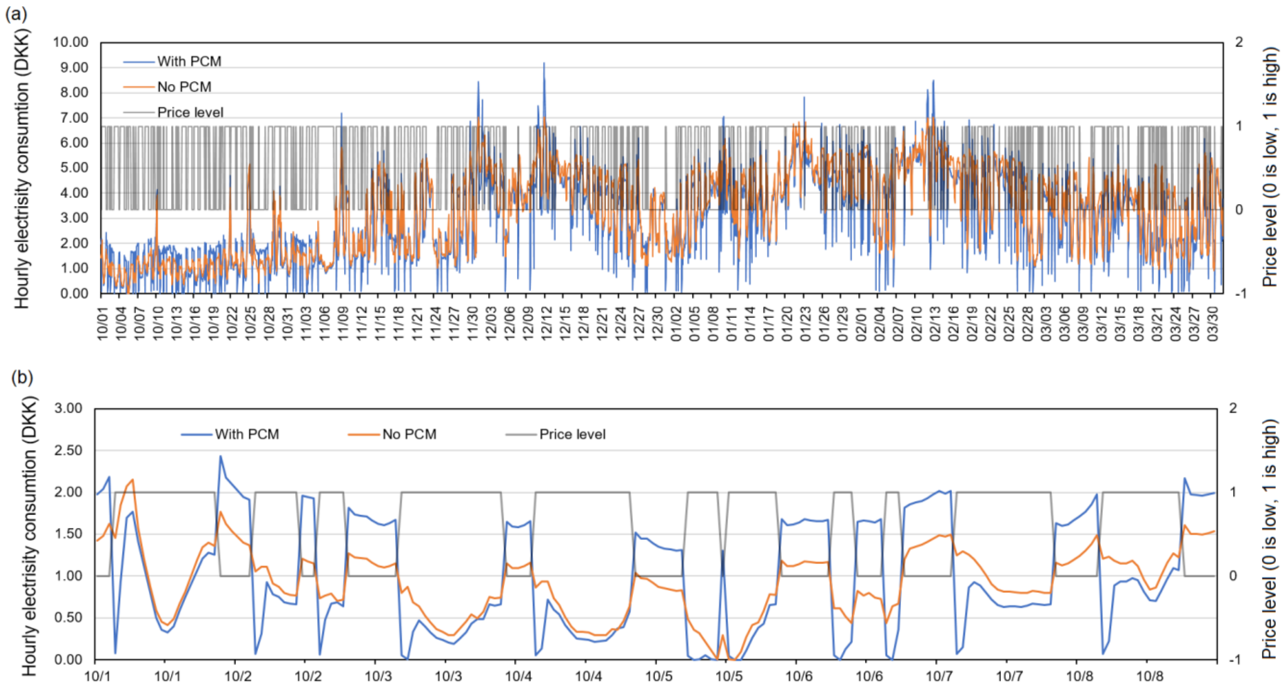


Figure 19. Hourly electricity cost of the HVAC systems with PCM and without PCM.

Table 4 compares the energy use and thermal comfort of the two HVAC systems with PCM and without PCM. With PCM storage, the energy consumption is decreased by 6.7 % compared to without PCM storage. The energy cost is decreased by 6.9 %. The thermal comfort levels of the 2 systems are similar, and the system with PCM has 1% fewer people feel comfortable. The PCM storage integrated with HVAC system has the potential to save building energy and guarantee good indoor thermal comfort even with high transmission and tax rates for electricity.

Table 4. The energy-saving potential and thermal comfort of HVAC system with PCM compares to the HVAC system without PCM.

	No PCM	PCM	Improvement with PCM
Consumption (MWh)	7.3	6.8	6.70%
Cost (DKK)	14447	13445	6.90%
Thermal comfort percentage (%)	90	89	-1%

5. Conclusions

The study of the PCM storage integrated with HVAC system for energy flexibility is done by both experimental and numerical study.

The experimental study aimed for the design optimization of the PCM storage based on the study of the heat transfer mechanism in the PCM storage unit during the charge and discharge periods. The experimental study includes the temperature in the PCM storage, the impact of the PCM amount on the charge and discharge processes, the impact of discharge inlet air temperature and airflow rate on the discharge process, and has the conclusions that:

1. The more the PCM plates, the more latent heat provided by the PCM storage, but the longer the charge and discharge time required for the PCM storage. The PCM close to the inlet charges/discharges faster than the PCM closer to the outlet. The air path in the PCM storage should not be too long to achieve the most PCM activation.

1. The fewer the PCM plates, the shorter time it takes to charge and discharge the PCM, but the outlet air temperature from the PCM storage is less stable and lower than the PCM freezing temperature for most of the discharge time.
2. The lower the discharge inlet air temperature, the less time it takes to discharge the PCM; the lower the airflow rate, the longer it takes to discharge the PCM. The temperature effectiveness depends more on the airflow rate than the discharge inlet air temperature.
3. The different solutions have different advantages and drawbacks, which makes it essential to choose the right solution for real applications based on their purpose. The design of the PCM storage should be with fewer PCM plates if the PCM storage needs to have a fast response for both charge and discharge periods, for example, extra heat supply during the HVAC defrost period. A medium-sized PCM storage is recommended for applications where PCM should be charged/discharged fast, with high and stable outlet air temperature especially during the discharge period, in the case of peak hour shifting of the grid. A bigger-sized PCM storage is recommended when the relatively long charge period can be guaranteed, for example, solar energy storage or plant heat recovery.

A medium-sized PCM storage is chosen for the simulation work, considering its relatively high-temperature effectiveness, fast charging ability, and high and stable heat supply during the discharge period. The experimentally verified EnergyPlus model simulates the performance of the electricity price control for peak hour shifting of the electric grids and the energy-saving potential of the PCM storage integrated with heat pump system and has the conclusions that:

1. The HVAC heating setpoint control based on the electricity price without PCM storage has the energy-saving potential without reducing room thermal comfort, but the energy-saving amount is limited due to the high electricity transmission and tax cost.
2. The PCM storage integrated HVAC system is efficient to shift the peak hour load of the grid. Compared to the HVAC heating setpoint control based on the electricity price without PCM storage, the system saves 7 % energy bills while obtaining a similar indoor thermal comfort level.

Further work includes the night cooling effect of the PCM storage integrated with heat pump system during summer.

Acknowledgment

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8.2 Article – HVAC 1

Stabilt indeklima: Nyt køleloft med indbygget varmepumpe og energilager kan fastlåse indblæsningstemperaturen og sikre konstant temperatur

Af: Babette Peulicke Slott, energiantropolog ved Teknologisk Institut og Mie Falck, konsulent ved Teknologisk Institut

Et nyt køleloft kan sikre stabilt og energieffektivt indeklima på hospitaler og i klasseværelser. Køleloftet kombinerer ventilation, køling og varme i én integreret løsning.

At sikre et stabilt indeklima, som samtidig er energieffektivt, er en kompleks opgave. Det gælder særligt på hospitaler, hvor kravene er skærpede: Her skal udsving i temperaturen være ekstremt begrænsede. En løsning, der kan dække hospitalers behov kan samtidig være brugbar for en lang række andre institutioner. Det gælder eksempelvis folkeskoler, som generelt oplever tilbagevendende indeklimaudfordringer.

Netop dette var baggrunden for et nyt forskningsprojekt med JS Ventilation, Neogrid Technologies, Teknologisk Institut og Aalborg Universitet som projektpartnere. Virksomheden havde allerede udviklet køleloft med hybrid ventilation og intelligent styring, men så et behov for mere komplekse løsninger, der også kunne indeholde opvarmning. I projektet ville man derfor videreudvikle teknologi fra eksisterende kølelofter og udvikle en ny type køleloft med ventilationsaggregat, indbygget varmepumpe og energilager.

Udfordringen

Den store udfordring er de skærpede krav til indeklima på hospitaler, herunder sengeafsnit og operationsstuer: Indblæsningstemperaturen må højst svinge med +/- 1 grad. Hen over en hel dag vil temperaturen gradvist ændre sig, men hurtige, kortvarige svingninger må ikke opstå.

Det kræver derfor, at man kan fastlåse indblæsningstemperaturen og sikre en konstant temperatur. Med en varmepumpe er det en udfordring, da den med jævne mellemrum skal afrimes. Når det sker, slukker pumpen og ventilationen kører kortvarigt alene. Selvom der er tale om en begrænset periode, kan temperaturen alligevel nå at falde markant – helt op til 5 grader. Det er særligt et problem, når varmepumpen skal præstere meget som eksempelvis i opvarmningsperioden om vinteren med lav udetemperatur.

Løsningen

At fastholde en stabil indblæsningstemperatur med en varmepumpe var derfor omdrejningspunktet for projektet. Her demonstrerede partnerne, hvordan løsningen kan være at kombinere ventilationsaggregat og indbygget varmepumpe med et faseskiftende energilager.

Energilageret er et eksternt modul, der sidder separat fra ventilationsaggregatet. Under normal drift sendes hovedmængden af den opvarmede luft til lokalet samtidig med at en mindre del dirigeres til energilageret, som dermed løbende varmes op. Når varmepumpen slukker for at afrime omdirigeres den samlede mængde luft, så den først passerer gennem energilageret inden den blæses ind i lokalet. Energilageret sikrer på den måde, at luften fastholder den samme temperatur – selv når varmepumpen ikke er aktiv. Hele processen varer omkring et minut inden varmepumpen igen går i gang.

Særligt energilageret har været nyt at arbejde med. Lageret består af firkantede blokke på 10-15 mm tykkelse indeholdende en saltopløsning. Disse stables i en mængde, der passer til luftstrømmen i det pågældende ventilationssystem. Saltopløsningen skifter fase fra flydende til fast omkring 35 grader. Opløsningens særlige egenskaber betyder at temperaturen kan fastholdes selv mens der frigives energi.

Når det faseskiftende materiale går fra fast til flydende form, kræver selve faseskiftet en stor mængde energi. På samme bliver der frigivet en lige så stor energimængde når materialet igen går fra flydende til fast form. Man kan altså oplade energibatteriet ved at smelte det faseskiftende materiale, og aflade det ved at lade det stivne.

Fordelene ved den nye løsning

Fordelene ved den nye løsning er mange.

"Det at vi kan fastlåse indblæsningstemperaturen er unikt. Hurtige temperatursvingninger kan derfor undgås og det betyder helt konkret at hospitalerne vil kunne få stor gavn af løsningen" forklarer Kim Kronby fra JS Ventilation.

iCeiling kan også anvendes i skoler og den kan anvendes meget lokalt som for eksempel i et enkelt problematisk klasseværelse eller på en enkelt hospitalsstue. Der er en fleksibel løsning, der også kan styre luftmængden efter den aktuelle elpris. Derudover er det en fordel, at der er tale om én samlet løsning, som er plug-and-play.

"Ventilationsanlægget med kølevarmepumpe skal bare i stikkontakten. Med konventionelt anlæg skal der også tilslutning til varmeanlæg og eventuelt køling. Det undgår man her" forklarer han videre.

Da løsningen er en videreudvikling af Cool Ceiling kan det klare et stort kølebehov, fordi det både kan opleves køling fra selve ventilationen og via strålingskøling fra loftet. Det betyder, at man kan køle mere uden indeklimagener, og samtidig holde en lav byggehøjde.

Projektet afsluttes i sommeren 2021 og er støttet af EUDP under projekt nr. 64 018-0612.

8.3 Article – HVAC 2

Intelligent styring og energilager kan skabe energifleksibel ventilation i praksis

Af: Babette Peulicke Slott, energiantropolog ved Teknologisk Institut og Mie Falck, konsulent ved Teknologisk Institut

Ved hjælp af eksternt energilager og intelligent styring sikres både energifleksibel drift og et stabilt indeklima.

Et forskningsprojekt med projektpartnerne JS Ventilation, Neogrid Technologies, Teknologisk Institut og Aalborg Universitet som projektpartnere har i løbet af de seneste år udviklet et nyt køleloft, som kombinerer ventilation, køling og varme i én integreret løsning. Køleloftet skal sikre stabilt og energieffektivt indeklima på blandt andet hospitaler ved at kombinere ventilationsaggregat med en varmepumpe.

Det er en kompleks udfordring på grund af varmepumpen: Med mellemrum skal pumpen afrime, hvilket betyder at den slukker. Selvom der kun er tale om en kort periode kan temperaturen blive påvirket ganske markant.

Det nye køleloft
Løsningen blev en kombination af et eksternt energilager og en intelligent styring.
Energilageret er et eksternt modul, der sidder separat fra ventilationsaggregatet. Under normal drift sendes hovedmængden af den opvarmede luft til lokalet samtidig med at en mindre del dirigeres til energilageret, som dermed løbende varmes op. Når varmepumpen slukker for at afrime, omdirigeres den samlede mængde luft, så den først passerer gennem energilageret inden den blæses ind i lokalet. Energilageret sikrer på den måde, at luften fastholder den samme temperatur – selv når varmepumpen ikke er aktiv. Hele processen varer omkring et minut inden varmepumpen igen går i gang.

Styring med intelligens på flere niveauer
Kompleksiteten i ventilationsløsningen kræver en intelligent styring. I projektet er Neogrid ansvarlig for at etablere kommunikation med ventilationssystemet, hvilket indebærer indeklimasensorer, at etablere dataopsamling og cloudforbindelse.

"Vi ville lave en ventilationsløsning, der er intelligent. Med intelligent mener vi, at den er cloudforbundet, så der kan udveksles data. Det betyder, der løbende kan optimeres i forhold til indeklima og energi" fortæller Pierre Vogler-Finck, Forsker hos Neogrid og med en PhD. i energioptimering af bygninger.

"Vi vil gerne hen mod mere datadrevet drift. Det er den tilgang, der adskiller sig fra CTS, som har været mere automatikfokuseret" fortsætter han.

Styringen afgør positionen af spjældene og kontrollerer indblæsningstemperaturen med udgangspunkt i flere parametre herunder varmepumpen, indeklimadata fra sensorer samt luftmængden i køleloftet. Der er tale om en intelligent, fleksibel løsning på flere måder. Energilageret tilføjer en anden dimension af intelligens end man normalt ser: Selve lageret består af en faseskiftende saltopløsning, der kan fastholde temperaturen selv når varmepumpen ikke er aktiv. Det betyder, at man i praksis får en energifleksibel ventilationsløsning. Det underbygges yderligere af, at der også kan styres efter prissignaler. Det gælder både den aktuelle elpris og den forventede.

Teknologi
For at kunne lykkes med at lave en effektiv intelligent styring var det afgørende at finde den rigtige varmpumpe. Det krævede for eksempel en model, hvor kompressoren ikke kun har indstillingerne on/off, men kunne styres trinløst.

"Kernen var, at vi skulle bruge helt standardløsninger, men anvende dem anderledes. Vores usecases er noget andet end man er vant til, så vi skulle få det til at hænge sammen med fabrikantens specifikationer uden at det er for stort et indgreb" forklarer Pierre Vogler-Finck.

At designe det faseskiftende energilager var også kompliceret. Der skulle en del forsøg til for at få finde den optimale størrelse på lageret. Det endte med at blive en afvejning mellem tryktab og kapacitet. Hvis man øger kapaciteten, øger man også tryktabet.

Datadrevet bygningsdrift kræver åbne systemer
Projektet demonstrerer hvordan datadrevet bygningsdrift – særligt i forhold til ventilation – gør det muligt at opdage fejl og regulere løbende. Det kræver dog teknologier, der giver mulighed for styring som denne. De fleste anlæg er ikke tænkt til at blive anvendt sådan. Hvis der i fremtiden skal flere løsninger som denne på markedet, er det vigtigt, at de anlæg, der udvikles, er tænkt til at interagere med andre systemer.

"Der skal ikke tænkes i isolerede, enkeltstående løsninger. Hvordan kan det her produkt være en god brik i en kombination med andre? Ansvarsfordeling og datadeling er kompliceret, så hvis vi skal have flere åbne systemer, kræver det en kulturændring" siger Pierre Vogler-Finck.

Projektet afsluttes i sommeren 2021 og er støttet af EUDP under projekt nr. 64 018-0612.

8.4 Dimensioning tool guide

Dimensioneringsværktøjet kan simulere indeklima og energiforbrug på rumniveau, og sammenligne forholdene for hybridventilation og traditionel ventilation med PCM varmelager.

Beregningerne er forsimplede for at reducere kompleksiteten af inputdata for på den måde at gøre programmet lettere tilgængeligt. Dette gør, at beregningerne er lavet ud fra en række antagelser, herunder at bygningen optager og afgiver varme på timebasis. Luftmængden og indblæsningstemperaturen bestemmes ud fra den samlede varmebalance.

Programmet startes ved at åbne filen Simuleringsprogram.xlsm og trykke på startknappen. For at køre programmet er det nødvendigt at have Microsoft Excel installeret og give tilladelse til at køre makroer.

8.4.1 Forside

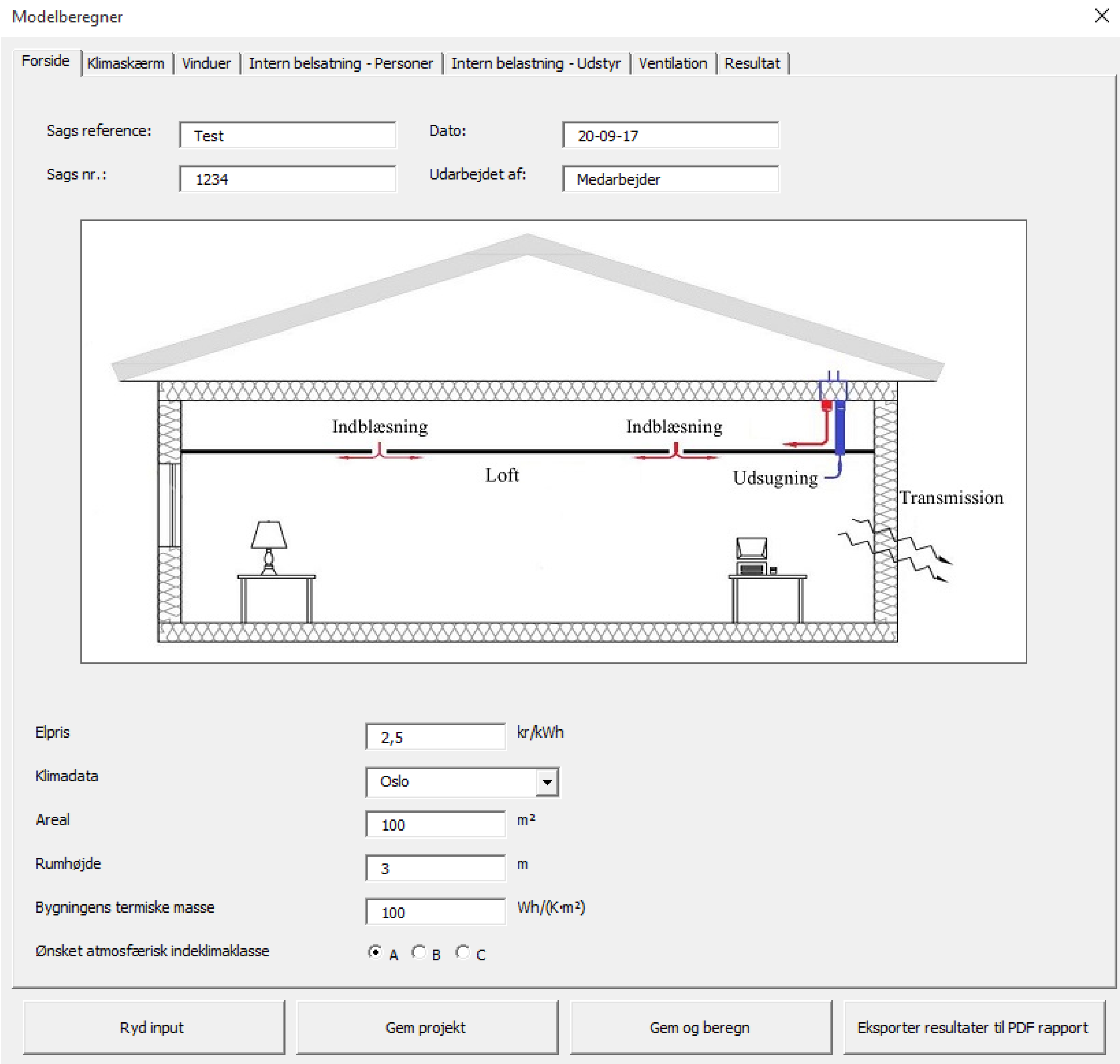
På forsiden indtastes sagsnavn, sagsnr., dato, gennemsnitlig elpris, rummets areal, højde og bygningens termiske masse. Ydermere vælges der, hvilke klimadata som ønskes anvendt og den ønskede atmosfæriske indeklimaklasse. I version 1.0 er det muligt at vælge klimadata fra København, Oslo og München.

Bygningens termiske masse beskriver hvor meget energi der kan lageres i bygningen. Som udgangspunkt benyttes nedenstående værdier:

Beskrivelse	**Indvendige konstruktioner**	**Varmekapacitet Wh/(k·m²)**
Ekstra let	Lette vægge, gulve og lofter, f.eks. skelet med plader eller brædder, helt uden tunge dele	40
Middel let	Enkelte tungere dele, f.eks. betondæk med trægulv eller porebetonvægge	80
Middel tung	Flere tunge dele, f.eks. betondæk med klinker og tegl- eller klinkebetonvægge	120
Ekstra tung	Tunge vægge, gulve og lofter i beton, tegl og klinker	160

Tabel 1 – Kilde: SBI anvisning 213

Det ønskede atmosfæriske indeklima bestemmer den minimale tilførsel af friskluft. Indeklimaklasse A svarer til 36 m^3/h, indeklimaklasse B til 25 m^3/h og indeklimaklasse C til 14 m^3/h. Denne valgte luftmængde vil blive tilført når ventilationsanlægget er tilgængeligt.

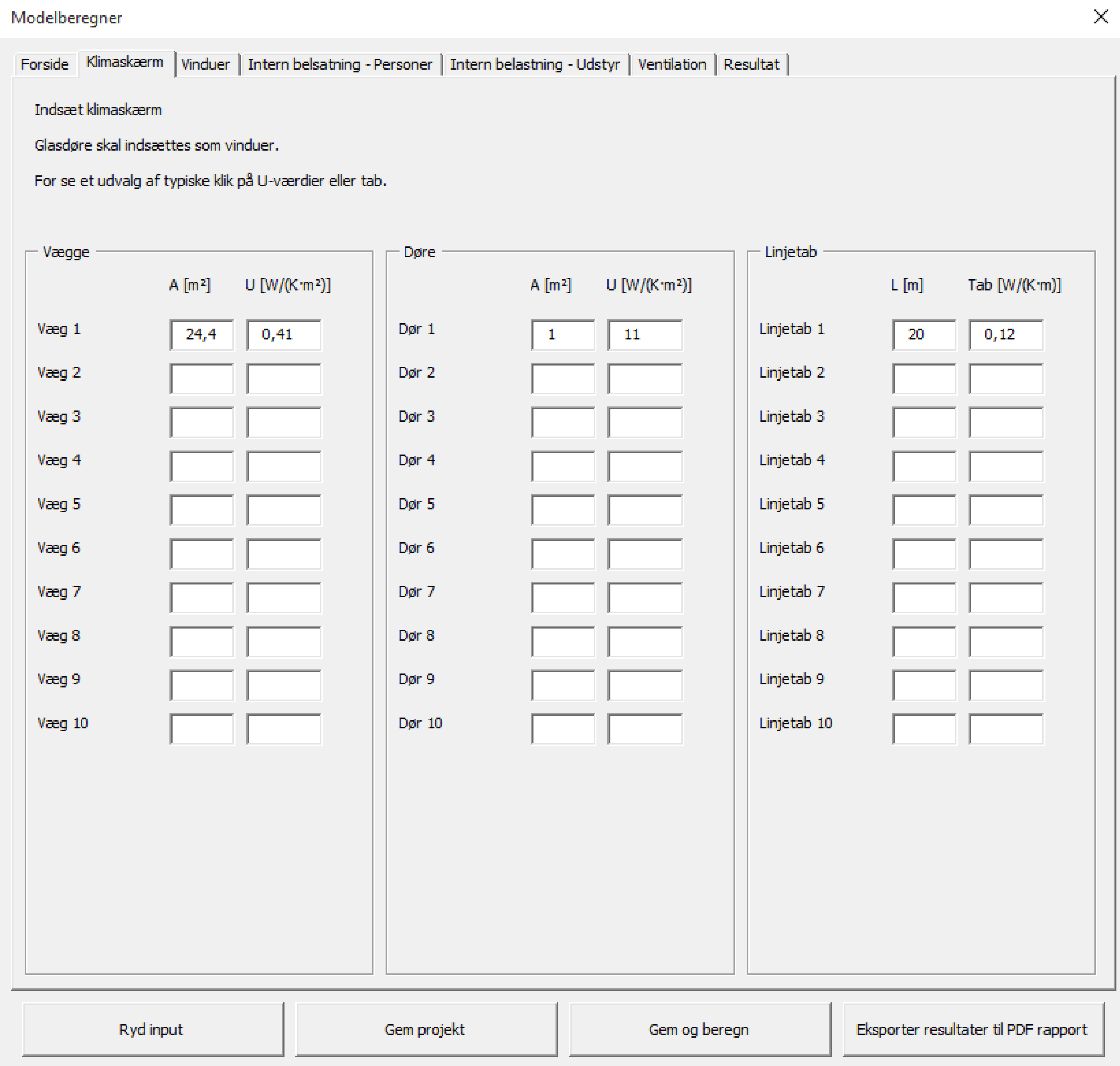

Modelberegner
Forside
Klimaskærm
Vinduer
Intern belsatning - Personer
Intern belastning - Udstyr
Ventilation
Resultat
Sags reference:
Test
Dato:
20-09-17
Sags nr.:
1234
Udarbejdet af:
Medarbejder
Indblæsning
Indblæsning
Loft
Udsugning
Transmission
Elpris
2,5
kr/kWh
Klimadata
Oslo
Areal
100
m²
Rumhøjde
3
m
Bygningens termiske masse
100
Wh/(K·m²)
Ønsket atmosfærisk indeklimaklasse
A
B
C
Ryd input
Gem projekt
Gem og beregn
Eksporter resultater til PDF rapport

8.4.2 Klimaskærm

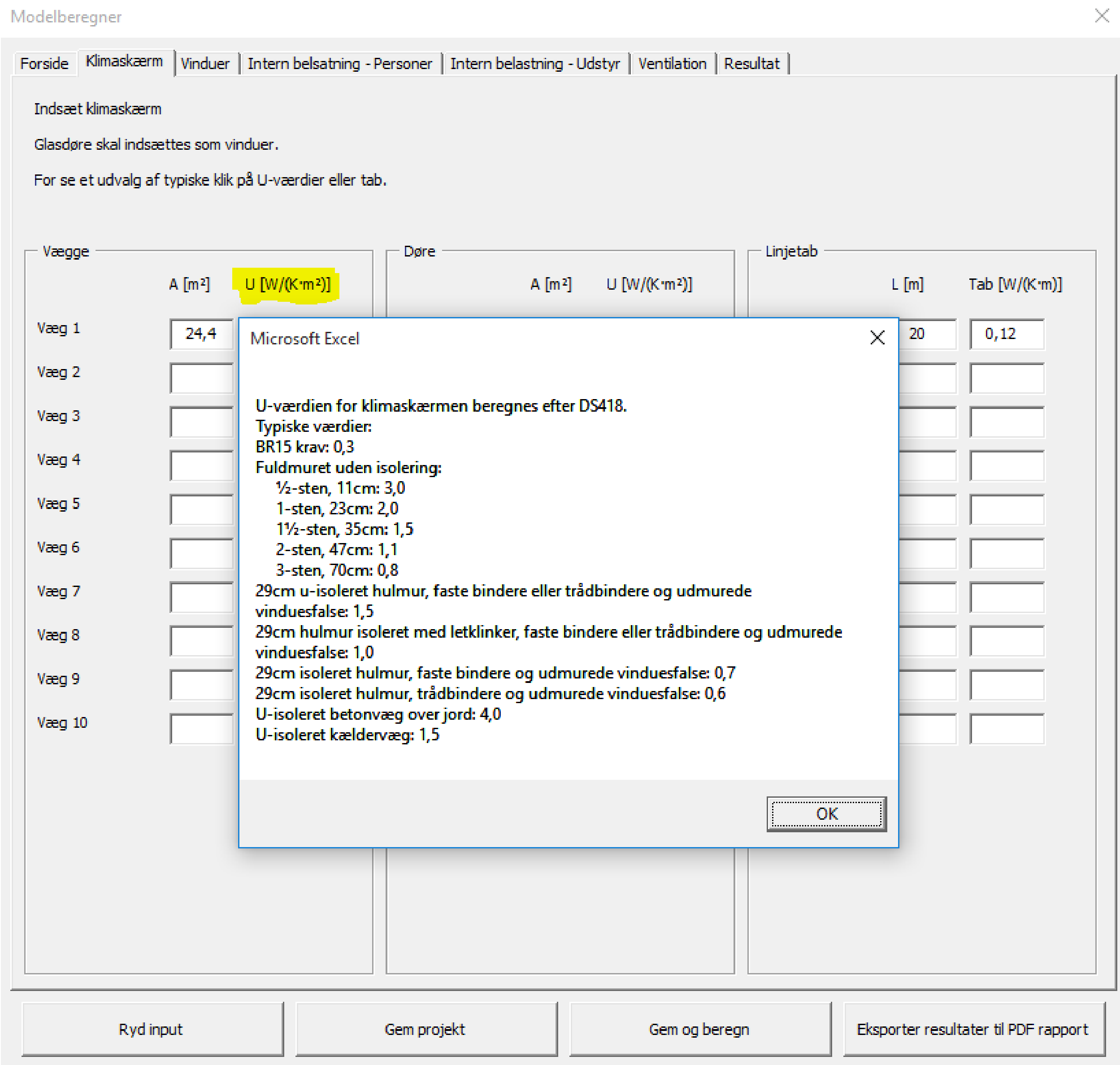
Under fanebladet Klimaskærm defineres klimaskærmen. Alle ydervægge indtastes med et areal og en U-værdi. Indvendige vægge medtages ikke, da disse antages at være adiabatiske, dvs. uden varmetransmission eller varmeoptag.

Døre indtastes ligeledes med et areal og en U-værdi. Såfremt der er glasdøre skal disse indtastes som vinduer for at medtage solindfaldet.

Linjetab indtastes med en længde og et tab. Linjetab og U-værdier beregnes efter DS418.



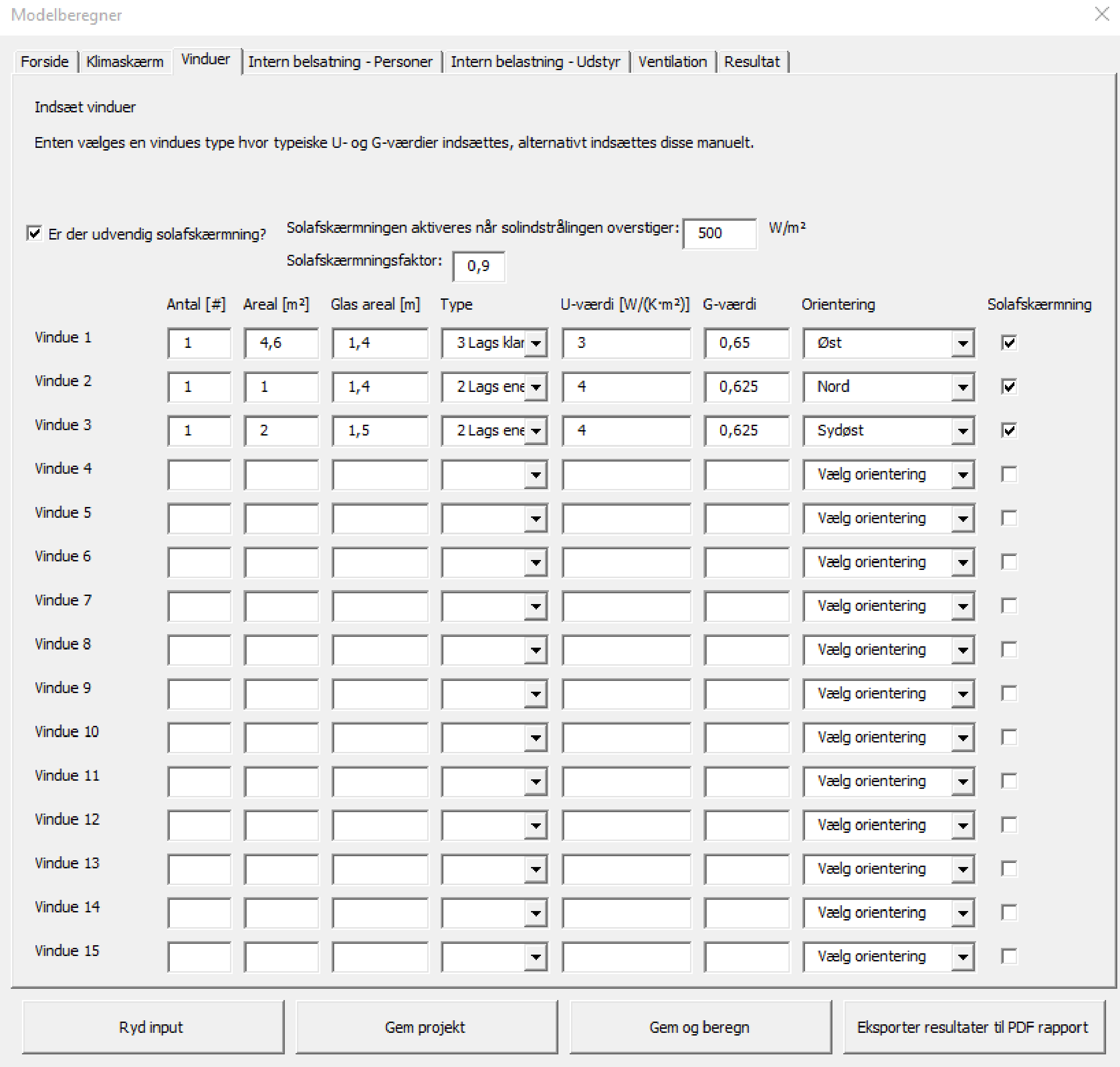
Kendes U-værdier eller tab ikke kan en række typiske værdier vises ved at trykke på teksten af værdien, markeret med gul på nedenstående skærmbillede.


Modelberegner
Forside
Klimaskærm
Vinduer
Intern belsatning - Personer
Intern belastning - Udstyr
Ventilation
Resultat
Indsæt klimaskærm
Glasdøre skal indsættes som vinduer.
For se et udvalg af typiske klik på U-værdier eller tab.
Vægge
A [m²]
U [W/(K·m²)]
Døre
A [m²]
U [W/(K·m²)]
Linjetab
L [m]
Tab [W/(K·m)]
Væg 1
24,4
20
0,12
Væg 2
Væg 3
Væg 4
Væg 5
Væg 6
Væg 7
Væg 8
Væg 9
Væg 10
Microsoft Excel
U-værdien for klimaskærmen beregnes efter DS418.
Typiske værdier:
BR15 krav: 0,3
Fuldmuret uden isolering:
½-sten, 11cm: 3,0
1-sten, 23cm: 2,0
1½-sten, 35cm: 1,5
2-sten, 47cm: 1,1
3-sten, 70cm: 0,8
29cm u-isoleret hulmur, faste bindere eller trådbindere og udmurede vinduesfalse: 1,5
29cm hulmur isoleret med letklinker, faste bindere eller trådbindere og udmurede vinduesfalse: 1,0
29cm isoleret hulmur, faste bindere og udmurede vinduesfalse: 0,7
29cm isoleret hulmur, trådbindere og udmurede vinduesfalse: 0,6
U-isoleret betonvæg over jord: 4,0
U-isoleret kældervæg: 1,5
OK
Ryd input
Gem projekt
Gem og beregn
Eksporter resultater til PDF rapport

8.4.3 Vinduer

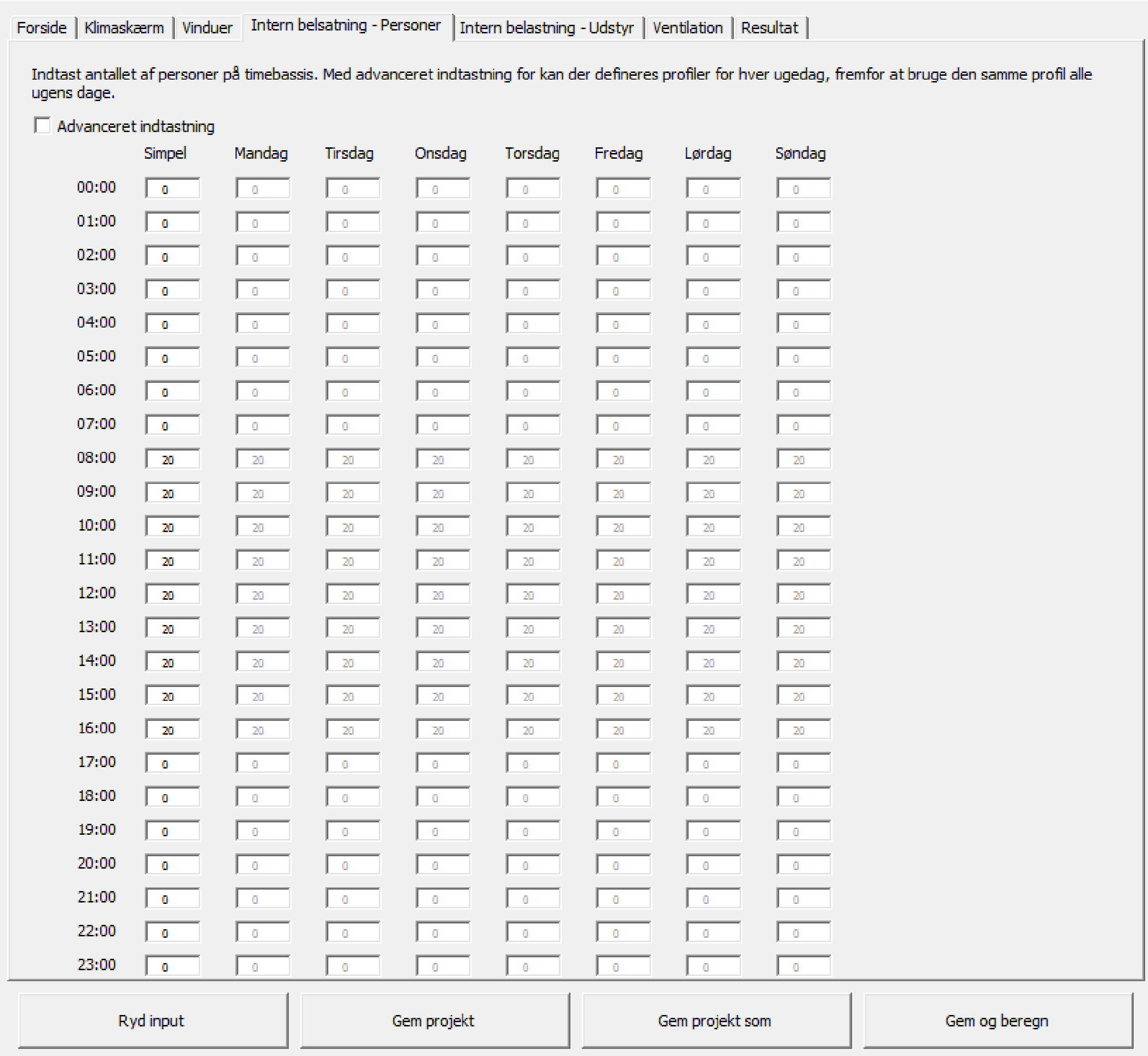
Under fanebladet Vinduer indsættes alle vinduer og glasdøre. For hver indtastning er det muligt at definere hvorvidt der er solafskærmning. For at beregne transmissionstab og solindfald kræves meget data for hver type vindue, - alle disse data kan oplyses af producenten. Ved at trykke på U-værdi eller G-værdi åbnes et popup vindue med standard værdier. Alternativt kan der vælges en bestemt vinduestype. Gøres dette bliver U-værdi og G-værdi automatisk udfyldt.

Hvis solafskærmning vælges vil den automatisk blive aktiveret når solindfaldet overstiger den valgte grænse. Solafskærmningsfaktoren angiver hvor stor en andel af solindfaldet der bliver afskærmet. Med en solafskærmningsfaktor på 0,9, som vist i nedenstående figur, vil kun 10% af varmen fra solen blive lukket ind i rummet.



8.4.4 Intern belastning fra personer og udstyr

På fanerne Intern belastning angives det interne varmetilskud fra personer og udstyr. Personbelastningen indtastes som antal personer og udstyret indtastes i Watt. Der indtastes på timebasis for på den måde at kunne simulere en varierende belastning. Hvis "Avanceret indtastning" vælges kan belastningen defineres for hver dag i ugen, og hvis denne mulighed fravælges benyttes den samme profil hver dag.



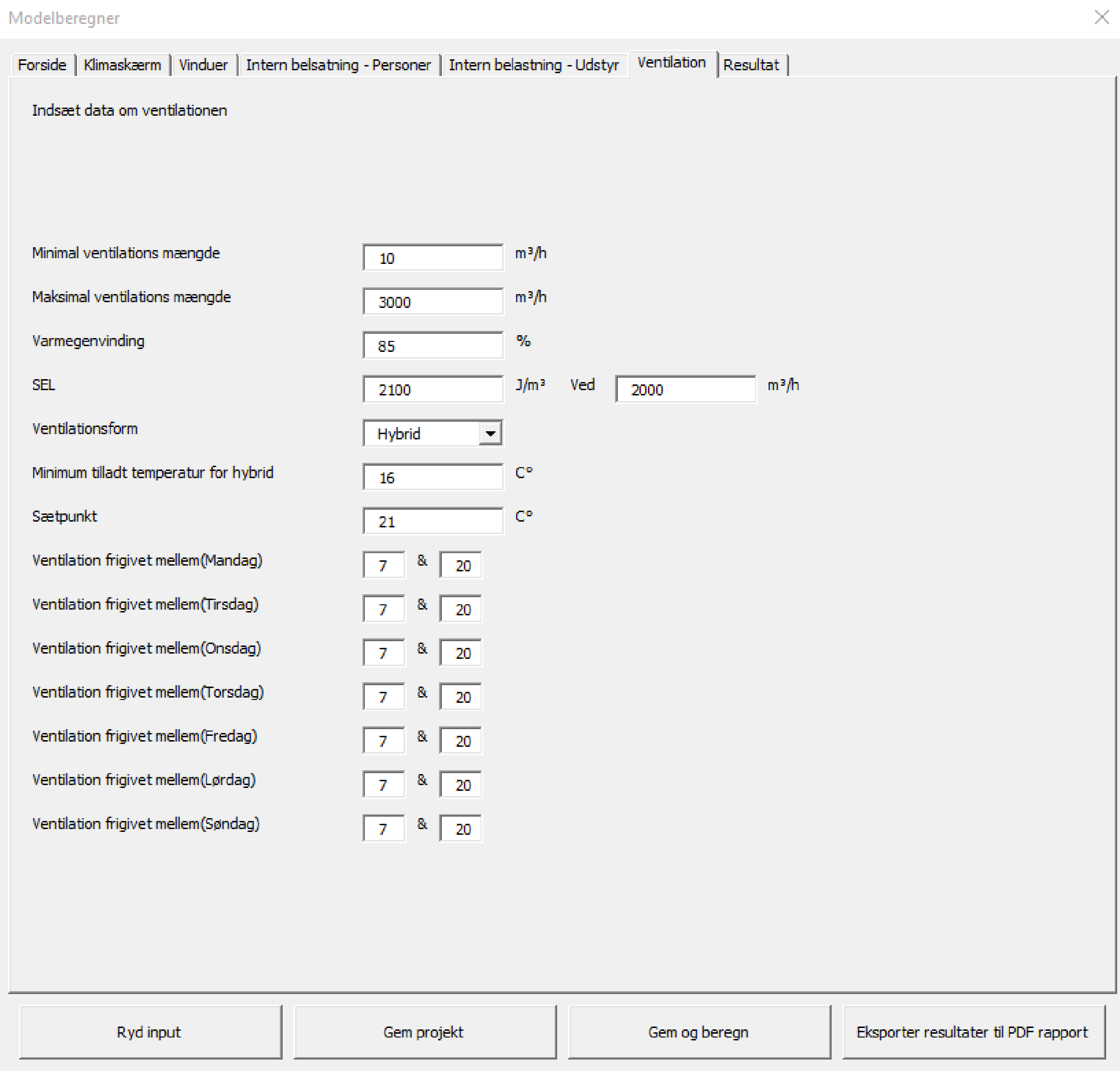
8.4.5 Ventilation

Under fanen Ventilation indtastes data for ventilationsanlægget. Kapaciteten for ventilationsanlægget til rummet defineres sammen med varmegenvinding, elforbrug, ventilationsform, temperaturer, setpunkter og driftstider. Indblæsningstemperatur og ventilationsmængde vil blive tilpasset så setpunktet holdes, såfremt at der er tilstrækkelig kapacitet.

Elforbruget angives ved en given luftmængde, hvorefter det faktiske elforbrug bliver beregnet ud fra proportionallovene.

Vælges "Hybrid" som ventilationsform vil luften blive suget ind gennem et spjæld i facaden i stedet og indblæsningsventilatoren blive slukket, når dette er muligt. Det kræver, at udetemperaturen er over temperaturgrænsen og at der ikke er et opvarmningsbehov i lokalet. Vælges "Balanceret" som ventilationsform vil ventilationen fungere som et traditionelt ventilationsanlæg.

Driftstiderne bestemmes på dagsbasis, - uden for driftstiden vil ventilationsanlæg være slukket. Såfremt ventilationsanlægget ventilerer flere rum end det simulerede, angives alle data som den kapacitet der kan tilføres det simulerede rum.



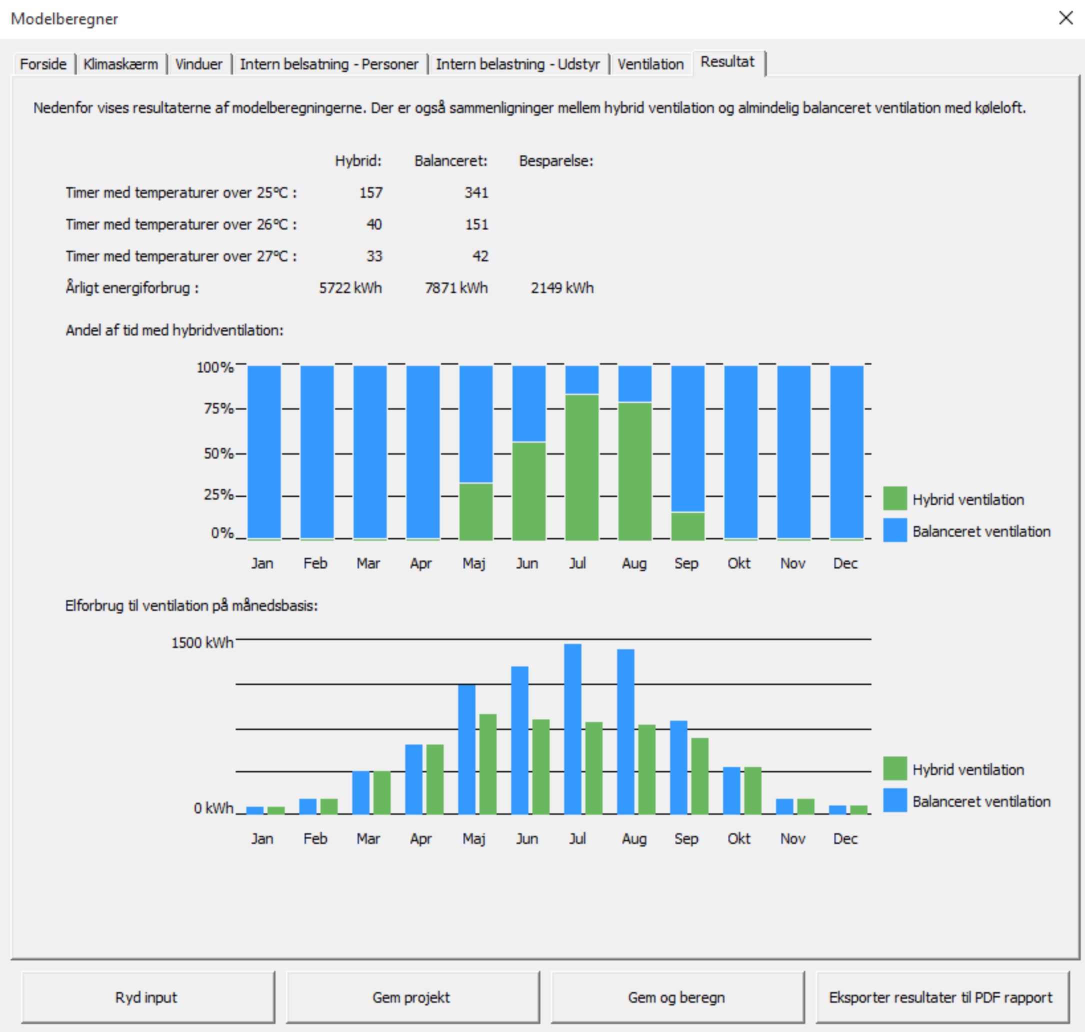
8.4.6 Resultat

På fanen ”Resultat” kan resultatet af simuleringen ses. Både indeklima og energiforbrug bliver her evalueret, og der sammenlignes mellem traditionelt balanceret ventilation med køleloft og hybridventilation med køleloft. Før resultaterne vises er det vigtigt, at der trykkes ”gem og beregn”.

Det er angivet hvor mange timer i løbet af et år, hvor temperaturen overstiger henholdsvis 25°C, 26°C og 27°C. Når der er mange timer, hvor temperaturen er over setpunktet er det et tegn på, at der ikke er tilstrækkelig kapacitet i luftmængden. Det årlige energiforbrug er udelukkende elforbruget til ventilationsanlægget, og besparelsen er den potentielle besparelse ved at skifte fra balanceret ventilation til hybridventilation.

På den første graf ses, hvor stor en del af tiden det har været muligt at køre med hybridventilation. Kun timer, hvor ventilationen er tilgængelig er taget i betragtning.

Den anden graf viser elforbruget til ventilation på månedsbasis.



For mere detaljerede resultater klik på ”Eksporter resultater til PDF rapport”. PDF-rapporten indeholder et resume af inputdata, økonomiske beregninger samt en visualisering af det termiske indeklima.

8.4.7 PCM

På fanen ”PCM” kan et eventuelt PCM lager dimensioneres, ud fra de indtastede data beregnes afladningstemperaturen og længden op afladningen i timer. Det vigtigt, at der trykkes ”gem og beregn”. Først indtastes luftmængde, højde af PCM lager, h_c, afrimningstiden, T luft ind(temperaturen ind i PCM lageret under afladning), T PCM (temperaturen for faseskiftet) og T indblæsning.