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Investigation of cold storage integration in a Danish data center

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Abstract

White-box simulation of flexible cold storage operation as a part of heat, ventilation and air conditioning (HVAC) systems of small- and medium-size datacenters is an important, but underinvestigated topic. In this work, an experimentally validated model of the phase-change material (PCM) cold storage and a Modelica system model of the data center are presented. The aim is provide a simulation tool that can be used by data centers and HVAC manufacturers to estimate the benefit of using sustainable technologies when designing innovative cooling solutions.

Highlights

- Empirical model of a latent cold storage
- Heat reuse model of a Danish datacenter
- Modular control of the cold storage units
- Model validation with experimental data

Introduction

Thermal management in datacenters implies a non-trivial control design that must be implemented in tune with the equipment dynamics and the topology of a server room (Joshi et al., 2012). In addition, the testing of innovative cooling technologies such as latent thermal energy storage requires taking informed decisions about the type of controllers, temperature set points, implementation of a part load regime (Boucher et al., 2004). The complexity of these decisions comes from the need to meet constraints imposed on the prototype and the cooling system (Jensen et al., 2022). The aim of this work is to predict through dynamic simulation in Dymola how an experimentally designed phase-change material heat exchanger (PCMHX – representing the latent cold storage) would operate under viable control settings when integrated in a Danish datacenter cooling system. To achieve this, system-level simulations were performed.

Previous studies on the application of PCM focused primarily on office and residential buildings (Aridi et al., 2022). In this work, we investigate the PCM cold storage for industrial cooling, which has not been widely considered and requires different design and operation methods (Liu et al., 2020). PCM cold storage has become increasingly attractive for data center application in recent years (Yuan et al., 2021).

The comparison of an experimental prototype dynamics under imposed conditions constitutes the relevance of this research. The innovation results from simulation of different operation regimes to conclude on performance and feasibility of the final design within the considered server room in a Danish data center. The identified operation conditions are proposed for full and part load chiller operation based on practical considerations.

Methods

As shown in Figure 1, the simulation considers a PCMHX in a hydronic loop in series with a chiller and 8 cooling coils. The outside air stream entering the server room is cooled down by the cooling coils, heated up by the server racks inside the server room and disposed through the exhaust. The validation was based on the mapping of the monitored cold storage operation data, obtained in laboratory environment.

Simulation tool

The Modelica Buildings Library was used to set up water and air flow models of the existing cooling system in Modelica language and an experimentally established empirical model was used for building the PCMHX component.

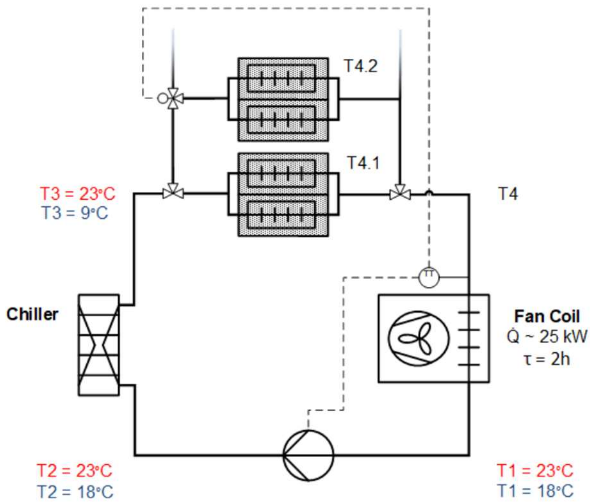

Figure 1: Schematic integration of PCM cold storage units in the hydronic cooling loop.

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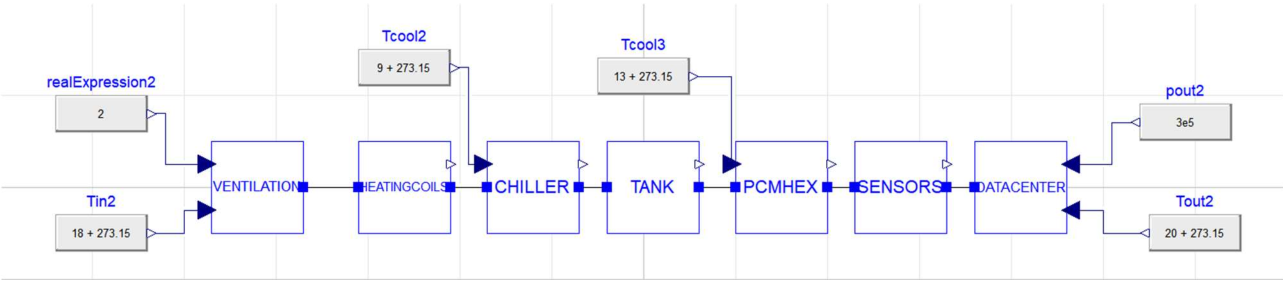

Figure 2: Validation model in Modelica (schematic).

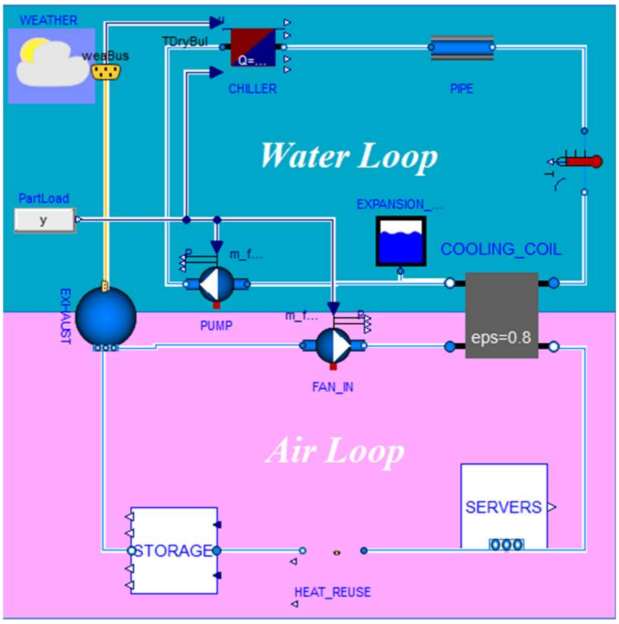

Figure 3: Prediction model in Dymola.

Experimental setup and validation model

A 115l PCM cold was tested in a laboratory setup connected in series to two heating coils and a laboratory cooling unit via a heat exchanger - emulating the data center's heat load and the air-to-water chiller, respectively.

The validation model represeting this setup was implemented in Python in form of both a lookup table and a black-box model fitting the table data. This model has been used to test the baseline control of the PCMHX and pre-optimize the number of units nessesary to satisfy the cooling capacity imposed on the water loop. The main purpose of the validation model was to ensure reliability of the novel cooling solution that integrates the PCM cooling units.

Combining the lookup table approach with simplified fluid dynamics approach, a grey-box validation model of a larger system (Figure 2) has been implemented in pure Modelica language and compared to the Python-generated validation data. Two operation regimes were simulated depending on the ambient conditions and time of the day:

1. PCMHX is charged by the chiller at 9 °C set point, the data center cooling demand is covered by the chiller and/or free cooling (blue ink in Figure 1)
2. PCMHX is discharged through the fan coils at 23 °C with the aim to keep the chiller off when the electricity price is high (red ink in Figure 1).
3. Both the chiller and PCMHX provide cooling due to impossibility of PCMHX to cover the demand alone.

Case study and prediction model

The HVAC system of a small-size Danish data center was utilized as a case. It was designed to keep the temperature of the servers in the range defined by international regulations. It consists of two fluid circuits: a hydronic loop cooled by an air-to-water chiller and rejecting heat through cooling coils; an air loop cooled by the cooling coils; a free cooler (a fan bringning the outside air in) and heated by the server racks, After interacting with servers, the air leaves the server room and enters a storage room where it mixes with the indoor air and then exits the building.

This study introduces the validated PCM cold storage model to the original case configuration. The simplified components of Figure 2 were replaced by heat exchanger (for cooling coils), air flow and control components from Modelica Standard and Buildings Libraries. The updated system is shown in Figure 3 where PCM is modeled as a customized pipe component.

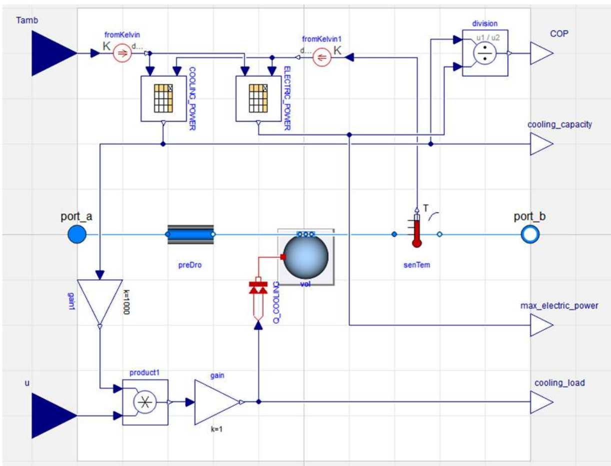

Figure 4: Chiller model.

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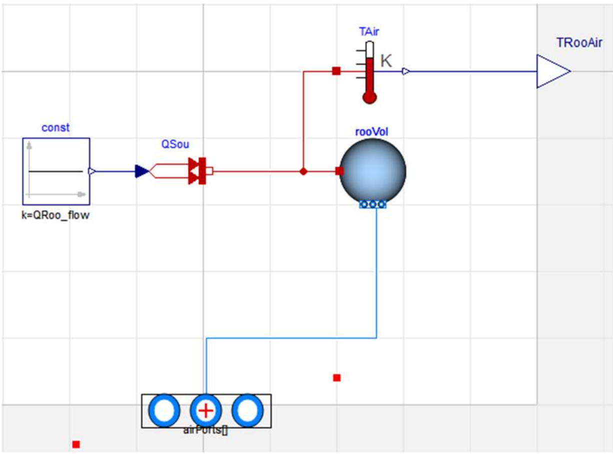

Figure 5: Server room component.

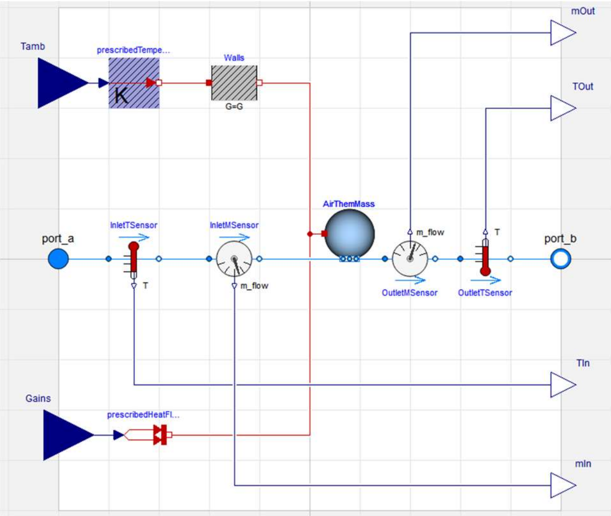

Figure 6: Storage room component.

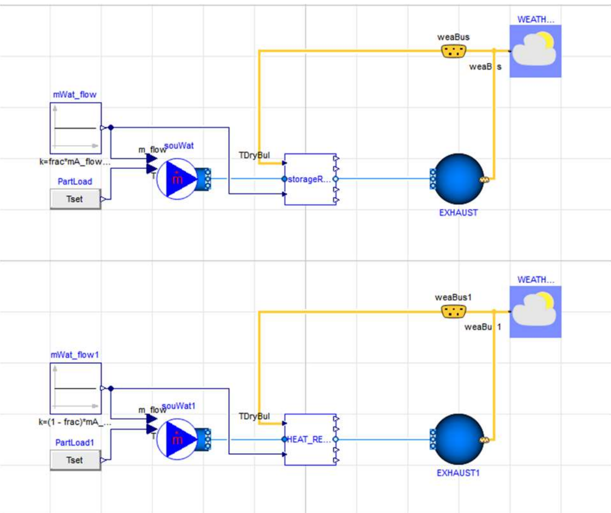

Figure 7: Independent heating system test for the office spaces used for waste heat utilization.

The model in Figure 3 (without the STORAGE and HEAT_REUSE components) was used to predict the yearly variation of baseline control of both water and air flows and compare it to the case where the cases where flow through the storage room (STORAGE component) and PCMHX storage are added.

The customized water chiller model was set up as shown in Figure 4. It uses lookup tables based on manufacturer data that calculate cooling capacity and electric power as functions of ambient and return water temperatures.

The first-order fluid model of the server room had been adopted with slight modifications from the Buildings Modelica Library, as shown in Figure 5.

To account for existing heat reuse in the data center, a similar model was added to the air flow loop representing the storage room. In this model shown in Figure 6, the influence of ambient temperature and internal heat gains were taken into account through Standard Modelica Library components, since the additional heat exchange with the outside air and indoor environment cannot be neglected unlike in the server room model.

Finally, the heat reuse system consisted of a heat pump, a radiator and office rooms (not shown). Here, the detailed room model from the Buildings Library was defined with a constant heat flow power from the servers to exclude minor variation of the server temperature. The electricity consumption of the water- and air based systems supplying heat to the data center offices and the storage room, respectively, have been calculated in isolation from the server room model configuration shown in Figure 7. This calculation serves as a reference for finding the amount of server-generated waste heat available for data center comfort heating.

Preliminary results

Figure 8 shows the validation results comparing the measured state of charge (SOC) of the PCM cold storage prototype and that predicted by the empirical model.

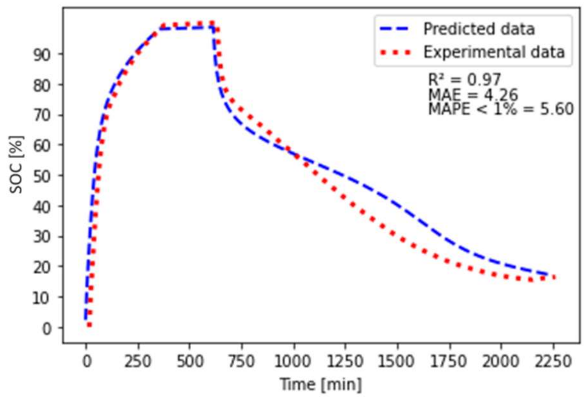

Figure 8: Validation of PCMHX SOC.

The resulting curves were in good agreement for the charging process. During discharging, a deviation was observed which however did not play a significant role in the prediction model since there are no active elements included in the PCMHX actuation on discharge.

The simulation of the prediction model shown in Figure 9 shows that it was sufficient to use only PI controller signals (blue curve, bottom) to keep the server room temperature at 25 ºC (blue line, top).

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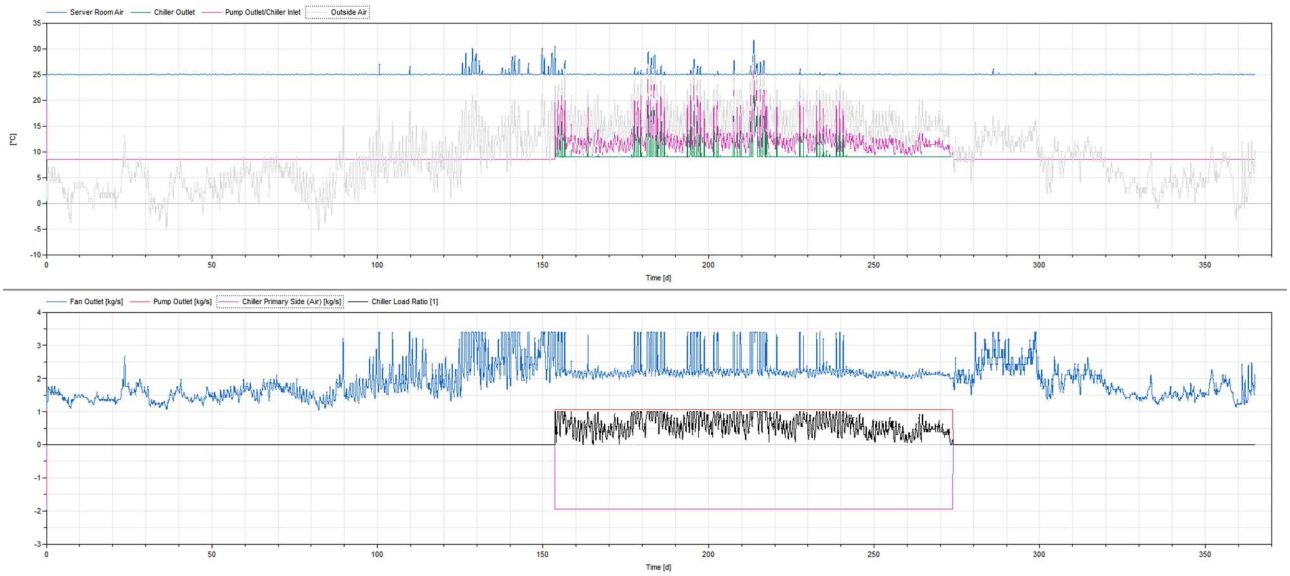

Figure 9: Yearly simulation of the baseline prediction model

It was found in relation to the same simulation that the additional hysteresis control of the pump and the chiller was nessesary to maintain the temperature within the acceptable boundaries during summer months and September.

The water setpoint set at 23 ºC has been successfully maintained in some periods by increasing the number of PCM units to 8. However, in other periods, the model predicted that more units or the chiller's part load operation are nessesary.

Conclusion and discussion

The models of the phase change material storage unit have been created and validated in Python and Modelica and integration of the cool storage and heat utilization system has been simulated as a white-box model. The control necessary to run the HVAC system throughout the year has been identified and simulated.

It has been found in pre-optimization study that 8 PCM units were enough to cover the data center demand in the first control regime. However, this turned out to be impractical in the yearly simulation of a prediction model. The simulations showed that most of the time either a larger number of storage units is necessary, or chiller had to be run in the part-load mode to maintain the water operation point at 23 ºC. Therefore, the identified operation conditions are proposed for full load chiller operation and part load chiller operation based on practical considerations.

The developed model provides a convenient simulation tool for one-to-one comparison of different ways of utilizing the waste heat generated by the data center servers. The ongoing work in relation to the considered system includes comparison of suitable designs for a heat recovery system. So far two types of local heat reuse solutions have been considered, through ventilation and by air-to-water heat pump. These types of local waste heat reuse will be further compared to district heating.

Acknowledgement

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