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Free cooling potential of a PCM-based heat exchanger coupled with a novel HVAC system for simultaneous heating and cooling of buildings

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ABSTRACT

This article presents a simulation-based study that estimates the primary energy use of a novel HVAC system for different configurations of a thermal plant. The main characteristic of the system is its ability to provide simultaneous heating and cooling to buildings by using a single hydronic circuit with water temperatures of about 22 °C all year round. Four different configurations of the thermal plant were analyzed. A district heating-cooling network was considered as baseline. Other configurations included the use of a reversible air-to-water heat pump coupled with free cooling devices. In particular, a model of a PCM-based heat exchanger was developed in this work by using the programming language Modelica. This device was designed to store cold energy during night-time and release it during daytime through the water circuit. Results for a typical office building model showed that the integration of free cooling devices can significantly reduce the primary energy use of the novel HVAC system. In particular, the thermal plant configuration including the PCM-based heat exchanger made it possible to almost completely avoid the use of mechanical cooling, leading to annual primary energy savings of about 67% when compared with the baseline thermal plant configuration.

1. Introduction

According to the Intergovernmental Panel on Climate Change, anthropogenic greenhouse gas (GHG) emissions have been the dominant cause of the observed warming of land and ocean surfaces since the mid-20th century. Continued emissions of GHG will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of irreversible impacts for people and ecosystems (Eickemeier et al., 2014).

Buildings account for 32% of total global final energy use and 19% of all global GHG emissions (Eickemeier et al., 2014). Population growth, migration to cities, household size changes, and increasing levels of wealth and lifestyle will contribute to significant increases of building energy use and related emissions. Therefore, research in the field of energy efficiency in buildings represents a crucial path towards the mitigation of climate change.

Thermal energy storage systems are valuable assets to enable more environment-friendly use of energy in buildings. One of the main benefits of using thermal storage is that it can contribute to matching energy supply and energy demand when they do not coincide in time. Generally, there are three approaches that can provide a thermal energy function: sensible heat, latent heat and chemical energy. Among these three approaches, latent heat thermal storage systems using phase change materials (PCMs) have attracted wide interest for building applications due to their ability to provide high energy-storage density and their ability to store thermal energy at relatively constant temperatures (Sharma et al., 2009). Zhu, Ma, and Wang, (2009) divided the possible building applications of PCMs into four categories: passive building systems, active building systems, peak load shifting and free cooling.

For passive building systems, PCMs are encapsulated into the building envelope to increase the thermal mass. The material melts during the daytime and solidifies during the night-time. This helps prevents rooms from overheating during the daytime in warm months. With regard to active building systems, the storage capability of PCMs can be integrated into systems such as solar heat pump systems, heat recovery systems, and floor heating systems. Apart from their functional purposes, these systems also enhance the heat transfer performance of PCM storage. As for peak load shifting, electricity demand and tariffs vary significantly during the day and night due to the changes in weather conditions and in the demands from industrial, commercial and residential activities. PCMs can be used to store cool energy by using cheap night-time electricity, and then using this cool energy later.

Free cooling, which is the main focus of this work, is a technique

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Nomenclature

T_s	Set-point temperature of water leaving the thermal plant [°C]
T_E	Temperature of water entering the thermal plant [°C]
$\dot{Q}$	Thermal power added/removed by the thermal plant [W]
$\dot{m}_w$	Water mass flow rate [kg/s]
$c_{p,w}$	Specific heat of water [J/kgK]
PEF	Primary energy factor [-]
Q_p	Primary energy use [kWh]
$\dot{W}_{HP}$	Electric power of the air-to-water reversible heat pump [W]
COP_{actual}	Actual Coefficient of Performance of the air-to-water reversible heat pump [-]
$\dot{m}_{air,nom}$	Nominal air mass flow rate for fans [kg/s]
$c_{p,air}$	Specific heat of air [J/kgK]
$\dot{Q}_{coo,nom}$	Cooling load at nominal condition [W]
ε	Effectiveness of the dry cooler [-]
$T_{E,nom}$	Nominal temperature of water entering the thermal plant [°C]
$T_{in,air,}$	Nominal temperature of air entering the dry cooler (Ambient temperature) [°C]
$\dot{W}_{fan,nom}$	Nominal fan electric power [W]
$\dot{W}_{fan}$	Fan electric power [W]
$\dot{m}_{air,actual}$	Actual air mass flow rate in the dry cooler [°C]
$h_{conv,i}$	Convective heat transfer between water and wall [W/m^2K]
Nu	Nusselt number [-]
k_w	Thermal conductivity of water [W/mK]
k_{PCM}	Thermal conductivity of PCM [W/mK]
τ	Daily time of operation of the system at full load [h]
Q_L	Latent heat storage capacity of PCM [J/kg]
ρ_{PCM}	Density of PCM [kg/m^3]
Q_{hea}	Annual heat delivered to the water flow by the heat pump [kWh]
Q_{coo}	Annual heat extracted from the water flow by the heat pump [kWh]
$W_{el,hea}$	Annual electricity used in heating mode [kWh]
$W_{el,coo}$	Annual electricity used in cooling mode [kWh]
$HSPF$	Heating Seasonal Performance Factor [-]
$CSPF$	Cooling Seasonal Performance Factor [-]
Re	Reynolds number [-]
Pr	Prandtl number [-]

defined as “that amount of cooling which can be obtained from existing, additional or modified system components during low ambient conditions and used to partly or fully offset the load on mechanical refrigeration plant” (Saulles & De, 1996). Typically, outdoor cold is stored during low ambient conditions at night and it is released with a time delay during daytime in order to provide space cooling to buildings. Several works have been carried out in relation to the use of PCMs for free cooling applications in buildings.

Nagano et al. (2006) proposed a floor supply air conditioning system in which air is supplied to a room through porous floor boards. A packed PCM bed is embedded below the floor boards. During the night, circulation of cool air through the under floor space allows cold energy to be stored so that during daytime it can be used to remove the cooling load from the room. Experimental results for an office space showed that 89% of the daily cooling load could be stored each night. Turnpenny, Etheridge, and Reay, (2001) conducted experiments on night-time cooling using a heat pipe incorporated with PCM. In their experiment, they analyzed parameters such as temperature, discharging character of the PCM and cooling potential of the storage unit. They also revealed that replacing conventional air-conditioning units with the proposed system in 2000 offices around United Kingdom would reduce CO2 emissions by 430 t per year. Takeda et al. (2004) studied a ventilation system that features direct heat exchange between ventilation air and PCM granules. The potential of such a system to reduce ventilation load during summer was investigated for eight cities in Japan using computer simulation. The maximum benefit was obtained in Kyoto, with a reduction in ventilation load by approximately 63%. Osterman, Butala, and Stritih, (2015) developed a latent heat storage unit for space heating and cooling. In summer, cold is stored during nights and delivered during the day to reduce cooling load, whereas in winter, heat from solar air collectors is stored for heating during morning and evening hours. A simulation study carried out for a reference office space showed that energy savings in summer are approximately 58 kW h. Stritih and Butala (2011) presented an alternative method of cooling and ventilation in buildings, which combines increased thermal mass and night ventilation by integrating PCM into the ceiling. Calculations were made for four representative European cities with different climate conditions. Average energy savings were between 18% and 74%, depending on the selected scenario.

It is noted that, in previous studies, free cooling PCM storage units are normally used in connection to air-based systems, where ventilation and sensible cooling loads are satisfied by circulating air through the space. In this case, the discharging process of PCM is handled by hot air passing through the PCM storage unit and the air thus cooled to comfort temperature is delivered to the space using fans.

Some studies have also investigated the use of free cooling PCM storage units in connection to water-based systems, where ventilation and sensible cooling loads are handled separately. These systems, in comparison to air-based systems, use water as heat carrier to satisfy the sensible cooling loads and therefore, fresh air for ventilation can be supplied at a minimum rate, which results in the reduction of the fan energy use. Tay, Belusko, and Bruno, (2012) investigated the useful energy that can be stored within a tube-in-tank PCM storage unit coupled to a chilled beam system. The study identified that the storage effectiveness ranged from 0.68 to 0.75. Wang, Niu, Paassen, and Van, (2008) developed a new design of a hybrid system, which is a combination of cooled ceiling, microencapsulated PCM slutty storage and evaporative cooling technologies. The energy saving potential of the proposed air-conditioning system was analyzed by using a well validated building simulation code, considering five representative climatic cities. The results indicated that the system offers energy saving potential up to 80% under northwestern Chinese climate and up to 10% under southeastern Chinese climate.

In this paper, a simulation-based study was conducted on a PCM-based heat exchanger coupled to a novel water-based HVAC system, where active beams are used as terminal devices for heating, cooling and ventilation of spaces. The particularity of such a novel HVAC system is its ability to provide simultaneous heating and cooling through a water loop that is near the room temperature. Supply water temperature of about 22 °C is delivered to all the zones in the building, no matter whether a single zone needs heating or cooling. A model of the novel HVAC system was developed by the authors using Modelica, and dedicated simulations were performed in order to evaluate the annual primary energy savings achieved thanks to the integration of the PCM-based heat exchanger.

1.1. Novel HVAC system description and PCM based heat exchanger

Existing large office buildings may require simultaneous heating and cooling. Interior zones of a building tend to overheat due to waste heat generated by internal factors (people, lighting and equipment), while perimeter zones require heating due to heat loss through

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