Space Heating Systems Integrating Heat Pumps and PCM Thermal Energy Storage Units in Swedish Single-family Houses: A Case Study

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ABSTRACT

This paper introduces a case study of the space heating system in a typical Swedish single-family house where the heating demand is covered by an air-source heat pump (ASHP). The highlight of this study is to evaluate the operational strategy of heating load shifting as one of the ways for demand-side management (DSM) by the integration of a heat pump and a thermal energy storage (TES) unit incorporating Phase-Changing Materials (PCM) in a common hot water radiator system. A quasi-steady state model on an hourly basis is adopted to evaluate the results of the load shifting. The performance of the heat pump and the TES unit is modelled based on the previous experimental investigations. The analysis shows that with the proposed layout of the hydronic heating system the load shifting can reach 9.5 kWh and the savings in electricity bills are estimated to be around 4% when implementing such operational strategy.

KEYWORDS: Air source heat pump; demand-side management; thermal energy storage; Phase-changing materials

1. INTRODUCTION

Commercial heat pumps have been gradually adopted as an energy-efficient solution for covering hot water demands in Swedish heating markets. Especially for low-density areas without district heating systems infrustractured, heat pumps can be implemented to replace biofuel boilers or electric heating for single-family houses in suburb or villages as a way to approach more individualized and efficient heat supply for heat-sparse areas. Heat pump is also a powerful tool for domestic demand-side management (DSM), since it is only electricity-driven and the control of that can be realized by the house owner. One of the DSM strategies, which is the load shifting of space heating in residential buildings, is deemed advantageous from both the power suppliers' and the users' perspective (Arteconi et al., 2012). When properly implemented, the load shifting can not only help decouple the power generation and utilization in a grid, but also benefit the users from difference of electricity tariffs between on-peak and off-peak hours. In order to achieve this strategy, an additional equipment for load shifting is bound to be coupled with heat pumps. Thermal energy storage (TES) has been widely adopted for such applications. In built environment, its principle is to actively store the excessive heat or cold when it can be produced more efficiently or economically (charging) and to utilize that (discharging) in other periods for keeping the desired indoor climate.

Although there are various forms of TES techniques, storage units which are actively integrated in the HVAC system through pumps or fans are one of the most common applications in buildings (Heier et al., 2015). When it comes to TES for space heating applications, water is normally the heat transfer fluids (HTF) and mostly the storage medium as well, since it directly carries the necessary heat to hydronic distribution systems, such as the hot water radiators and floor heating systems, thanks to its easy handle-ability. On the other hand, latent TES units utilizing high latent heat of PCM (Phase-Changing Materials) can save storage volume comparing to sensible TES units using water (Sharif et al., 2015). Up to the author's knowledge, several studies have investigated the coupling of TES with heat pumps for providing space heating in single-family dwellings. Nevertheless, they focus on simulating the systematic performance of TES units, which are either a thermally stratified water tank or a hot water buffering tank incorporating certain volumes of PCM in it by built-in models from commercial software (Arteconi et al., 2013; Kelly et al., 2014). No experimental results support the behaviors of the charging/discharging cycles of these TES units. In the present work, a system mathematic model is developed to describe the quasi-steady state performance of a space heating system in a typical Swedish single-family house as a case study. The space heating system integrates a variable-capacity air-source heat pump (ASHP) and a PCM-TES unit as the heat source. The model illustrates how a PCM-TES unit can contribute to the load shifting in an electricity tariff-oriented operational strategy based on the experimentally validated performance map of the storage unit and the heat pump. Additionally, the potential savings in electricity bills are calculated by the model.

2. METHODOLOGY

As a case study of incorporating PCM-TES unit into residential space heating systems, the layout of a common hot water radiator system in typical Swedish single-family dwellings is proposed in Fig. 1. The heating is provided by a state-of-the-art variable-speed ASHP using propane as the refrigerant. It is noted that the additional feature is the incorporation of a PCM-TES unit (2), which enables the load shifting through the control of the 3-way solenoid valve (3). This integrated solution assumes that the heating load of the house can be whenever fulfilled by either the individual operation of the heat pump or the simultaneous working of the heat pump and the discharging PCM-TES unit by a proper control.

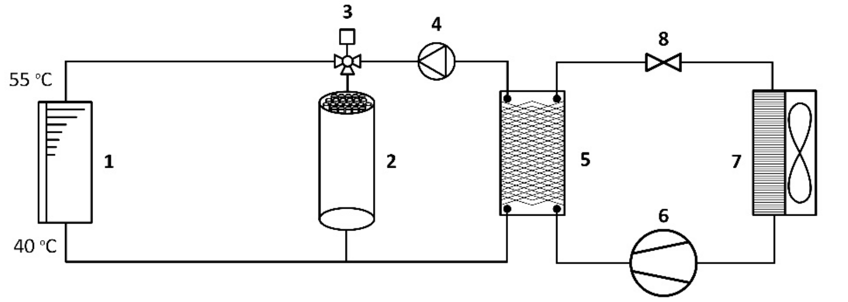

Figure 1: Layout of coupled heat pump and PCM-TES space heating system

2.1 System mathematic model

The performance in terms of the heating capacity, load shifting and electricity consumption of the abovementioned system is interpreted in a system mathematic model. This model is developed on the basis of a quasi-steady state taking the dynamic behaviors of the operation as a serial of hourly steady states. One of the variables in this model is the ambient temperature during the day, which leads to the variation in COP and heating capacity of the heat pump. The model outputs are also dependent on the charging/discharging strategy, to be more specific, the starting and ending time to activate the PCM-TES unit, because the thermal power input and output of the unit vary significantly with the timespan.

2.2 Heat pump model

A sub-model mapping the heat pump performance regarding the COP and the heating capacity at various compressor speeds is created using polynomial correlations. These parametric data are generated by the IMST-ART software package. A previous experimental study on the dedicated heat pump was carried out and validate the modelling results from the software (Xu et al., 2016).

2.3 PCM-TES unit model

Another sub-model characterizing the PCM-TES unit in terms of the charging/discharging power rate and the total time is developed based on the experimental data. A large-scale PCM-TES unit with 9.5 kWh storage capacity was tested in KTH in order to study the incorporation of such units into residential heating systems. The sub-model origin from the testing results assuming the scaling of the unit would not affect the melting/solidification time of the PCM. In this way, the PCM-TES unit can be sized to achieve different amounts of load shifting in the space heating system with known performance.

3. RESULTS

Fig. 2 shows the calculated heating load profile of a day in the heating season on the basis of hourly ambient temperature recordings in Stockholm. The dry-bulb temperature varied insignificantly from 2 ^{o}C to 4 ^{o}C during the day. In Fig. 2, the blue areas show the heating demands of the house while the yellow parts show the heating capacity supposed to be provided by the variable-capacity heat pump when incorporating the charging/discharging behaviors of the PCM-TES unit. It can be observed that the heating load is shifted from daytime to nighttime, when the electricity is approximately half- to two-third-priced. Such operational strategy is estimated to save around 4% of the electricity bills for the building owners on the condition that the total shifted thermal capacity is 9.5 kWh. A variable-capacity heat pump is regarded to be a powerful tool for the demand-side management in a space heating system when coupling with a TES unit.

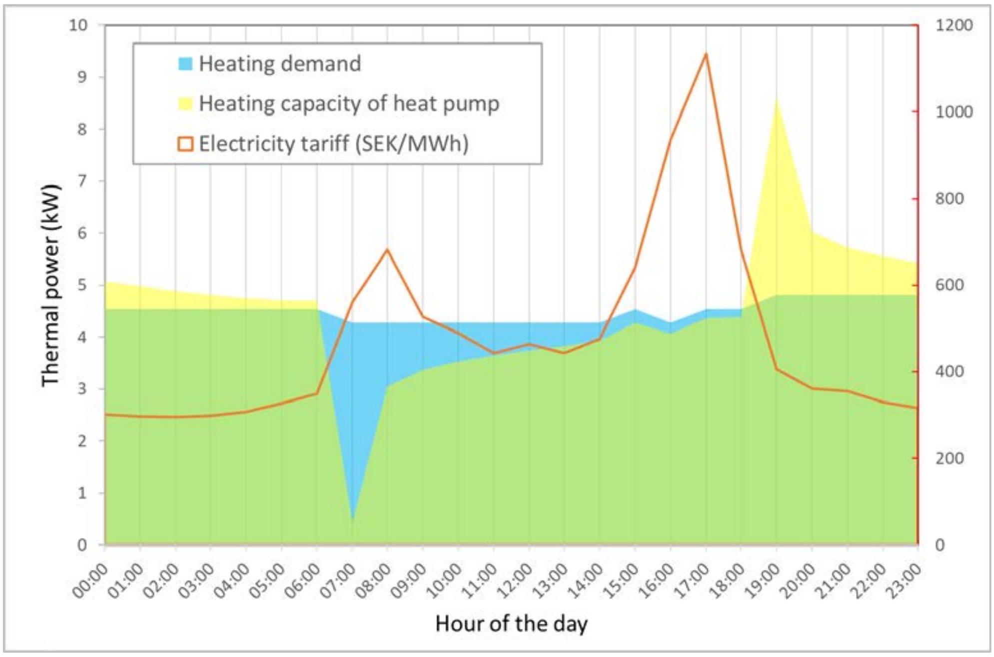

Figure 2: Hourly heating load with load shifting behaviors of a day.

4. CONCLUSIONS

This work theoretically assesses the operational strategy of heating load shifting in a typical Swedish single-family house of which the space heating is provided by a variable-capacity ASHP. The load shifting is achieved by a PCM-TES unit integrated in the hot water radiator system. Such design and proper implementation will bring benefits to both the grid and the building owner.

ACKNOWLEDGEMENT

This work was supported by the Swedish Energy Agency under the effsysEXPAND research program. The first author also expresses his gratitude to CSC for the financial supports.

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