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Flexible Low-Temperature Heat Storage for Heat Pump with Predictive control

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Heat pumps are increasingly popular all over the world. There is a general effort to increase the coefficient of performance. One of the options to increase this coefficient is to utilize auxiliary technologies. In this paper, two of such applicable technologies are tested: low-temperature storage in conjunction with predictive control, allowing the heat pump to operate with a minimum temperature difference. The idea is that, based on the outside temperature, the heat pump low-temperature source of heat is switched between the outdoor air temperature and the water temperature in the low-temperature storage. The paper is proposing a predictive algorithm for storage charging and discharging control based on the outside temperature. In this way, the heat pump can provide heating water for the heated object with a variable temperature currently required by the heating system of the object. The historical record of air temperature values in the city of Brno, Czech Republic, are used for the evaluation of the predictive control function. By applying the proposed predictive control, an increase in Seasonal Coefficient of Performance of 16.65 % was achieved compared to the basic operating state.

1. Introduction

Heat pumps (HPs) are a modern way of heating family houses and large urban units. The popularity of heat pumps has been growing intensively for three decades, and the number of installations is growing dynamically (EHPA, 2019). HPs are predominantly powered by electricity and for this reason, they represent locally emission-free sources of thermal energy, and their use leads to local reductions in CO_2 production, which is in many regions actively supported by the state or local government. The more intensive use of HPs in the residential sector contributes to the decrease in the prices of HPs and modern heating systems use a heating water temperature in the range of 30 - 50 °C (e.g. floor heating, large-surface radiators, etc.), which contributes to the efficiency of HPs operation. HPs also represent a promising element applicable in Demand side management systems and Smart grinds (Testi et al., 2020).
The technical parameters of HPs have long been improved by the gradual development of individual components (Chua et al., 2010), the development of new refrigerants (Longo et al., 2019) and increasing the service life of the entire HP technology. The parameter used to quantify the HPs efficiency is the Coefficient of Performance (COP), which expresses the ratio of instantaneous heating power and instantaneous electricity consumption. The instantaneous values of the monitored parameters change significantly during the heating season, so it is advisable to use the Seasonal Coefficient of Performance (SCOP). This parameter is the ratio of heat supplied to the heating system and the electricity consumed by the HP during the entire heating season. Considerable attention has been paid by HPs manufacturers and research teams in recent years to the development of new ways to control HPs. In this context, we will focus on air-to-water HP, which are the most used type of HPs. The primary control system of these HPs tries to optimize the heating water temperature depending on the instantaneous heat consumption in the building (equithermal regulation). Other control methods prefer to operate HPs during periods of the day with a lower electricity price or at the highest outdoor temperatures (Kuboth et al., 2019). The importance of this regulation rises with increasing variation in outdoor temperature during 24-hour periods. Additional requirements for regulation are placed in cases of supplementing

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the system with a heat storage (Liu et al., 2019). In recent years, several studies have been published evaluating the connection of HP with various methods of heat storage (hot water, gravel, phase change materials, etc.). A characteristic feature of these storage methods is the storage of thermal energy in the accumulator at the temperature required by the heating system. This causes a reduction in the efficiency of the accumulation by increasing the heat losses of the storage and at the same time worsening the SCOP of the HP, by preparing the heating water at a relatively high temperature.
The connection between HP and the heat storage can be supplemented using predictive control using short-term prediction of the course of external temperatures to determine the most suitable moments of HP operation (Pospíšil et al., 2019).
Another of the trends in the field of heat supply is the development of long-term heat storage to achieve seasonal accumulation. These systems use large-volume accumulators, where thermal energy is accumulated at a temperature corresponding to the requirements of a low-temperature heating system.
For these reasons, the authors of this study focused on a model evaluation of a residence-size heating system including HP and Low-Temperature Heat Storage (LTHS), where thermal energy is stored at a temperature close to the temperature of the ambient air. LTHS is considered in the form of a simple, thermally insulated water tank located near a heated object.

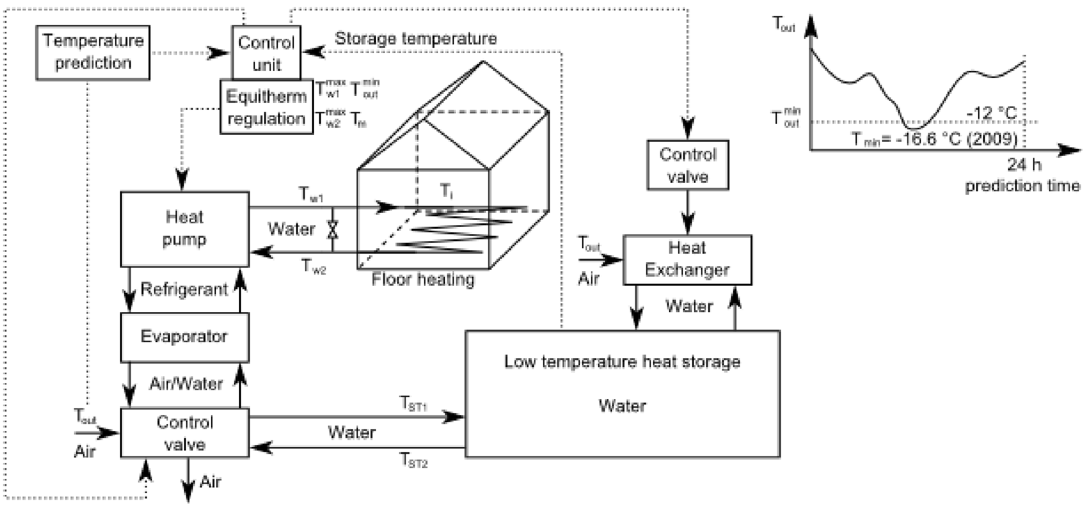

Figure 1: Considered heating system utilizing heat pump and low-temperature heat storage

These tanks are filled with water during the winter months, which can be used as a low-temperature source for HPs. Due to the placement of the tanks in the soil, the temperature in the tank naturally stabilizes in the range of 4 - 8 °C. Rainwater tanks are volume-significant tanks, and their use minimizes the financial demands for building another low-temperature source. In the presented model study, the authors compare several possible alternatives of HP operation. The variant using LTHS is connected with the use of predictive control using the prediction of the ambient air temperature and the active storage of thermal energy in LTHS during suitable periods. The assessment of individual alternatives is performed on historical records of the course of outdoor air temperature from the years 2008 to 2019 in the weather conditions of Central Europe, specifically in the City of Brno (CZ).

2. Mathematical model of the studied system

For the heating system shown in Figure 1, a corresponding mathematical model was created, including HP with low-temperature heat storage. The system connects the floor heating of the model building, HP, LTHS, necessary heat exchangers, and control unit. The main component of the whole system is HP. The coefficient of performance (COP) is the fundamental output characteristic of HP. The COP is determined as the ratio of the heating capacity $\dot{Q}_{HP}$ and the power input P_{HP}:

$$\mathrm{COP}=\frac{\dot{Q}_{HP}}{P_{HP}} \tag{1}$$

The COP for a HP is strongly influenced by the difference between the outdoor air temperature and the temperature of the heating water produced (Hepbasli and Kalinci, 2009). In this study, the COP dependence obtained from experimental data of new air-water HPs tested in 2015 and 2016 by the laboratory of the Czech Republic branch of the EHPA is used to describe the operating parameters of HP (Pospíšil et al., 2017).

$$COP = 0.0023\Delta T_{aw}^2 - 0.2851\Delta T_{aw} + 10.677 \quad (2)$$

where ΔT_{aw} is the difference between the temperature of water at the outlet of the condenser and the outdoor air temperature at the inlet of the evaporator.
In this study, a 10 m^3 container placed in the ground filled with water is considered as a LTHS. The size of the tank was determined to ensure sufficient heat capacity for the considered heating system. The calculated outdoor temperature in Brno is $T_{out}^{min} = -12\ °C$. However, the water in the LTHS does not freeze because it is buried in the ground, the temperature of which does not fall below 4 °C all year round. The assumed calculated heat loss of the considered residential building is 1 kW.
For the external calculation temperature -12 °C and the considered floor heating, the required heating water temperature $t_{w1}^{max} = 45\ °C$ and the return water temperature $t_{w2}^{max} = 35\ °C$ were chosen according to the stringent standards. For fluctuating outdoor temperatures, the necessary temperature difference between heating and return water and their actual values are determined at all times by using equithermal regulation.

2.1 Meteorological conditions

The primary parameter influencing the SCOP of the evaluated system with HP is the course of temperature in the heating period. The outdoor air temperature directly affects the instantaneous heat demand and also the instantaneous COP of HP value. Real meteorological data recorded in the central part of the city of Brno, representing a typical medium city (population of 400,000) in the central part of Europe (GPS 49.1961939N, 16.6071078E) were used for this study. The heating period in this locality lasts 210±10 days. The difference between day and night temperature for one day regularly reaches 4 -12 °C. Significant outdoor temperature differences during the individual days provide an excellent opportunity for 24-h predictive control ensuring priority operation of HP in periods with the highest daily temperature. Historical records of the course of outdoor temperature from 2008 to 2019 were used in this study for testing and evaluation of the studied heating system. Ten consecutive years ensure the statistical relevance of the formulated conclusions.

2.2 Predictive control

This section presents the proposed predictive control algorithm, which considers a block diagram of a simplified system, see Figure 2. The thermal gradient on the evaporator is 6 °C for the air configuration and 3 °C for water configuration to transmit a nominal heat flux of 1 kW. The diagram demonstrates that the basic heat source for the heating system is ambient air that can be used directly by the HP or can heat up the LTHS. At times when the ambient air temperature is lower than the water temperature in the LTHS, the heat from the LTHS is preferably used as a low-temperature source. Predictive control then has the task of controlling the charging/discharging of the LTHS so that the operation of the heating system is as efficient as possible. This is in line with striving to achieve the highest possible SCOP of HP.

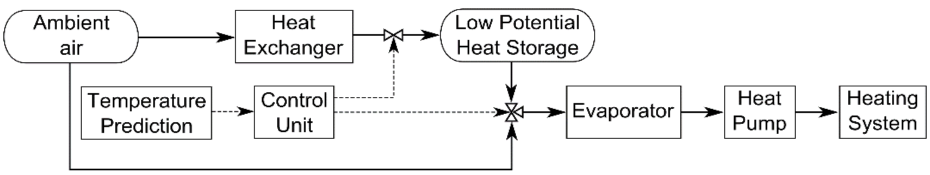

Figure 2: Block diagram of the simplified proposed system

The following points list the main parameters of the considered predictive LTHS charge/discharge control and HP operation.
Prerequisites and limitations:

- The LTHS is charged and discharged suddenly in 1-h intervals. The change is sudden, not dynamic. This affects the LTHS temperature and will influence the results.
- The LTHS is adiabatic. It is considered perfectly isolated from the surrounding ground which temperature does not drop below 4 °C. Omitting this heat source affects the LTHS's temperature, that can fall to 0 °C in the algorithm.
- The prediction of the outdoor temperature is known with sufficient accuracy for the next 24 hours.
- The LTHS temperature at the beginning of the heating season is 20 °C.

Conditions:

- Condition 1 – If the temperature in the LTHS is higher than the ambient air temperature, the LTHS starts to discharge. The detailed balance respects the heat gradients on all heat exchangers.
- Condition 2 – If the outside air temperature is higher than the water temperature in the LTHS, the LTHS starts to charge.
- Condition 3 – The lowest permitted temperature in the LTHS is 0 °C.

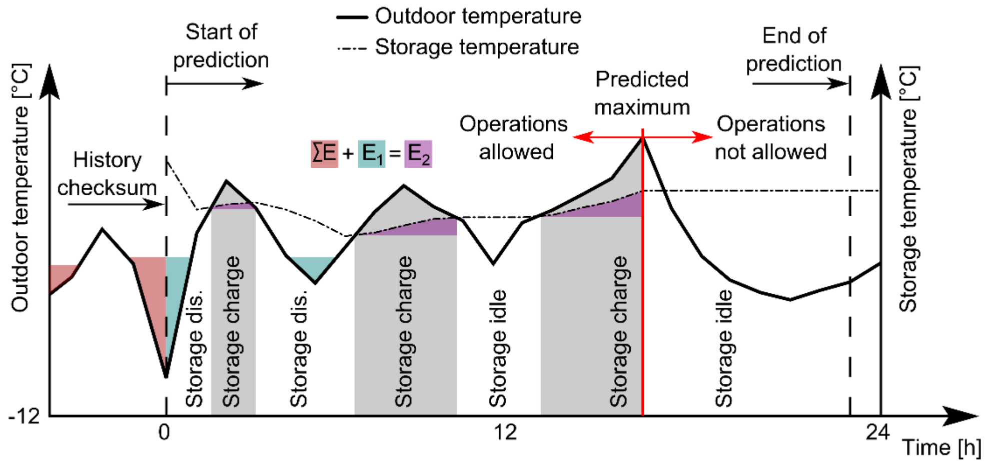

Figure 3: Illustrative example of LTHS charging and discharging periods during outdoor temperature fluctuations

The LTHS is charged during periods of the day with the highest air temperature and discharged during periods with the lowest air temperature. At the same time, predictive control checks that the amount of discharged and charged energy to the LTHS is equal during the monitored 24 h. Within all 24-h periods, it is possible to optimize the heat source preference for HP. Figure 3 shows the periods of LTHS charging and discharging during outdoor temperature fluctuations.

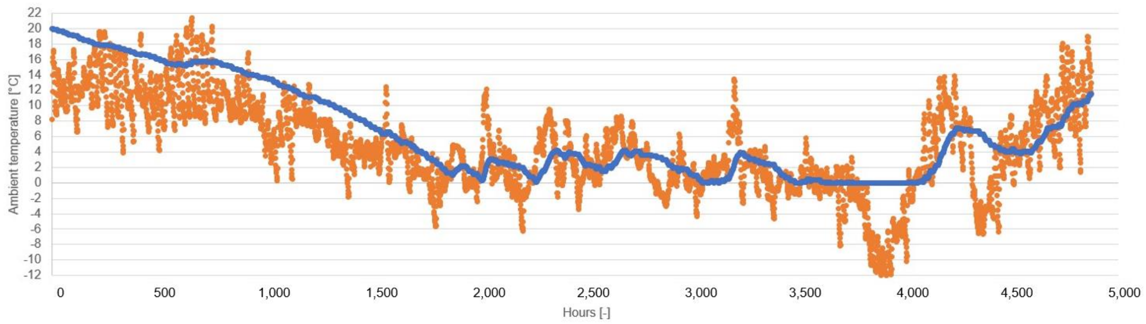

Figure 4: Hourly outdoor temperature (orange) and LTHS water temperature (blue) for the 2017 season

The predictive control algorithm begins by arranging the monitored hourly intervals into two sets. The first set is marked "RANK" and here the hours are sorted in ascending order by temperature. The second set is marked "TIME", and the intervals are sorted in ascending order by time from 1 to 24. The algorithm distinguishes 5 operating states of LTHS operation, described in Table 1.

The state in TIME 1 is executed and the algorithm continues at the next hour, in which a new prediction and state setting are performed. This is repeated throughout the entire heating season.

Figure 4 shows the dependence of the outdoor air temperature (orange color) and the calculated dependence of the water temperature in the LTHS during the heating season 2017. The water temperature in the LTHS is above the average daily outdoor air temperature for almost the entire heating period, which is a confirmation of the benefit of the proposed algorithm.

Table 1: Operating states of the algorithm

State	Description
State 1 no action	RANK 24 is the local maximum temperature. All hours that have a TIME higher than RANK 24 are always in this state. This state can also occur if neither condition 1 nor condition 2 occurs.
State 2 discharging – no monitoring	Unlike state 3, it does not need to record the discharged energy because it discharges excess energy that does not need to be stored. In this state, charging is not forced
State 3 discharging - monitoring	Unlike state 3, it does not need to record the discharged energy because it discharges excess energy that does not need to be stored. In this state, charging is not forced.
State 4 charging	Occurs when the temperature in the LTHS is lower than the ambient temperature. It can occur if other controls do not allow different state
State 5 forced discharge	It has priority over other states and starts when state 3 occurs. The amount of discharged energy is determined from RANK 1 in ascending order and the amount of recharged energy from RANK 24 in descending order until the RANKs meet.

3. Comparison of tested variants

The achieved SCOP was monitored to quantify the benefit of the proposed system connecting LTHS, HP, and predictive control. As part of the solution, three variants of operation of the heating system with HP were evaluated using a uniform methodology.

Variant 1 - HP utilizes heat from the air without the use of heat storage, without the application of predictive control and supplies heating water at a constant temperature of 45 °C.

Variant 2 – HP utilizes heat from the air, without the use of LTHS, without the use of predictive control, but uses equithermal regulation to heat the heating water only to the necessary temperature.

Variant 3 – HP takes heat from the air or LTHS, uses equithermal regulation and the designed predictive control.

The resulting SCOP values identified for the three variants tested using historical outdoor air temperature records for 10 heating seasons are shown in Figure 5. Above the columns of individual variants is the percentage increase in SCOP compared to Variant 1 in the relevant year.

From the above results, it can be seen that by including equithermal regulation for heating water temperature control, the SCOP increased by 7.0 % to 17.8 % compared to the basic Variant 1. Using predictive control and low-temperature heat source, the SCOP increased even more by 11.1 % to 21.8 %.

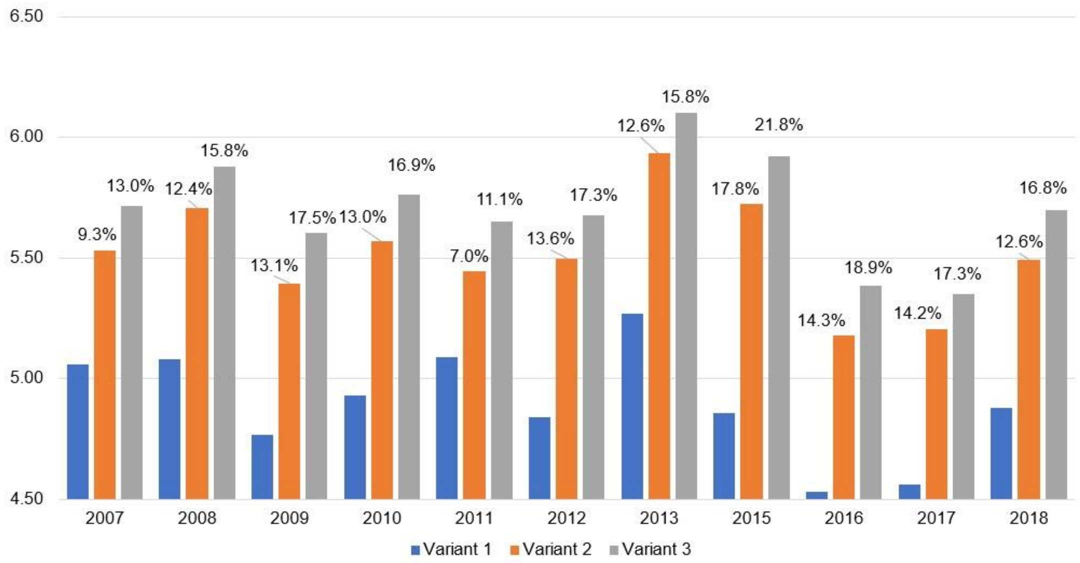

Figure 5: Results for SCOP values for all three variants with relative change based on Variant 1 (maximum heating water temperature of 45 °C.)

4. Conclusions

The paper presented a computational parametric study evaluating the potential of using a low-temperature heat storage to increase the SCOP of a heat pump. A sizeable underground container primarily intended for rainwater capture serves as a low-temperature storage. The evaluated configuration is a heating system for a residential object geographically located in the central part of Central Europe, specifically in the city of Brno (CZ). The proposed predictive control is focused on the use of intraday fluctuations in outdoor air temperature, which usually reaches 12 °C in this locality. A predictive control algorithm was designed to optimize the operation of HP and the charging of the heat storage in a perspective of 24-hour prediction of meteorological conditions. The study of various variants of HP operation shows that the utilisation of equithermal HP regulation allows an increase in SCOP by 12.7 % compared to the basic variant (HP operation preparing a heating water supply of a constant 45 °C). By adding the variant with equithermal regulation with a low-temperature storage tank and predictive control, the SCOP is increased by 16.5 % (compared to the basic variant). The use of a low-temperature storage and the control of its operation by predictive control has considerable potential to increase the SCOP, in the studied locality at the level of 5.7. The achieved values are in agreement with similar experimental research (Kuboth et al., 2019). This can be achieved by altering currently working HP's control software and eventually adding a generally available rainwater storage. Further research is required because the obtained values are from a preliminary study with many assumptions and limitations, but still shows great potential for SCOP improvement. Next step in the research should focus on a more detailed description of system behavior like losses into environment, storage temperature changes and focus on parametric studies with different media, temperatures, storage sizes or period monitored by predictive control (up to 72 h).

Acknowledgements

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