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Seasonal Benefits of Intraday Heat Accumulation in System with Air Source Heat Pump for Central Europe Climate Conditions

Jiří Pospíšil[a,*], Michal Spilacek[a], Marek Bartu[b], Daniel Marton[c]

[a]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 61669 Brno, Czech Republic
[b]Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 61669, Brno, Czech Republic
[c]Faculty of Civil Engineering, Brno University of Technology - VUT Brno, Veveri 331/95, 60200 Brno, Czech Republic
pospisil.j@fme.vutbr.cz

This article presents results of a study focusing on the evaluation of the real seasonal coefficient of performance (SCOP) of the air-to-water heat pump (HP) operating in specific conditions of the Central Europe. For evaluation is utilised a historical pattern of air temperatures from last 10 years. Real experimental data from the HP testing are used. The mathematical model is build-up which considers the behaviour of the considered building adhering to the demands on the supply of the heat energy. The influence of the HP operation during the warmer parts of the day with addition of the accumulation is assessed employing the created mathematical model. The model is used for parametric studies that evaluate utilizing of the accumulator and a method of heat pump control. The results show possible increase of SCOP up to 20 % with utilizing of predictive regulation. Studied configuration causes significant decrease of seasonal power consumption of air-to-water heat pumps.

1. Introduction

In the past 10 years, the heat energy control systems in buildings are primarily focusing on the control of internal temperature with the aim to minimize the heat loss. The new generation of the smart control systems is associated with the predictive regulation that takes into account the results of the predictive meteorological models. The forecast of sunlight is still burdened by great inaccuracy and cannot be utilised for predictive regulation. More accurate are forecasts of the outdoor temperature. When the prediction of the outdoor temperature pattern is known, it is possible to optimise the operation of the heat source. The predictive operation of the heat source has the greatest significance in the sources which have working parameters dependent on the outdoor temperature. The typical representative of such source is the ait-to-water heat pump (Sorbu and Sebarchievici, 2014). Today heat pumps control system is frequently preferring only the time intervals with the reduced price of electricity. This type of control can be conveniently combined with the predictive operation for reaching the maximal effectiveness of the system.

The coefficient of performance (COP) of HP that takes the heat from the ambient air is directly dependent on the air temperature. Under the climatic conditions of the Central Europe during the heating season, the intraday temperature typically changes in the range from 4 to 12 °C. This affects the immediate COP for up to 30 %. This piece of knowledge proposes an opportunity to increase the seasonal coefficient of performance (SCOP) of the heat pumps by the priority operation being in the parts of the day with higher air temperature. This system operation can be effective with accumulating part of the heat energy for the colder stretches of the day.

This article focuses on the analysis of the air-to-water HP operation with the aim to identify the potential to increase SCOP with the utilisation of the predictive control. The aim of this study is identification of possible increase of SCOP of the air-to-water heat pump with a predictive regulation in specific conditions of the Central Europe.

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To evaluate the potential of the predictive regulation the history of the outdoor temperature pattern was used – Central Europe, city of Brno (GPS 49.1961939N, 16.6071078E). European Heat Pump Association (EHAP) is located here. EHAP provides the measurement of heat pump parameters that were employed to compose this study. The Brno University Campus is a base for the continuous testing of HPs under natural conditions.
To assess the potential to increase SCOP by utilizing the predictive regulation of HP the following procedure was used: (i) detailed evaluation of long-term measurements of the outdoor temperature in the monitored location (time period from 2007 to 2016); (ii) determination of COP of air-to-water heat pumps introduced to the market in 2015; (iii) identification of SCOP within the scope of the conducted parametric study which focuses on the contribution of the predictive regulation.

2. Evaluation of the temperature ratios in the monitored location throughout the heating periods

The outdoor temperature is the most significant variable parameter that affects the COP of the air-to-water HP. This study includes evaluations of the long-term records of temperature from the meteorological station located in the city centre. Data from heating periods spanning from 2007 to 2016 were processed. The heating period is defined through the average daily temperature. The heating season starts when the average outdoor temperature, measured in two consecutive days, is lower than 13 °C. The heating season ends when the average outdoor temperature, measured in two consecutive days, is higher than 13°C. Duration of the heating season is given by the pattern of the actual environment temperature and its duration varies from year to year.
The variation in the temperature during the individual days of the heating season is the main parameter of this study. In the first step of the evaluation process the beginning of the 24-h interval was set. This interval was used to assess the temperature patterns in detail. The beginning of the 24-h interval has to allow a practical evaluation of intraday accumulation. For this purpose, it is necessary that the assessed 24-h interval allowed charging and subsequent discharge of the accumulator. To ensure this condition a moment when the day temperature pattern most frequently exceeds the average daily temperature was identified. This moment was identified and set to 9:20 AM. The evaluated 24-h interval was set from 9:20 AM to 19:19 AM, see Figure 1.

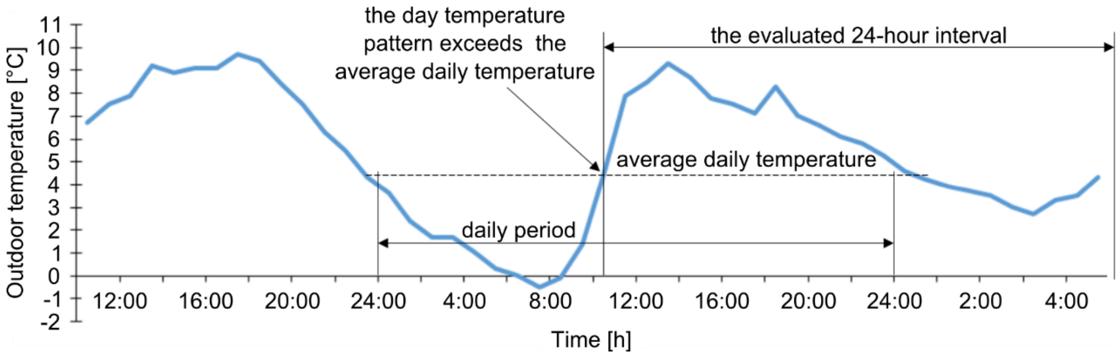

Figure 1: Graphic depiction of the evaluated 24-h interval

Further assessment of the temperature patterns is based on the statistical identification of the air temperature difference within the 24-h intervals. This parameter was from the long-term records assessed according to the average daily temperature, see Figure 2. This figure presents a dependency obtained for the maximal 24-h temperature T_{max} and dependency obtained for the minimal 24-hour temperature T_{min}. The dependency lines of T_{max} and T_{min} form a border of the area inside which are situated all the values from the monitored sample data. Figure 2 is extended by the average dependency lines for maximal and minimal temperature difference from average daily temperature.

3. Determination of COP for air-to-water heat pump

The basic parameter that is used to evaluate the heat pumps is the coefficient of performance (COP). COP represents the quotient of the heat pump power $\dot{Q}_{HP}$ and electric power P_{HP}.

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

The higher the COP the greater is the operating effectivity of the heat pump. COP changes based on the conditions under which the heat pump operates. COP is also affected by the temperature difference between the outdoor temperature and the heating water temperature (Hepbasli and Kalinci, 2009).

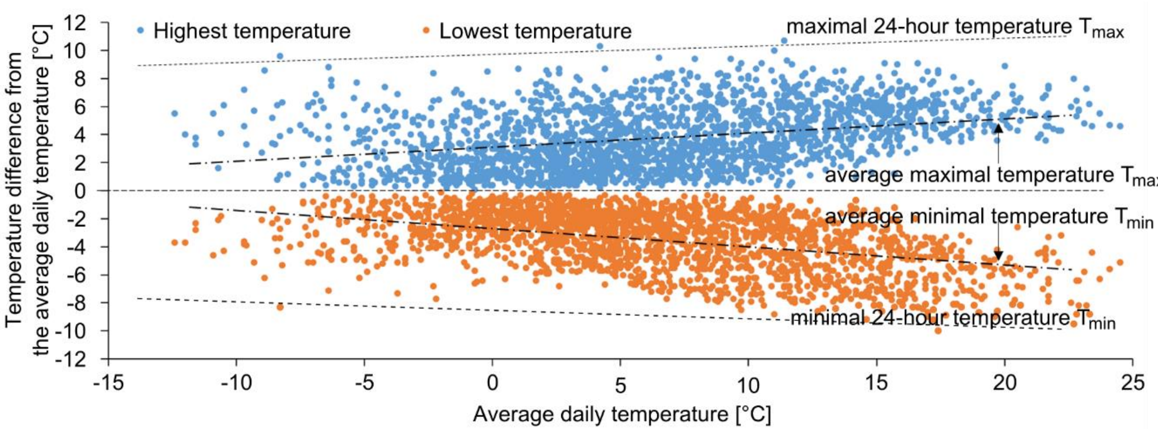

Figure 2: Relation of maximal/minimal air temperature during 24-h interval and average air temperature, heating seasons 2007-2016

This study employs COP values of air-to-water HP obtained in the year 2015 by an accredited measurement in the regional centre of European Heat Pump Association (EHAP), Czech Republic. When testing the air-to-water HPs, the units were placed into the climatic chamber where the normalised outdoor temperatures and relative humidity were changed. The units were tested in the air temperatures: 12 °C, 7 °C, 2 °C, -7 °C, and -15 °C. The HPs were tested in outermost points where the operation is guaranteed by the manufacturer. To simulate the heating system the HPs were connected to a hydraulic circuit. Testing was carried out using heating water with temperatures: 35 °C, 45 °C, 55 °C, and 65 °C. Constant conditions were kept during the measurement, i.e. constant temperature and air humidity, constant input and output temperature of heating water.
Based on the experimentally gained data a dependency of COP was obtained as a function of the temperature difference ΔT_{aw} between the temperature of air T_{aut} and the temperature heating water T_{w2}, see Figure 3 and Eq(2) and Eq(3). This dependency represents the mean value gained on the samples of air-to-water HPs tested in 2015. These are the newest models of HP that have been tested before introduction to the marked.

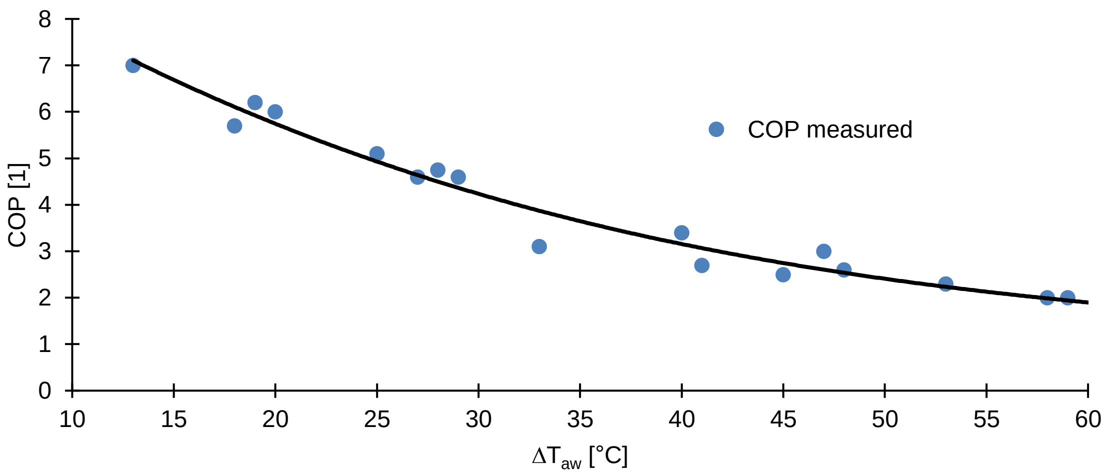

Figure 3: Dependency of COP on the temperature difference T_{aw}

The gained COP dependency is for the need of calculations expressed in polynomial expression:

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

where

$$\Delta T_{aw}=T_{w2}-T_{out} . \quad (3)$$

4. Model determination of seasonal coefficient of performance

4.1 System with HP and without heat accumulator

The economic assessment of the HP operation demands monitoring of HP operational parameters in a wider range of operational temperatures. The seasonal coefficient of performance (SCOP) represents an average heating COP for the heating season. First, direct hook up of the HP to the heating circuit without the accumulator is presumed. Setting of the SCOP is based on the average daily temperatures during the monitored 24-hour intervals and on the required heat output. The heat loss of the object $\dot{Q}_l$ is used to set instant values of the required heat output of HP:

$$\dot{Q}_l=\dot{Q}_{l,n}\cdot\frac{T_{in}-T_{out}}{T_i-T_e} \quad , \tag{4}$$

where $\dot{Q}_{l,n}$ is the computational heat loss of the object; T_{in} is an instant internal temperature; T_{out} is an instant outdoor temperature; T_i is a computational internal temperature; and T_e is a computational outdoor temperature. The immediate outdoor temperature is used for equithermal regulation of the heating water temperature. Lower outdoor temperature results in the need for higher temperature of the heating water. This ensures the balance between the supplied heat and the heat loss of the building. The heating system reacts to the specific outdoor temperature (T_{out}) reacts by correcting the temperature of the heating water (T_{w2}) as follows:

$$T_{w2}=(T_{w2,n}-T_i)\cdot\frac{T_{in}-T_{out}}{T_i-T_e}+T_{in} \ . \tag{5}$$

The average air temperature of each day during the heating season is attributed corresponding heat loss of the object ($\dot{Q}_l$). The amount of necessary heat energy during the 24-h interval is given by formula:

$$Q_{24}=24\cdot\dot{Q}_l \ . \tag{6}$$

The amount of necessary power for HP operation during the monitored day is calculated as

$$P_{24}=\frac{Q_{24}}{COP_{24}} \ . \tag{7}$$

The COP value varies from day to day. The COP is affected by the temperature difference between the outdoor temperature and the heating water temperature. Operation of the HP during the entire heating season can be assessed with use of the seasonal coefficient of performance (SCOP). Calculation of SCOP is based on the actual temperature pattern in the monitored location during the entire heating period. The resultant value of *SCOP* is obtained by an overall processing of the 24-hour intervals during the entire heating period:

$$SCOP=\frac{\sum COP_{24}\cdot Q_{24}}{\sum Q_{24}} \ . \tag{8}$$

The calculated values of *SCOP* are graphically presented in Figure 4 for studied years.

4.2 System with accumulation of the heat

The other assessed possibility of the HP powering takes into account addition of the heat accumulator to the heating system. Accumulator is a reservoir filled with water. The reservoir is connected to the system as a flow volume, see Figure 5. This type of accumulation does not require any additional temperature drop to charge/discharge the accumulator (Arteconi et al., 2012).

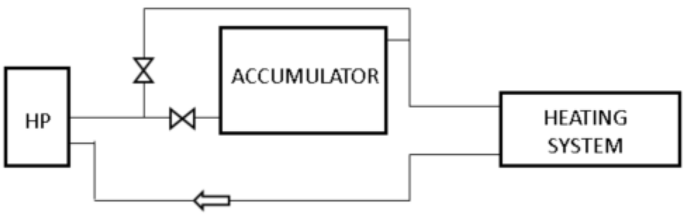

Figure 4: System with a flow volume accumulator

The utilisation of the heat accumulator allows to operate the HP in the given parameters only during the specific time periods of the day. The demand on the heat supply in the remaining time periods of the day is covered by the accumulated heat. This method of HP operation ensures the minimization of the number of starts. This is a significant operation advantage which favourably affects the reliability of the unit's operation and durability (Arteconi et al., 2013).
The benefit of heat accumulation that ensures priority operation of HP during the days with higher temperature is evaluated in this work. The influence of the HP operation during the warmer parts of the day is assessed by utilising the created mathematical model. Within the 24-h period a period needed for HP operation an interval τ_{HP} is identified:

$$\tau_{HP}=\frac{24}{k_{HP}\cdot COP_{24}} \quad (9)$$

Within the time interval τ_{HP}, HP supplies the heating system and the accumulator with heat in the amount needed during the 24-h interval. Coefficient k_{HP} presents the ratio of the nominal heat pump input P_{HP} and heat loss of the object $\dot{Q}_l$,

$$k_{HP}=\frac{P_{HP}}{\dot{Q}_l} \quad (10)$$

When assessing SCOP the following processes were used: (i) within the evaluated 24-h were identified period specific hourly intervals with the highest air temperature (τ_{HP}); (ii) the average air temperature was set for a set of hourly intervals identified in the previous step; (iii) COP_{τ} was set for the relevant average temperature from the previous step; (iv) $SCOP_A$ was calculated by an overall processing of all 24-h periods of the heating period,

$$SCOP_A=\frac{\sum COP_{\tau}\cdot Q_{24}}{\sum Q_{24}} \quad (11)$$

The calculated values of $SCOP_A$ are graphically presented in the Figure 5 for particular years.

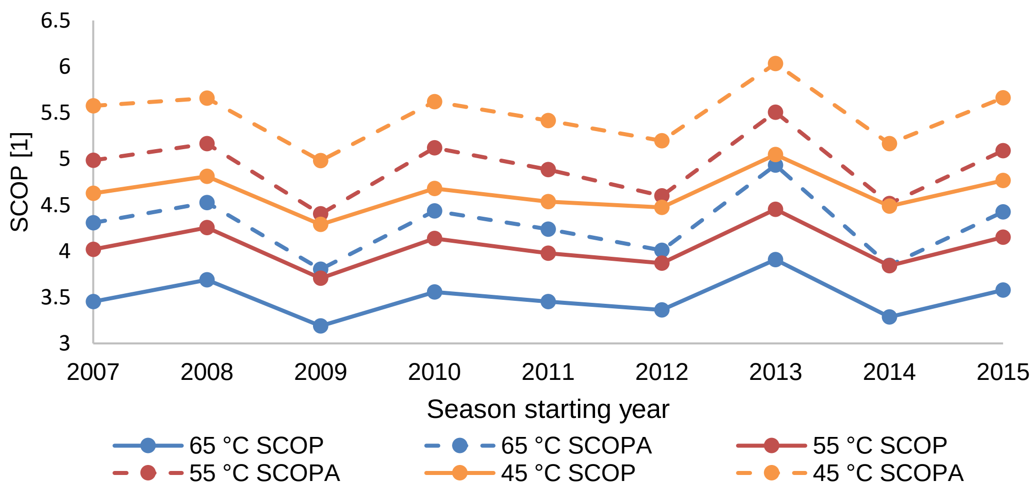

Figure 5: Identified SCOP and $SCOP_A$ in heating seasons 2007-2016

4.3 Identification of SCOP and $SCOP_A$ in real life conditions

Evaluation of the long-term operation of the HP was performed for configurations with and without accumulation. Air temperature patterns in the time period from 2007 to 2016 were used to set the real SCOP of the air-to-water HP operating in Brno, Czech Republic. The generalized dependency of heat pump COP (2) was used for evaluation. Following input conditions were used for carried out calculations: the internal temperature T_{in} = 22 °C; computational internal temperature T_i = 22 °C and computational outdoor temperature T_e = -12 °C.
The Figure 5 presents the results of carried out calculations for different heating water temperature in studied heating seasons, namely 45 °C, 55 °C and 65 °C. The label "SCOP" identifies the results obtained for system without accumulation of the heat. The label "SCOPA" identifies SCOP values obtained for system with accumulation. All results presented at the Figure 5 were obtained from carried out mathematical simulations.

5. Conclusions

This paper presented evaluation of the real seasonal coefficient of performance of the air-to-water heat pump operating without the accumulation in specific conditions of the central Europe. The real historical air temperature records were used for detailed evaluation of SCOP within the time period 2007 to 2016. The benefit of heat accumulation was evaluated with utilizing of built up mathematical model.

An accumulator enables priority operation of HP during the hours with higher outdoor temperature. From this study results, the potential for an increase of the SCOP of the predictively controlled HP is up to 20 % in geographic conditions of the Central Europe. That causes approximately 20 % decrease of seasonal power consumption. Increase of SCOP is more significant for heating seasons with higher average outdoor temperature. The HP system with accumulator ensures the minimal number of starts. This is a significant operation advantage which favourably affects the reliability of the unit's operation and durability.

This type of operation can be engaged by systems of predictive control of HP with utilizing weather forecast for estimation of outdoor air temperature changes.

The contribution of the study presents quantitative determination of SCOP potential increase for air-to-water HP in the heating systems with significant accumulation capacity. This solution seems to be a perspective way for more effective operation of air-to-water HP.

Acknowledgments

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