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Potential of predictive control for improvement of seasonal coefficient of performance of air source heat pump in Central European climate zone

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ABSTRACT

This paper compares different operation models of the air-to-water heat pump (HP). Detail focus of this study aims at a potential to increase seasonal coefficient of performance (SCOP) by utilising the predictive control. The considered predictive control uses an outdoor air temperature forecast for the upcoming 48 h. The predictive control operates the heat pump so that it runs, preferably, during the periods of the day with the highest air temperature. For a detailed assessment, a model of the heat supply system with a heat pump supplemented by a heat accumulator has been developed. The mathematical model involves detailed algorithm for time-dependent quantification of the heat demand for the considered model building. Dataset of real operation tests of the HP helps correctly evaluate the coefficient of performance (COP). An original algorithm of predictive control has been developed and tested for different operating parameters and different capacities of the heat accumulator. A long-term record of air temperatures from the last ten years is employed to evaluate the model. The mathematical model allows for a complex parametrical study to evaluate the relations of SCOP - accumulator capacity, SCOP - method of heat pump control.

1. Introduction

The general trend in the heating systems is to lower the energy consumption of heat sources. This objective can be achieved by improving the buildings' thermal properties or by enhancing operational efficiency of energy sources and heating systems. The efficiency of heat source operation is directly associated with its control. The basic method for regulation focuses only on the actual heat demand without any reference to the previous operational record or prediction of future operational states. This method of control is suitable for heat sources with constant efficiencies and energy prices. HPs use electricity as their power source and its price varies during the day. The controllers of HPs are made to shift the operation time to periods with lower electricity price. In order to eliminate operation of HPs during periods with higher electricity prices, it is necessary to implement an adequate utilization of thermal storage. Advanced systems of HPs control use either static models based on an operational history record or predictive models operating with a heat demand forecast. The long-time operational efficiency of an air-to-water HP can also be improved if the control unit accounts for the prediction of future outdoor temperature.

Research constantly strives to produce effective and eco-friendly ways of providing heating and cooling for buildings. One of the ways to achieve this goal is to use a heat pump (HP). HPs are a time proven and reliable technology but they still have a great potential for improvements. The hardware of the technology could be the state of the art with the coefficient of performance (COP) in the range of 3.2–4.5 [1]. However, the control units are still mostly rigid PID or equithermal regulation. With the development of modern computers and connectivity technology, a control unit for HP can be much more sophisticated and provide better operation options.

A great deal of research has been done in that field on employing different controlling approaches to HP. Numerous published studies by different authors describe new designs of the HP control units that apply a fuzzy control [2]. Another study presents

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Nomenclature

MPC	model predictive control
PCM	phase change material
EHPA	European Heat Pump Association
T_{min}	minimal daily temperature (°C)
T_{max}	maximal daily temperature (°C)
T_{out}	actual outdoor temperature (°C)
T_{in}	actual indoor temperature (°C)
T_{av}	average outdoor temperature in 24 h interval (°C)
T_e	standardized outdoor temperature (°C)
T_i	standardized indoor temperature (°C)
T_{w2}	temperature of heating water (°C)
$T_{w2,n}$	temperature of heating water for standardized outdoor temperature (°C)
ΔT_{aw}	difference between actual outdoor and actual heating water temperatures (°C)
$\dot{Q}_l$	actual heat loss of a building (W)
$\dot{Q}_{l,n}$	heat loss of a building for standardized temperatures (W)
$\dot{Q}_{l,av}$	average heat loss of a building in 24 h interval (W)
Q_{24}	total heat loss in 24 h interval (Wh)
$\dot{Q}_{HP}$	output power of a heat pump (W)
P_{HP}	input power (electric) of a heat pump (W)
P_{24}	energy input to heat pump in 24 h interval (Wh)
k_{HP}	ratio of nominal heat pump output power and heat loss of a building
COP_τ	coefficient of performance for average temperature of period chosen by predictive control
$SCOP_A$	seasonal coefficient of performance with predictive control and heat accumulation
ACU	heat accumulator

relatively simple mathematical models for optimization of air-source HP [3] and more sophisticated models for self-optimizing control systems in air-source HP [4]. Some control units were developed only for a particular type of heating systems. The [5] introduces a control unit which optimizes an air-source HP supplying a floor heating system. The ground source HPs can optimize operations with respect to long-term heat potential of boreholes [17]. Limited number of applications employs artificial neural networks for control units [6] and MPC [7]. All these approaches improve HP operations from 1.7 [3] to 20% [2]. Another approach that has been under intensive focus is to couple together renewable energy sources (namely PV panels) and HPs for household applications and thus lower electricity bills. Research in this field is taking advantage of today's advanced weather predictions [8] and reports success in the HPs self-consumption in theory and experiment alike [9]. Some authors optimize the control units of HPs for economical operation in the fixed scheme of time variable electricity prices [10]. More complex approach was tested for economical HP operation via real time pricing [11]. Another operation approach was tested for buildings with sufficient production of electricity from PV panels [12]. HPs installations are frequently connected with water heaters. The [13] introduces appropriate control system developed especially for these installations.

Advanced algorithms for HP control are also advantageous for applications in smart grids where they can provide better grid stability and foothold for decentralized energy grids [1]. Weather forecasts are not useful for the area of energy production only, but also for actual energy consumption. Better prediction of building's energy losses is also reported to provide a higher efficiency of HPs [14]. Even for this purpose, advanced models were developed using Stochastic Model Predictive Control and weather predictions [15]. The prediction of energy losses is more important for buildings with large-scale HVAC systems [16].

Predictive control of air-to-water HP has a significant potential for improvement of a seasonal coefficient of performance (SCOP) that subsequently causes a shorter return on investment [18]. This study focuses on assessment of the potential to increase the SCOP that is attainable via selection of appropriate operating parameters. The study in no way aspires to evaluate real operating costs paid by owners of the HPs. Similar work has been previously done in a short paper by Kandler et al. [19] who took advantage of HP, PV panels, and weather forecast. The model and data are not well described and the results are scarce, the prediction is considered only 24 h ahead, but it reports a significant boost in performance and cost reduction. More detailed work has been done by Fischer et al. [10] who coupled PV panels with HP. The self-consumption of electricity from PV is of the main focus and they reported a significant cost reduction. However, the COP of the HP was lowered by running mostly in times with low electricity prices, but also with low outdoor temperatures. The cost reduction was between 6 and 16%. Another important result is that influence of a forecast error is marginal. The carried-out literature review shows high sensitivity of HP controlling systems to temperature fluctuations during day periods. These fluctuations differ for different locations. So, it is impossible to develop a generally valid control system optimized for different geographical conditions. There is still a relevant need to develop HP predictive control algorithm optimized for a specific temperature pattern valid in a location of HP future installation.

This article focuses on a detailed assessment of the potential improvements acquired through the usage of a predictive control for an air-to-water HP. This type of HP represents a heat source whose operational parameters are highly dependent on the outdoor temperature. The dependency of COP of the mentioned HP on the varying outdoor temperature supports the importance of the predictive control usage [20]. This method of regulation prefers operation in periods when the outdoor temperature is higher. Various predictive controllers for HPs are being developed with this aim. These systems generally use local meteorological condition forecasts. The prediction of the outdoor temperature is usually known with a sufficient accuracy for the next 72 h. Any predictions for longer time intervals are often burdened by significant errors and they are not accurate enough for the purposes of the HP's predictive control. This state is sufficient enough to meet the requirements of the predictive control used for air-to-water HPs. The predictive control is able to identify periods with the most efficient operational conditions for HP for the next several hours (days).

In Central Europe, the outdoor temperature varies from 4 to 12 °C during the day. These fluctuations allow for a significant improvement of SCOP when an appropriate predictive regulation is used. The real contribution of the predictive control to the improvement of SCOP is related, among other factors, to the usable volume of the thermal storage. For this reason, the systems using HP with the predictive control require integration of an additional thermal storage. Accumulators most often use direct heating of water and less often heating of adequate phase change material (PCM). The optimal volume of the thermal storage can be chosen by a complex assessment of the technical parameters of a HP, operational demands of a heating system and the outdoor temperature progression.

The authors of this study focused on a detailed assessment of the potential improvement of SCOP of an air-to-water HP located in Central Europe, namely in the City of Brno (49.1961939 N, 16.6071078 E). Various algorithms usable for predictive control are compared and special attention is being paid to the quantification of the potential improvement of SCOP via: (i) change in the length of the time horizon used by the predictive control, (ii) change in the volume of the thermal storage and (iii) change of the HP's output power. Tests were carried out on historical records of the outdoor temperature acquired from the central part of the city of Brno in time-period from 2007 to 2016. Technical parameters of the HP that are used in this study were acquired from the measurements conducted by local laboratory European Heat Pump Association (EHPA), located in the Czech Republic. These parameters represent averaged operational values of the air-to-water HP measured by EHPA during 2015 and correspond to the new HPs placed on the market in 2015 and 2016.

The study works with a method for quantification of a potential for improvement of SCOP which contains the following steps: (i) assessment of the historical outdoor temperature records, (ii) correlation of COP of the model HP with the outdoor temperature, (iii) quantification of SCOP for a specific heating season. This sequence of steps is employed for assessment of all intended cases.

The main goal of this work is assessment of benefits of the HP predictive control algorithms. Two operation algorithms of a heat pump predictive control were proposed and tested. The proposed algorithms are based on information about 24 h and 48 h weather forecast of air temperature. The tested HP control algorithms do not account for prices of electricity. The predictive control algorithms are primarily optimized to increase the HP's SCOP. The quantification of the related increase in the HP's SCOP is carried out for meteorological conditions valid for the City of Brno. The SCOP was evaluated on the historical ten-year air temperature pattern obtained from in-situ measurement. The particular temperature conditions of the studied location provide unique results valid for this part of the Central Europe.

2. Historical record of outdoor temperature in the studied location

A comparison of tested predictive models is conducted on the basis of historical data of outdoor temperature from 2007 to 2016. These records of outdoor temperatures have been previously collected in the central part of the urban area located in the City of Brno (pop. 400,000). For the purposes of the study, the periods of heating seasons are identified. The beginning of a heating season is defined as three consecutive days in which the mean outdoor temperature drops below 13 °C. Similarly, the end of a heating season is defined as three consecutive days in which the mean outdoor temperature rises above 13 °C. The time span of heating seasons in individual years differ, but in general falls within a range from 190 to 240 days.

In the following data analysis, the mean outdoor temperature for each day is calculated. Those temperatures are the most common parameter used for the HP's efficiency factor evaluation. Their usage is adequate for gross estimation of daily average COP of the HP. Since the mean outdoor temperature does not include any information about temperature fluctuations during the day, the maximum temperature T_{max} and the minimum temperature T_{min} are identified for each day to capture the temperature changes. Fig. 1 shows the maximal and minimal daily temperatures for all days in all heating seasons from 2007 to 2016. The maximal temperature difference for all individual days is expressed as a function of the daily temperature average. The set of points in the graph is bounded from above by the line “maximal 24-h temperature T_{max}” and from below by the line “minimal 24-h temperature T_{min}”. Those lines are diverging from each other with the rising daily average of the outdoor temperature. The boundary lines cannot be used correctly for assessment of COPs since they do not represent the statistically significant number of days. For assessment of the HP's performance, it is appropriate to use the “average maximal temperature T_{max}” and the “average minimal temperature T_{min}” (see Fig. 1). The daily average difference of the outdoor temperature increases with the rising average of the daily outdoor temperature. Fig. 1 also presents a group of points corresponding to an average daily temperature above 13 °C. These points represent local extremes occurring during the heating season. These are the days with a markedly elevated temperature that mostly occur randomly at the beginning or at the end of the heating season.

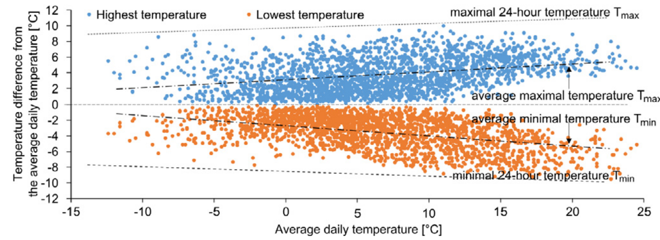

Fig. 1. Max. and min. outdoor temperatures during 24-h intervals expressed as relation of the average daily temperature, heating periods 2007–2016.

The outdoor temperature typically fluctuates within a range of 4–12 °C during one day. Statistical evaluation of the outdoor temperature recorded in individual days shows that the average difference of intraday temperature increases with the rise of the daily average temperature. This trend is significant for the daily average temperature above minus 5 °C. For days with a lower average daily temperature, this is no longer valid. Under conditions with a mean daily temperature below minus 5 °C, the average difference of intraday temperature is close to 8 °C. Fig. 1 shows that the values of individual days have a considerable variance around the average maximal temperature and also around the average minimal temperature. For this reason, the mean values of the minimal and maximal intraday temperature cannot be used for the detailed evaluation of the SCOP of the air-to-water HP. For the correct SCOP evaluation, it is necessary to separately evaluate the progression of the outdoor temperature during each day of the heating season. This procedure was used to obtain the results presented in this paper.

3. Heat pump coefficient of performance

The HP's coefficient of performance (COP) is a basic parameter used for evaluation of a heat pump effectiveness. The COP is equal to the HP's heat power $\dot{Q}_{HP}$ divided by the electric power P_{HP}.

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

The operation effectiveness of the HP rises with the increase in COP. The COP is strongly affected by the temperature difference between the input heat flux and the output heat flux of the HP [21].

For this study, we defined a so-called model air-to-water HP. For this model HP, the relation between the COP and the temperature difference was obtained from real measurements carried out by the European Heat Pump Association, Czech Republic branch (EHPA). The relation represents the average value obtained from measurements of all air-to-water HPs tested by EHPA in 2015 [22]. The tested HPs were models introduced to the market in 2015 and 2016. In Fig. 2, the obtained dependency of COP is expressed as the function of ΔT_{aw}. The temperature difference ΔT_{aw} is expressed as a difference between the temperature of the outdoor air T_{out} and the temperature of heating water T_{w2} (Eq. (3)).

The obtained relationship between the COP and the temperature difference has the following 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. Heat pump with daily updated control

This chapter deals with the determination of the potential for SCOP increase using the predictive control and supplementing the system with a heat accumulator. The potential for the SCOP increase is determined by comparing the HP operating without the predictive control and the HP operating with the predictive control. The predictive control considered in this chapter takes into account the daily updated prediction of the outdoor temperature.

4.1. Heat pump without predictive control

The HP and its parameters have to be monitored under a wide range of temperatures to properly assess the HP's operation. The main indicator in this work is considered to be the HP's seasonal coefficient of performance (SCOP). The first evaluated configuration, shown in Fig. 3, is a direct connection of the HP to the heating system. This heating loop does not include any kind of thermal accumulator. COP, based on the outdoor temperature, is calculated for each hour of the 24-h interval. SCOP is then defined from the particular COPs.

Use of predictive control algorithms requires accurate time dependant quantification of heat demand of the model building. These are general requirements for all configurations considered in this paper. The heat demand calculation must be involved in predictive algorithms, too. The heat demand of the heating system supplied by the HP is considered as equal to the actual heat losses of the model building $\dot{Q}_l$. The heat loss involves the heat flux through the envelope of the building (walls, windows and doors) plus heat utilized for heating of incoming fresh air, necessary for air exchange in the rooms. The standard heat loss $\dot{Q}_{l,n}$ is calculated for standard air temperature. The actual heat loss of the model building is

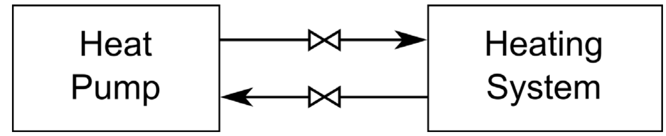

Fig. 3. Scheme of simple system with heat pump.

continuously calculated for real temperatures using the following equation:

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

where $\dot{Q}_{l,n}$ is the heat loss of the model building for a standardized indoor temperature T_i and standardized outdoor temperature T_e. The T_{in} is the actual indoor temperature of the building, T_{out} is the actual outdoor temperature.

The temperature of the heating water is a parameter directly influencing the COP value of HP. This temperature must be controlled by an equithermal regulation which uses outdoor temperature as its input parameter. The result is an inverse proportion of temperature of the heating water temperature to the outdoor air temperature. That provides equilibrium between the heat supply by the heating system and the heat loss of the building. The formula providing the heating water temperature T_{w2} for a specific outdoor temperature (T_{out}) is written below:

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

Where $T_{w2,n}$ is the computational temperature of heating water corresponding to the standardized outdoor temperature T_e.

To account for thermal inertia of the building, the losses of the building are not considered to be dynamically changing each hour but instead to be constant for each 24-h interval; the losses are calculated from the interval's average outdoor temperature (T_{av}) using the following formula:

$$Q_{24} = 24 \cdot \dot{Q}_{l,av}. \quad (6)$$

$\dot{Q}_{l,av}$ is calculated the same way as $\dot{Q}_l$ but the T_{out} is replaced with T_{av}.

The specific amount of heat power that has to be produced by HP in order to fully cover the heat losses of the building during the 24-h interval is calculated as follows:

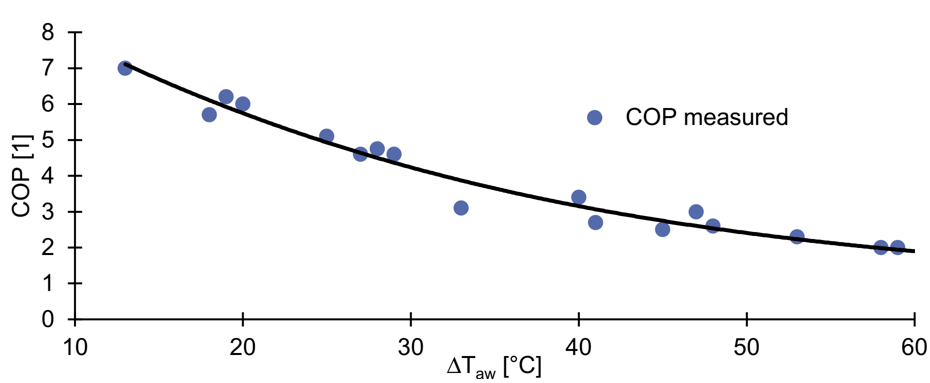

Fig. 2. Relation between COP and temperature difference ΔT_{aw}.

$$P_{24} = \frac{Q_{24}}{COP_{24}}. \quad (7)$$

The value of COP is different for each 24-h period (day) and is affected only by the difference between the heating water temperature and the outdoor temperature. To evaluate the performance of the HP during the entire heating season, a seasonal coefficient of performance (SCOP) can be applied. SCOP is essentially a weighted average value of each day's COP where every day of the heating season is accounted for, meaning that the SCOP is dependent on the temperature pattern of the given location.

$$SCOP = \frac{\sum(COP_{24} \cdot Q_{24})}{\sum Q_{24}}. \quad (8)$$

The model evaluation of the HP operation was performed for following conditions. These conditions are used for all configurations considered in this paper. Hourly temperature values, measured throughout the heating seasons 2007–2016, were used for evaluation of SCOP of an air-to-water HP. The measurements took place in Brno, Czech Republic. For evaluation of the instant heat power output of the HP, generalized dependency of HP's COP (2) was employed. The following temperature inputs were used for identification of heat loss of the model building: the uniform indoor temperature of the building $T_{in} = 22\,°C$; the standard uniform indoor temperature $T_i = 22\,°C$ and the standard computational outdoor temperature $T_e = -12\,°C$. Three different computational temperatures of heating water $T_{w2,n}$ were tested: 45 °C, 55 °C and 65 °C.

Results of SCOP calculations are graphically presented for different heating temperatures in Fig. 6 for all studied years. The SCOP value varies significantly throughout the years. This behaviour is affected by the nature of each heating season. The heating seasons differ in the average outdoor temperature and also in the number of days included in the heating season. As the temperature of the heating water decreases, the HP's SCOP value increases. The following SCOP values were calculated for the first evaluated year (2007): $T_{w2,n} = 45\,°C$ .. $SCOP = 4.5$; $T_{w2,n} = 55\,°C$ .. $SCOP = 4.0$; $T_{w2,n} = 65\,°C$ .. $SCOP = 3.5$.

4.2. HP with daily updated predictive control

Another configuration of the HP control is to enhance the previous configuration by adding a heat accumulator. The proposed configuration is shown in Fig. 4 and is called “theoretical” because it considers an infinite accumulator, which means it is always able to provide energy to cover the heat loss of the building. The infinite accumulator does not require temperature drop in order to be charged or discharged, either [23].

Developed algorithm identifies the periods of the day with the highest air temperatures. The predictive control operates the heat pump so that it preferably runs during the periods of the day with the highest air temperature, see Fig. 5. The time interval for operation of HP is determined in relation to the predicted heat demand of the heating system.

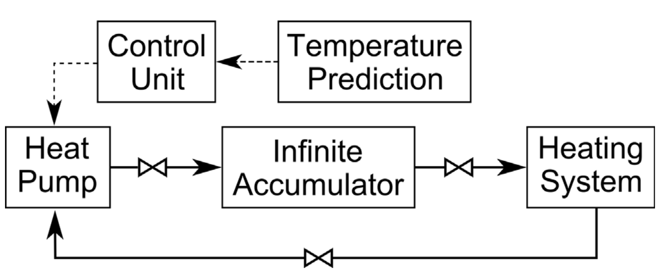

Fig. 4. Configuration of HP connected to infinite accumulator.

For an infinitely large accumulator, there is no need to monitor the immediate operating capacity or charge level. This configuration assumes that in the warmest periods of the day, it is always possible to store all the heat produced by the heat pump into the accumulator. The configuration further assumes that there is always enough heat in the accumulator to cover the needs of the heating system during the cold period. Each day, the calculation algorithm provides a balance between the amount of heat supplied to the accumulator and amount of heat removed from the accumulator. The configuration represents a significant idealisation. Using the historical record of the outdoor temperature, it is possible to determine the theoretical SCOP value achievable at the maximum possible utilization of intraday outdoor temperature fluctuation. Every day of the heating season is evaluated individually. The influence of the outdoor temperature on the previous and the next day is not considered in this configuration. One day is defined by a time interval 00:00–23:59. This controlling approach represents the simplest application of predictive control with minimal requirements on the control unit. The approach also matches with the practical implementation of HP predictive control that updates the outdoor temperature forecast once in every 24 h. Moreover, this approach is also easily applicable when evaluating the historical records of the outdoor temperature.

With the infinite accumulator in the heating circuit, it is possible to operate the HP only during the hours with the highest outdoor temperature. The heat loss of the building in the remaining hours is covered by the accumulated heat. Intraday balance is kept in equivalence between the demand of the heating system and HP production. A number of starts and overall operating hours is smaller than without the accumulator. Since the lifetime of several HP's components is rather limited, accumulator may actually prolong durability of the HPs [24].

A mathematical model was developed to evaluate the HPs with infinite accumulator that operate only in the warmest hours of a day. To cover the accumulator discharge in every 24 h period, the HP must operate in a certain period or periods that are defined as τ_{HP}:

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

k_{HP} is a coefficient that represents the ratio of the nominal HP output P_{HP} and heat loss of the building $\dot{Q}_l$:

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

To evaluate the SCOP of the HP, the following procedure was followed: (i) intervals within the 24-h period with the highest outdoor temperatures were identified and sorted in a descending order; (ii) the operating period τ_{HP} was defined by the 24-h period heat loss of the building for the intervals from the previous step; (iii) an average outdoor air temperature was calculated from the operating period defined in the previous step; (iv) using the average temperature from the previous step, a COP_τ was calculated; (v) daily COP_τs for the entire heating season were calculated, $SCOP_A$ of the heating season is determined as a weighted average:

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

Evaluation of the long-term operation of the HP was carried out

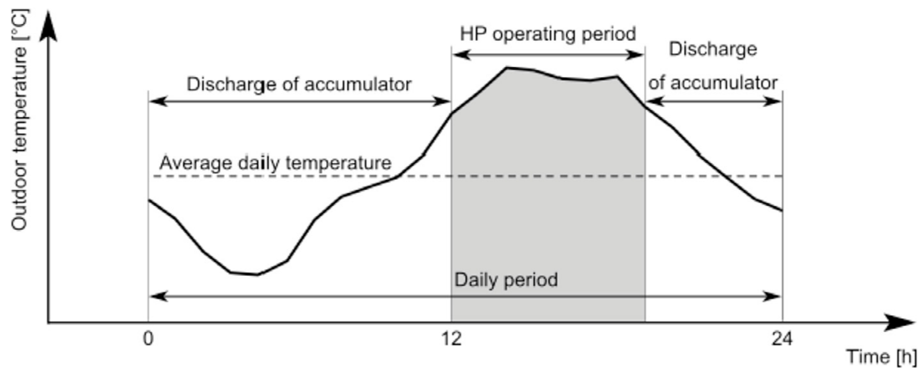

Fig. 5. Schema of HP operation periods identified by intraday predictive control.

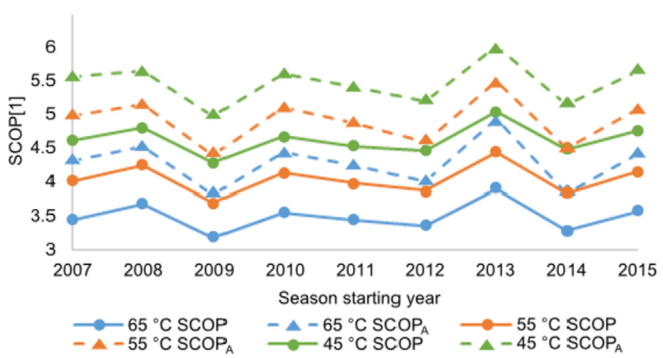

Fig. 6. Identified SCOP and SCOPA for air temperature pattern of heating seasons 2007–2016.

for configurations with and without the infinite accumulator. The outdoor temperatures from the heating seasons 2007–2016 were used to evaluate the seasonal coefficient of performance of the air-to-water HP. The calculated values of $SCOP_A$ are graphically presented for heating water temperature of 45 °C, 55 °C and 65 °C in Fig. 6. The label “SCOP” identifies the results obtained for the configuration without accumulation of the heat. The label “$SCOP_A$” identifies SCOP values obtained for the configuration with daily updated predictive control and with an accumulation of heat. All results presented in Fig. 6 were obtained via mathematical simulations. The results of this study show an interesting potential of a HP predictive control. The predictive control increases the SCOP by up to 20%. The results are valid for the geographic conditions of Central Europe which are characterized by significant intraday temperature fluctuations. Engagement of the predictive control and the infinite accumulator enables an approximate 20% decrease in overall HP power consumption. The SCOP increase is more significant for heating seasons with a higher average outdoor temperature.

This chapter compared two theoretical air-to-water HP configurations. In the first case, the SCOP was calculated for a configuration completely without the heat accumulation. In the second case, the SCOP for a theoretical configuration including the infinite heat accumulator was defined. However, every real heating system is associated with a certain, not negligible accumulation capability. When the system actively supplements the heat accumulator, the storage capacity is significantly increased but still rather limited due to the limited size of the accumulator. Greater storage capacity allows to take advantage of possibly greater optimization capabilities utilizable by predictive control.

5. Heat pump with hourly updated predictive control

This chapter focuses on use of hourly updated predictive control for regulation of the HP operation. The predictive control runs the HP, preferably, in warmer time periods. During these periods, the HP will cover immediate demands of the heating system for heat supply and ensure accumulation of thermal energy in the accumulator. During periods of low outdoor temperatures, the HP is not operated and the accumulator is being discharged. The predictive control cannot be used without a suitable accumulator. The appropriate size of the accumulator can be determined using the calculation model.

Two different accumulator capacities connected to the heating system were tested in the study. The capacity of the first accumulator was chosen to match the heat loss of the model building during the coldest day of the heating season. This accumulator is referred to as “ACU 100%.” The capacity of the second accumulator “ACU 50%” was set as a half of the storage capacity of the first accumulator. The connection of a real accumulator requires a continuous monitoring of the actual charge of the accumulator. When the accumulator is not fully charged, the HP is operated during periods of the highest outdoor air temperature. In this case, the HP operation is close to the operation of the configuration with the daily updated predictive control. If the demand of heat for the heating system increases, it is necessary to extend the operation times of the HP even for hours with a lower outdoor air temperature. The predictive control is still trying to exclude the operation during the colder hours of the day. Use of predictive control therefore requires feedback for the control unit about the current state of the accumulator charge, see Fig. 7.

5.1. Algorithm for hourly updated predictive control

To evaluate the influence of predictive control, an algorithm was developed to identify suitable periods of HP operation. This algorithm is based on a short-term prediction of the outdoor air

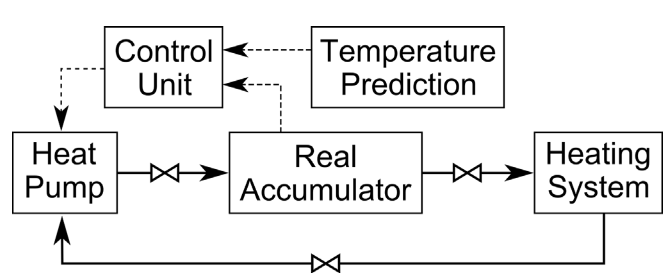

Fig. 7. Configuration with predictive control of heat pump and real accumulator.

temperature available for the upcoming 24 h. The predictive control algorithm itself consists of several follow-up steps that repeatedly evaluate the progression of the predicted outdoor temperature and the current state of the accumulator charge.

The predictive control administers the energy accumulated in the accumulator to provide the heat supply with the highest COP of the HP for a specified period of time (the upcoming 24 h). The accumulator is charged and discharged during the 24-h period. At the end of the 24-h period, the accumulator is assumed to be completely discharged. In the upcoming hour of operation, the observed 24-h period is shifted by 1 h. The temperature development over the upcoming 24 h is updated. The predictive algorithm repeats the identification of the appropriate heat pump periods with the highest outdoor temperature, see Fig. 8.

If the accumulator is fully discharged, the heat pump will operate continuously with the heat power corresponding to the immediate demand of the heating system. In this mode, the control unit disregards the current outdoor temperature. Continuous running of the HP takes up to a period of time determined by the predictive control as appropriate for charging the accumulator.

Fig. 8 shows the temperature prognosis for a specific 24-h period. The vertical line indicates the end of the 24-h period. Periods with the highest air temperature are indicated when the HP is running and the accumulator is charging. The heat pump does not work in other periods. During these periods, the heat for the building is supplied by a gradual discharge of the accumulator. The current state of the accumulator charge is presented in Fig. 8 where it is indicated with a dashed line. The HP running plan is updated in the following hour in a time period shifted by + 1 h.

The assumption of the accumulator's full discharge is related to the effort to make maximal use of the accumulator's capacity. Lower water temperature in the accumulator causes a reduction in the heat loss of the accumulator. For practical applications, the accumulator would not be completely discharged for safety reasons. The minimum charge level would be set to 20%.

The 24-h interval may be extended or shortened, as required. The following chapters present results of a parametric study aimed at comparing HP operating parameters, depending on the predictive control used for the length of the evaluated interval. In particular, the predictive intervals of 24 h and 48 h were compared.

5.2. Predictive interval: 24 h

The algorithm described in the previous chapter was put to use in a parametric study using the outdoor temperature prediction for the next 24 h. During calculation, the HP heat power "HP100%" was determined as the heat production corresponding to the maximum model heat supply demand on the coldest day of the relevant heating season. Other tested HP heat powers correspond to 150% and 200% of the maximum model heat supply demand. These HP

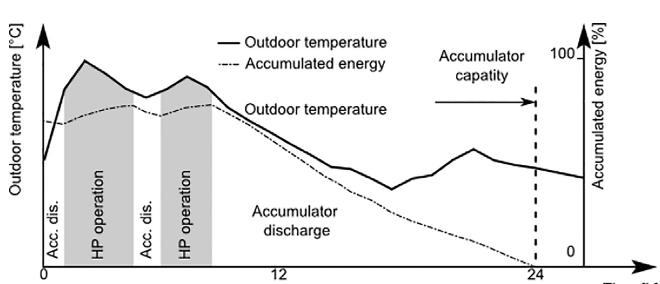

Fig. 8. Illustrative record of HP operating with predictive control for particular outdoor temperature pattern.

heat powers are labelled "HP150%" and "HP200%", respectively. Two different accumulator capacities were considered in the parametrical study. The capacity of the first accumulator "ACU100%" corresponds to a 24-h operation of a heat pump with the heat power HP100%. The other accumulator "ACU50%" has half the capacity of the "ACU100%". The generally defined HP heat powers (HP100%, HP150%, HP200%) and accumulator capacities (ACU50%, ACU100%) enable us to work with the acquired dependencies for an arbitrary building, based on available heat demand requirements.

The parametric study tested all combinations of the considered parameters. Historical records of the outdoor temperatures were used for the evaluation. The temperature record was limited for the heating seasons of 2007–2016. Figs. 9–11 present the average values of the monitored parameters obtained from the carried-out evaluation.

Fig. 9 shows the calculated dependencies between the number of operating hours and the heat power of the HP. With the increase of the HP heat power, the number of HP operating hours decreases. The number of operating hours is further influenced by the temperature of the heating water. The increase of the heating water temperature causes an increase in the HP operating hours. Capacity of the accumulator does not affect the number of the HP operating hours.

Fig. 10 presents dependence between the HP number of starts and the heat power of the HP. The trend of the individual dependencies is not unequivocal. However, the decrease in the HP number of starts and increase in the heat power of HP are noticeable. The tested algorithm of the predictive control provides a

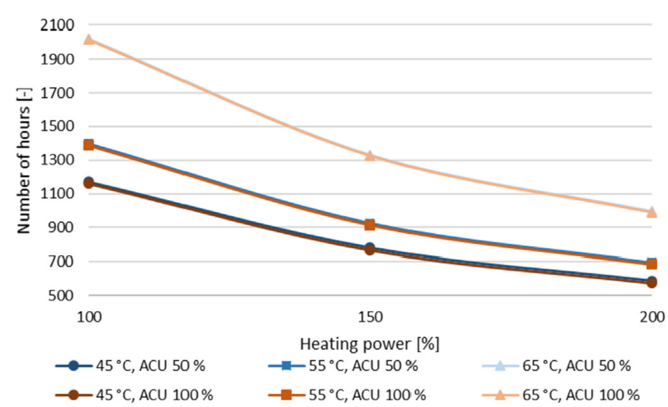

Fig. 9. Relation between the number of working hours and the heat power of HP.

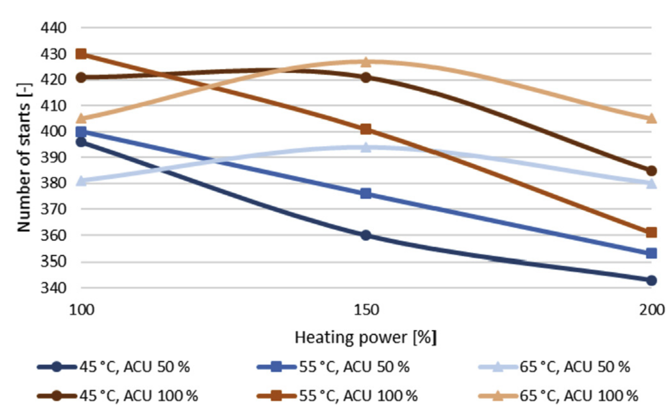

Fig. 10. Relation between number of starts and heat power of HP, predictive control 24 h ahead.

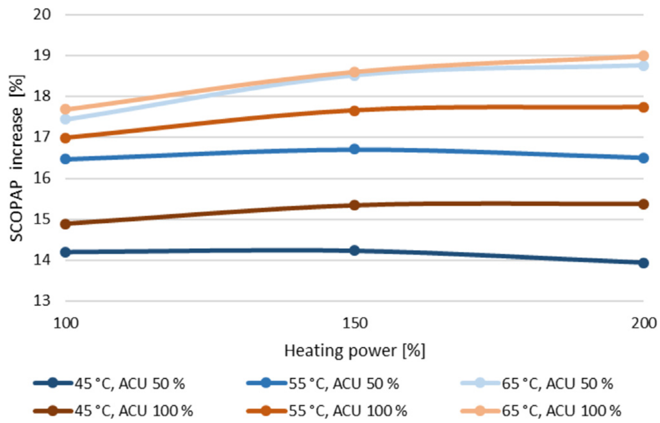

Fig. 11. Relation between increase of SCOP and heat power of HP, predictive control 24 h ahead.

greater number of starts when using a larger "ACU100%" accumulator compared to the "ACU50%" accumulator.

Fig. 11 shows an increase in the SCOP of HP using the predictive control in comparison to the operation without the predictive control. The increase in the HP heat power causes the increase in the SCOP thanks to the more intensive use of periods with the increased outdoor air temperature for the heat pump operations. The increase in the SCOP is more important for heating systems with a higher heating water temperature. The highest achievable SCOP increase value is 19% for one heating season.

5.3. *Predictive interval: 48 h*

The same evaluation method was put to use in a parametric study using the outdoor temperature prediction for the upcoming 48 h. Figs. 12–14 present the average values of the monitored parameters obtained for all combinations between HP100%, HP150%, HP200%, ACU100%, and ACU50%. The monitored parameters were evaluated on a pattern of historical air temperature records from heating seasons 2007–2016.

The general trends in the behaviour of the presented relations of the monitored parameters obtained for temperature prediction for the next 48-h interval are close to the trends presented in the previous chapter for the next 24-h interval. The same number of operating hours is necessary to ensure the same heat supply, see Fig. 12. Extending the predicted temperature period leads to a significant reduction in the HP number of starts, see Fig. 13. Extending the predicted temperature interval causes an increase in the SCOP of the HP. The highest achieved SCOP increase value is 23% compared to the option without the predictive control, see Fig. 14.

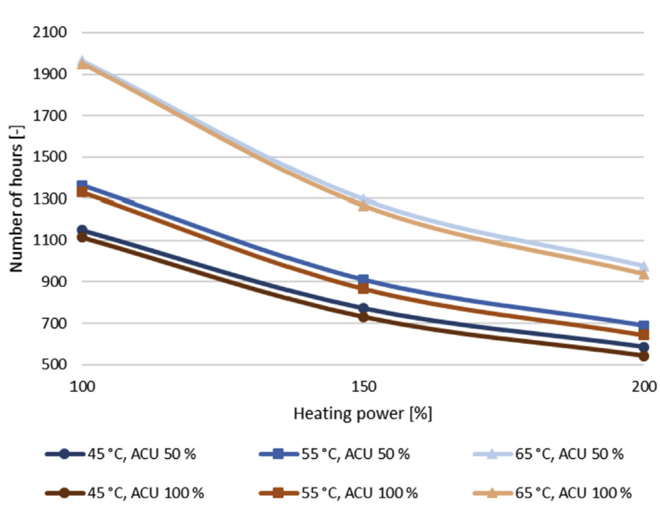

Fig. 12. Relation between number of working hours and heat power of HP, predictive control 24 h ahead.

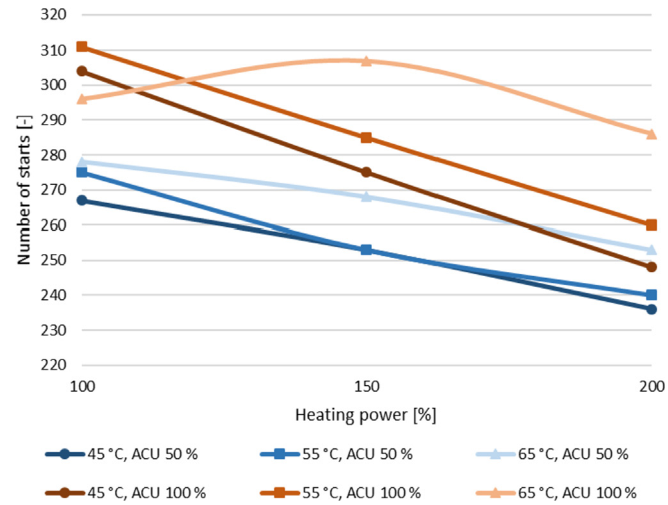

Fig. 13. Relation between number of starts and heat power of HP, predictive control 48 h ahead.

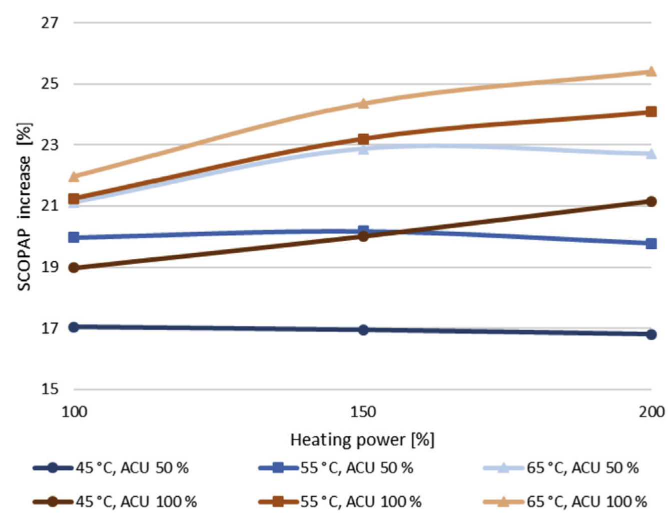

Fig. 14. Relation between increase of SCOP and heat power of HP, predictive control 48 h ahead.

6. Conclusion

The presented study focuses on quantification of the potential of the SCOP increase that may be available when predictive control to operate the heat pump is employed. The predictive control together with a heat accumulator enables operation of the HP during time periods with the highest outdoor temperature. The mathematical model of the heat pump configuration, the accumulator, and the heating system requirements was developed and tested for purposes of this study. The procedure detailed in this article quantified the SCOP of the model air-to-water HP operating under climatic conditions of the Central Europe. The historical long-time records of outdoor air temperature were utilized for the presented study. In the sub-steps of the study, SCOP was quantified for 4 specific configurations: (i) HP running without the predictive control, (ii) HP running with the intraday predictive control, (iii) HP running with the predictive control tracking a 24 h temperature prediction, (iv) HP running with the predictive control tracking a 48 h temperature prediction.

Trends in the behaviour of the main operating parameters were obtained by comparing the evaluated configurations. The presented results were obtained for temperature conditions of the City of Brno located in the climatic zone of the Central Europe. The results of this study demonstrate that the potential of heat pump predictive control is an increase in the SCOP by up to 23%. This increase in SCOP corresponds to approximately 20% decrease in a year based power consumption. The potential increase in the SCOP rises with an increase in the average air temperature of the heating season. Applying the predictive control further reduces the number of HP starts, which is an important operating parameter that significantly affects the HP's lifetime.

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