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Testing method for evaluation of a realistic seasonal performance of heat pump heating systems: Determination of typical days

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Abstract

The seasonal performance of heat pumps is often projected on the basis of static performance tests in combination with seasonal boundary conditions. A novel approach uses dynamic simulation methods and a Hardware-in-the-Loop (HiL) test bench. It allows to realistically consider system dynamics and influences of a system control. Therefore, approaches for the determination of test days for the calculation of the seasonal performance of heat pump heating systems are investigated. Different procedures are analyzed using a comprehensive simulation model consisting of the heat generation, the heat distribution system as well as the heat source and heat sink. Different types of heat pump systems are considered. Subsequently, reference simulations are carried out for the complete period of operating time of the heat pump system. Thereafter, the test procedures are applied to the simulation model and simulated as well. The seasonal performance received from the reference and the test procedure's simulations are compared. The results show that a clustering of relevant weather data by the k-medoid method yields in the smallest deviations in seasonal performance of reference simulation and simulation of the test procedure.

Keywords - Heat pump, Simulation, Testing method, Seasonal performance

1. Introduction

The momentary efficiency expressed by the coefficient of performance (COP) of heat pump systems varies immensely with influencing factors like temperature of the heat source, temperature level of the heat demand and part load behavior. The Seasonal Performance Factor (SPF) describes the overall efficiency of heat pump systems for the full period of a heating season. While the COP under static conditions can easily be investigated with steady-state experiments, the investigation of the SPF is more complex. The changing boundary conditions, as well as dynamic effects, such as start-up behavior have to be taken into consideration.

Standard procedures for the determination of the efficiency of heat pump heating systems do not consider the dynamic interaction of the heat pump and the building including the thermal masses of storages and the heat distribution system or the system control and refrigerant cycle control. This is also why there is no incentive for the heat pump manufacturer to design intelligently controlled heat pump heating systems. Considering existing heat pump tests, it seems rather advantageous to design heat pumps that perform well under static conditions. This is not automatically beneficial for the seasonal performance of the heat pump built into a real heating system.

One possible way to determine the SPF of a heat pump system experimentally is the use of the hardware in the loop (HiL) concept. For the investigation the heat pump system is mounted on the test bench and operates normally. The environment of the heat pump system, consisting of heat source and heat sink is emulated by the test bench which exchanges signals with a simultaneously running simulation. This approach allows the heat pump system to be tested under realistic working conditions. HiL test benches have been developed at the Institute for Energy Efficient Buildings and Indoor Climate (EBC) in Aachen. However, it is not the scope of this paper to describe these test benches in detail.

In order to receive a realistic estimation of the overall efficiency of the heat pump system for the period of one year the system is tested under typical conditions representing the boundary conditions that will occur during the operating time of the heat pump system. The challenge is to receive results, as realistic as possible, whilst keeping the test cycle as short as possible. This paper investigates possible procedures that can be used on a HiL test bench to experimentally determine the SPF of heat pump systems.

For this purpose simulation models of a dwelling, equipped with different heat pump systems, are set up and used to evaluate the accuracy of the tested procedures. Existing approaches for testing procedures of heat pump systems are taken into consideration and adapted.

2. Term definitions and control volumes

Different definitions of terms and control volumes exist. The ones used in this paper are described in the following. The COP describes the ratio of the instantaneous provided heat flow rate to the instantaneous electrical power consumption of the heat pump.

$$\mathrm{COP} = \dot{Q}_H / P_{\mathrm{el}} \tag{1}$$

The SPF describes the ratio of provided heat by the heat pump system over the whole period of one year/heating season to the electrical energy consumed over the same period of time.

$$\mathrm{SPF} = Q_{\mathrm{H}} / W_{\mathrm{el}} \tag{2}$$

Guidelines and standards often define the seasonal COP (SCOP) as a calculated seasonal efficiency representing the SPF (see e.g. standard EN 14825). The SCOP is used in cases in which the COP is projected on annual time series of heat source and heat sink temperatures through a calculation method. These are static calculation methods that base on the static determination of the heat pump's COP in testing procedures standardized by EN 14511. As the procedure developed here is not going to use statically measured COP values, seasonal performances are determined using the term SPF according to (2).

Fig. 1 shows a heat pump heating system with an air-to-water heat pump, a combined storage which functions as buffer and domestic hot water storage and the building with its heating system. The storage holds an electric auxiliary heater. The control volume "heat pump" is used in static testing procedures (e.g. according to EN 14511) and includes electric power consumption of the source and loading cycle drives. The system control volume "HPS" includes the power used for auxiliary heaters and considers the heat flow measured behind the storage, thus including storage losses. This second control volume is the one relevant for the user and used for further evaluations within this paper (index HPS).

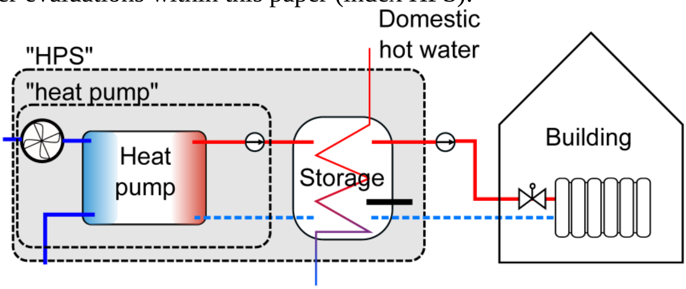

Fig. 1: Scheme of a typical heat pump heating system with control volumes.

3. Existing methods

Different methods exist for seasonal evaluations of heating systems. The Concise Cycle Test is a procedure to investigate the performance of a solar combi system, consisting of solar collectors and a conventional second heat source, such as a boiler. It has been developed by the SPF Institute at the University of Applied Science of Rapperswil in Switzerland. This test bases on a twelve day long test of the system hydraulics which is used to fit and validate a simulation model [1].

A dynamic testing procedure for ground-coupled heat pump systems has been developed by the Centre Scientifique et Technique du Bâtiment, Sophia Antipolis, France [2]. A combination of quasi realistic experiments and simulations is carried out. For the experiments the heat pump is mounted onto a test rig. The other parts of the system, such as geothermal collectors, the heating system and the building physics are simulated. In order to evaluate the annual efficiency of the tested heat pump system an annual simulation is carried out. For twelve days, one day per month, the simulation gets slowed down to real time and the simulation model of the heat pump gets replaced by the real heat pump via the test bench. The data of this one day long experiment is then used to create a characteristic grid for the heat pump model, carrying out the simulation of the following interval. Two approaches for the selection of test days for the real time experiments are suggested. For one the average energy demand is replaced with the average hourly values of all days of the month. The other approach takes days of the month that well match the monthly average energy demand of the building and the average radiation values for the respective month.

Another method was developed at the Institute of Thermodynamics and Thermal Engineering in Stuttgart, Germany [3]. In contrast to the prior mentioned testing methods, the components of the heating system, such as heat pump, solar collectors and buffer storage, get tested individually, not as a connected system. Subsequently, the experiment data is used for parameter identification in order to retrieve characteristic parameters for simulation models. The software TRNSYS is used for an annual simulation of the complete system.

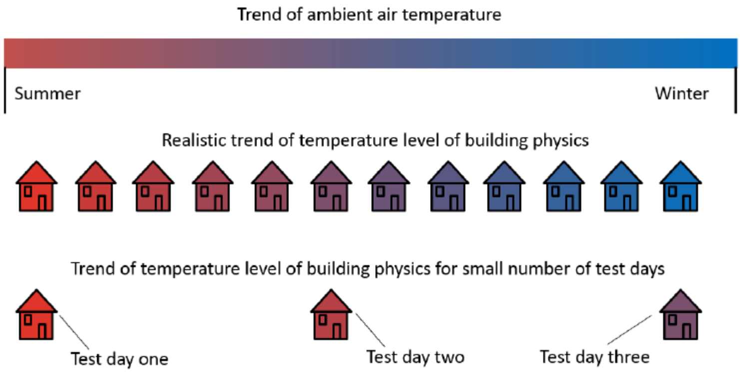

Fig. 2: Illustration of energy-shifting effect. Red: high temperature, blue: low temperature

A common challenge for these kinds of testing procedures is the energy shifting effect that is illustrated in fig. 2. Condensed typical weather data represents weather characteristics of a whole year/ heating period. As a result the transition from summer to winter is shortened, leaving no time for the heat, stored within the building physics, to be released. This leads to a reduced heat demand during winter, as part of the heat load is covered by the unrealistic warm building physics.

4. Development of test procedure

4.1. Concept of HiL

The concept of the test bench is that physical components are tested in a simulated environment. The test bench consists of a conditioned laboratory and a supply unit emulating the virtual environment [4]. The heat pump and the buffer storage are installed inside of the conditioned laboratory; the remaining components are emulated by simulation models, see fig. 3.

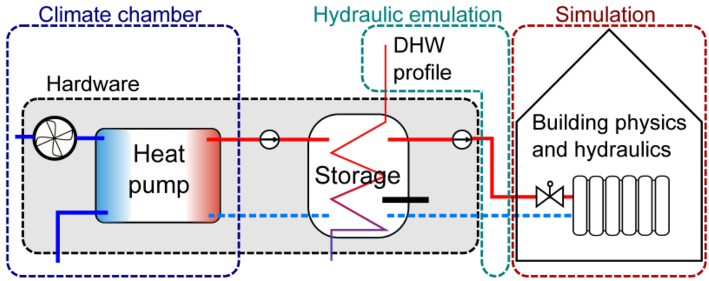

Fig. 3: Illustration of the HiL concept for an air-to-water heat pump heating system

Realistic weather data is used, in order to provide the heat pump with realistic heat source temperatures. The supply and return lines between the buffer storage and the hydraulic system and between the buffer storage and the field of solar thermal collectors (not shown in the figure) are connected to the supply unit. Simulation models for the virtual components and the virtual building use weather data and data for the internal loads to calculate the temperature of the return line mass flow with respect to the temperature of the supply line mass flow. Heat exchangers condition the return line mass flow according to the simulation of the components.

4.2. Evaluation method

The investigation in this paper does not make use of the test bench. The procedures are rather tested by using dynamic simulations only. Each testing procedure is evaluated in three steps: A reference simulation (index “ref”) of each system is done for the whole evaluation period (one heating season or a year) and the $SPF_{ref,HPS}$ is calculated. Then the testing procedure is simulated and an SPF_{HPS} is calculated. Finally, the two SPF are compared to each other by calculating their deviation.

Different types of heat pump systems are chosen: An air-to-water heat pump system as shown in fig. 1, an air-to-water heat pump system extended by a solar thermal collector that supplies heat to the storage and a brine-to-water ground-coupled heat pump system. All three systems are analyzed with and without domestic hot water (DHW) generation. This leads to a total of six investigated system configurations.

4.3. Simulation set-up

All used models presented in this paper are based on the object-oriented modelling language Modelica [5]. The compilation and simulation of each model is executed using the software Dymola [6]. The reference model emulates a dwelling with a radiator heating system, supplied by different heat pump systems. The building model was developed at the EBC. It is insulated according to the German Heat Insulation Ordinance of 1984. The selected radiator heating system is configured for supply temperatures of 55 °C and return temperatures of 45 °C. Each room is equipped with a thermostatic valve. The set-point for each room is 20 °C and constant throughout the year. The required supply temperature is controlled by an ambient temperature dependent heating curve. A heating period limits the operating time of the hydraulic heating system to the time between September, 15th and April, 15th. The building parametrization, the design of the heating system and the used user profiles including domestic hot water profiles are described in detail in [7]. The model of the building physics is freely available in the model library "AixLib", see [8]. The heat pump is modeled using a table-based black-box model and is also described in detail in [7]. The weather data used for the simulations and the determination of typical days is the one of the German Metrological Service's test reference year for region 5 (Essen, Germany) [9].

4.4. Sensitivity analysis

The first step to develop the testing procedures is a sensitivity analysis which investigates the influence of different boundary conditions on the SPF_{HPS}. Both the ambient air temperature and the solar radiation are subject to the sensitivity analysis. For each simulation one of the influencing factors of the weather of the test reference year gets altered, whereas the others remain original. After the simulation of the reference systems, for each altered influencing factor the SPF for each simulation is calculated. This analysis leads to relative factors for each system configuration and each influencing weather factor, and will be used in the procedures, see below.

4.5. Choice and development of investigated procedures

Among the procedures investigated are the aforementioned existing ones. One investigated procedure is the "equal distance method", were typical days are found by choosing days from the weather file in equal distance to each other and in the chronological order in that they occur in the weather file. Another procedure is the "typical average days method": The weather file is split into intervals and each test day is formed from average weather data of its interval for each hour of the day. This procedure leads to artificial days instead of realistic diurnal weather characteristics. The aforementioned procedures do not lead to satisfactory results. Instead of these procedures, most promising ones are presented below.

4.6. Least squares method

The first procedure choses typical days according to least squares using real weather data for each test day, received from the test reference year. For the selection of typical test days, the operating time of the heat pump system is divided into n_d intervals. Each interval gets represented by one of the days within the interval. For each interval the average value and the fluctuation of diffuse solar radiation, direct solar radiation and ambient air temperature are calculated. Subsequently, the same values are calculated for each day within the operating time of the heat pump system. For each interval, the day providing the smallest deviation between the daily values and the values for the corresponding interval, is selected to represent the interval during the testing procedure. The selection of the representative days is carried out, using a weighted least squares method, by means of minimizing (3).

$$\min_n \sum_i \left(\left[\frac{\updownarrow x_i^* - \updownarrow x_{n,i}}{\updownarrow x_i^*} \right]^2 \cdot (a \cdot f_i)^2 \right) + \min_n \sum_i \left(\left[\frac{\bar{x}_i^* - \bar{x}_{n,i}}{\bar{x}_i^*} \right]^2 \cdot {f_i}^2 \right) \quad (3)$$

Here, i is an index indicating the weather characteristic, n is the number of days in each interval, $\bar{x}$ is the average weather characteristics for an individual day, $\updownarrow x$ represents the fluctuation of weather characteristics for an individual day. $\bar{x}_i^*$ and $\updownarrow x^*$ are the respective values for an interval. f is the weighting factor according to sensitivity analyses. a is a factor weighting fluctuation against average values, which is set to 0.1 in this study.

In order to prevent transient effects from interfering with the testing procedure and to solve the energy-shifting issue the intervals between each pair of adjoining test days are simulated. The end values of each simulation serve as initial values for the following experiment. This approach allows the stored heat within the building physics of the virtual dwelling to drop realistically with the seasonal drop of ambient air temperatures, during the transition from summer to winter.

4.7. K-medoids clustering method

In contrast to the procedure described before, the selected test days in the second procedure do not represent an interval of the test reference year, but represent a cluster of days with similar weather conditions, occurring during the operating time of the heat pump system. These days may occur chronological far apart during the test reference year. The procedure uses the k-medoids clustering method, to divide the pool of days, forming the operating time of the heat pump system, into n_d clusters of days with similar weather conditions. For the k-medoids clustering method (4) is minimized.

$$\min \sum_{i=1}^{k} \sum_{x_j \in S_i} \left\| x_j - \mu_i \right\|^2 \quad (4)$$

x_j is a data point, μ_i the medoid of the cluster S and k the number of clusters. Applied to the selection of typical days for the testing procedure, the data points represent weather characteristics of a day within the operating time of the heat pump system. For the weighting of the individual weather characteristics the results of the sensitivity analysis are used. The distance between a specific day and a cluster center is calculated according to (5)

$$\sum_{x_j \in S_i} \left\| x_j - \mu_i \right\|^2 = \sum_i \left(\frac{\bar{x}_i^* - \bar{x}_i}{\bar{x}_i^*} \cdot f_i \right)^2 \quad (5)$$

$\bar{x}_i^*$ is the average weather characteristic for the cluster center, $\bar{x}_i$ is the average weather characteristic for a specific day and f_i is the weighting factor derived from the sensitivity analysis. The k-medoids clustering method requires the number of clusters n_d and a set of starting points as a starting basis. The method will then allocate all days within the operating time of the heat pump system to the cluster center with the most similar weather characteristics. In a second step new centers for each cluster are determined. Subsequently, the allocation starts all over again. These steps are repeated until the centers of the clusters stop changing.

For the experiment the selected test days are ordered by their chronological order of their appearance during the test reference year. A simulation of the intervals between the test days solves the problem of energy-shifting.

4.8. Simulated selcetion method

In contrast to the procedures investigated in the previous sections, the third method does not select the typical days with respect to the weather, but uses an annual simulation of the heat pump system to determine which days are most representative. Firstly a preliminary test of the heat pump is carried out in order to gather data then used to create a rough grid, describing the characteristics of the heat pump which is then used to parametrize a table based heat pump simulation model. Subsequently, a simulation for the operating time of the heat pump system is performed, using the model parametrized before. The result of the simulation is the basis for the selection of the most representative days. Therefore, the simulation results are divided into $n_d/2$ intervals. The performance factor is calculated for each interval. Additionally, the same values for each consecutive pair of days within each interval are calculated. Two consecutive days are selected from each interval in order to represent the corresponding interval for the test procedure. For the selection of the test day pairs (6) is minimized for each interval:

$$\min_i \left(\frac{|\mathrm{IPF}_i - \mathrm{DPF}_n|}{\mathrm{IPF}_i} \cdot f \right) \quad (6)$$

IPF is the interval performance factor, DPF the performance factor for a pair of test days, *i* is the number of the interval and *n* is the number of the pair of test days. *f* is a weighting factor resulting from the sensitivity analysis. The number of consecutive days, selected as representative days for each interval is depending on the operating intervals of the heat pump. It has to be ensured, that each sequence of possible test days contains at least one heat pump operation. If this was not the case, the sequences of potential test days would not be comparable. In order to prevent the energy-shifting effect to interfere with the accuracy of the testing procedure the experiment gets paused after each pair of test days. The initial values for the test of the next pair of test days are received by simulating the heat pump system for the period of time between the two pairs of test days, using the simulation model of the annual simulation.

For the simulated investigation of the simulated selection method the preliminary tests of the heat pump system are replaced by simulations of a grid based heat pump model. Since the original simulation model is based on a grid as well, the resulting grid of the preliminary test simulation will match the original grid almost perfectly. This could lead to unrealistically accurate results of the simulation of the procedure, compared to its execution on a HiL test bench.

5. Discussion of simulation results for different procedures

System configurations without DHW generation are simulated only for the heating period, systems with DHW generation for the whole year. Accordingly, the number of typical days are chosen.

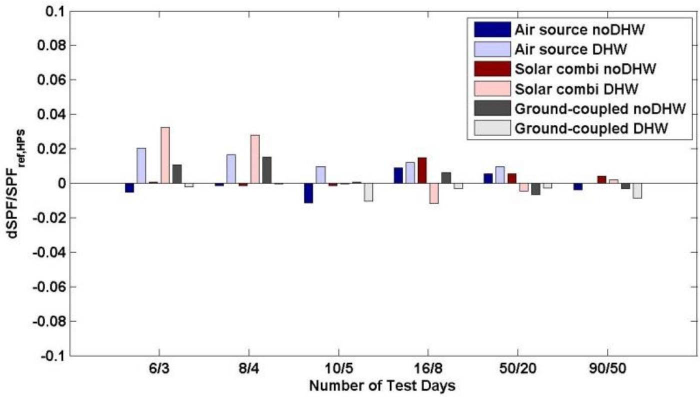

Fig. 4: Simulation results of SPF_{HPS} for k-medoids clustering method

Exemplary results for the k-medoid clustering method are shown in fig. 4. Even for small numbers of test days the relative deviation between reference simulation and simulation of the clustering method does not exceed 4 %. For at least ten test days for systems providing domestic hot water supply, respectively five test days for systems without, the procedure provides results for the efficiency of the heat pump system with a relative deviation smaller than 2 %. It is also shown, that the accuracy of the procedure strongly depends on the type of heat pump system. In general, with an increasing number of test days the deviations get smaller. However, this is a discontinuous trend as dynamic simulations of different test days are part of the results.

Tab. 1 shows that for 8/4 test days the k-medoids clustering method is expected to provide the best accuracy for the evaluation of the SPF of the investigated heat pump system. However, the average accuracy of the k-medoids clustering method regarding the estimated heat demand is insufficient for 8/4 test days. Therefore, the simulated selection method provides the best combination of accuracy of the estimated efficiency of the heat pump system and accuracy of the estimated heat demand. However, it is noticeable that in general the relative deviations of the heat demand exceed the relative deviations of the SPF values. The reason for this trend is that the procedures are carried out with respect to the results of the sensitivity analysis (least squares and k-medoid) or the simulated selection according to performance factors. The weighting factors provided by this sensitivity analysis only measure the impact on the SPF. They do not indicate their impact on the heat demand.

Tab. 1: Average deviations for all considered system configuration for the three investigated testing procedures for a number of 8 or 4 (w/o DHW generation) test days.

	$dSPF_{HPS,rel}$	$dSPF_{HPS,max}$	$dQ_{HPS,rel}$	$dQ_{HPS,max}$
Least squares	2.5 %	3.9 %	4.6 %	10.9 %
k-medoids	1.6 %	2.8 %	8.0 %	14.8 %
Simulated selection	1.7 %	3.3 %	2.9 %	7.7 %

6. Summary and outlook

The simulation results show that the typical days according to least squares method according to k-medoids clustering method and the simulated selection method are able to provide results for the SPF with a deviation of less than 4% for all tested heat pump systems, if the number of test days is at least eight for systems providing DHW and four for systems without generation of DHW.

The investigated testing procedures do not take into account the changing user behavior between seasons and between weekdays and weekends. The effect of different weather conditions and the effect of different heat insulation standards on the performance of the testing procedures have not yet been investigated.

The next step of the development process is to validate promising testing procedures on the HiL test bench, using a physical heat pump.

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