Quick seasonal performance testing for heat pumps

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Abstract

To determine the seasonal performance of heat pumps for energy labelling this study proposes a two-point-method that could conceivably be an alternative to the European standard EN 14825 and similar test standards such as ISO 13256. Heat pumps were tested in line with the EN 14825. The reduction of measurement points, from between five to seven (EN 14825) to only two (two-point-method), leads to 60 % savings in cost and time. It is shown that the shortened method can be used to determine the seasonal energy efficiency of heat pumps with the same degree of precision compared to EN 14825.

Introduction

Space and water heating is the largest source of global energy consumption in residential buildings, accounting for up to 56 % of the final energy use in households in 2010 and estimated to increase about 180 % until 2050 (Berardi 2017). Today, energy efficiency in buildings, and thus in the heating sector, is a prime objective for global energy policy makers (Chua 2013).

As a high-efficiency and low-emissions solution, several studies have identified heat pumps (HP) as the most promising technology for meeting future space heating needs. For example, Connolly, Lund and Mathiesen (2016) recently presented a comprehensive scenario for a 100 % renewable energy system in Europe using HPs in hybrid heating systems, e.g. a combination of solar thermal energy and HPs. Further, Mathiesen, Lund and Carlsson (2011) have shown the prospective value for HPs, especially regarding flexible electricity consumption.

In this context, methods to determine the seasonal performance of HPs under transient operating conditions have been of particular interest to researchers and engineers. These methods reflect the influence of compressor speed variation on seasonal performance and thus efficiency losses can be observed during transient operation (Corberán et al. 2013; Cuevas and Lebrun 2009). Dongellini, Naldi and Morini (2015) showed that HPs with variable speed compressors obtain higher seasonal performances than fixed speed HPs. Recently, Menegon, Soppelsa and Fedrizzi (2017) developed a dynamic test procedure reflecting the variation of the compressor speed as it would in the field for variable speed equipment. Haller (2013) developed three similar approaches of dynamic test methods for the determination of the performance of HPs combined with solar thermal systems. Most probably in the future, standardized test methods could incorporate dynamic approaches. However, the aforementioned approaches are still in the development stage and lack of reproducibility.

Current standardized test methods, in contrast, are based on steady-state approaches (fixed compressor speed), and are designed to deliver reproducible results. While dynamic testing supports the development of the HP during the R&D phase, standardized laboratory testing is needed to label and to compare the performance of different HPs. Mandatory product efficiency standards have been adopted in many countries in the past decades. As of 2013 around 81 countries are using labels and standards (Lloyd Harrington and Jack Brown 2014). Paul

Waide (2011) found out that in the five major economies, the US, China, the EU, India, and Japan, efficiency standards have been set out for more than 100 products, including HPs. Generally, these regulations reference the respective national technical standard to determine the seasonal performance of HPs. Several technical standards such as EN 14825 (FNKä 2016), ANSI/AHRI Standard 210/240 (AHRI 2008) and ISO 13526 (1998) are based on similar testing and calculation methods.

These standardized test methods are of very high complexity – associated with high costs – which led to resistance by the industry for several years during the standardization process (Hill 2001). For instance, the overall verification of the values declared on the European Energy Label according to EN 14825 currently takes three weeks of measurement and costs about 30.000 USD. Consequently, the current test method used for the determination of the seasonal performance of HPs contradict the intended property of a well-designed test procedure to be inexpensive (Lutz 2010). For these reasons, product design, R&D and compliance checks by market surveillance authorities require many expensive and complex tests in terms of time, resources and qualified personnel involved. Consequently, market surveillance activities are predominantly insufficient in the EU. (Pahal et al. 2013).

The optimization of the standardized seasonal performance test method with particular focus on economic aspects is an issue not yet sufficiently investigated in the literature. This study proposes a two-point-method as an alternative for product engineers to make the seasonal performance testing on HPs shorter and less expensive. The two-point-method uses the same methodology as defined in the aforementioned standards, but with reduced testing.

Experimental Details

In this paper, we demonstrate the reduction of measured operating points using the example of the European test standard EN 14825. In the EU, HPs are assigned an energy label according to the EU energy labelling regulation (European Commission 2013a; European Commission 2013b). To determine the classes on the EU energy label, this regulation refers to the European Standard for seasonal performance measurements of air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling; the EN 14825.

Coefficient of Performance (COP) measurements according to the current European test standard EN 14825 were carried out in accredited testing institutes in Germany. For reasons of comprehensibility, in this paper, only the experimental results of the brine/water HPs are presented. Similar results were found for air/water HPs. Detailed information about the tested brine/water HPs is given in Table 1.

TEST STANDARD EN14825

The EN 14825 is the current test standard for the determination of the seasonal coefficient of performance (SCOP) and the seasonal space heating energy efficiency η_s. It is composed of a measurement part, which describes the measurement of the COP at defined operating states, and a calculation part, which describes the calculation of the SCOP from the COP values, related climate zones and the power consumption in non-active modes (e.g. standby mode). The classification of a heat pump on the energy label refers to η_s, which is calculated from the SCOP. With regard to brine/water HPs the EN 14825 contains five measurement points at different temperatures, which refer to five operating states – one under full load and four under part load conditions, shown in Table 2.

As brine/water HPs operate with a constant source temperature the part load conditions are achieved by the variation of the supply temperature. However, for a general consideration of all types of heat pumps and all applications of supply temperature levels the part load conditions are analyzed with the correlated outside air temperatures.

For the calculation of the SCOP the measured COPs are interpolated over the typical European seasonal outside air temperature range (from -25 °C to 15 °C) to achieve the COP characteristic curve of the HP. To achieve SCOPs for different climate conditions the EU is split into three simplified climate zones based on hourly weather data: warmer (w), average (a) and colder (c) climates. Each color corresponds to a climate zone, as shown in the map of the EU in the inset of Figure 1.

To conclude for the SCOP the temperature-BIN-method is used. As shown in Figure 1 this method weights the outdoor air temperatures by their occurrences (assumed hours per year). Energy efficiency calculations are carried out at each outdoor

Table 1. Investigated brine/water HPs.

HP#	Design Heating Capacity (kW)	Investigated Supply Temperature (°C)	Seasonal Space Heating Energy Efficiency η_s (%)	Energy Efficiency Class
1	10	55	130.34	A++
2	12	35	219.00	A+++
3	42	55	138.80	A++
4	6	55	117.10	A+
5	18	55	126.90	A++
6	5	55	122.40	A+
7	19	55	123.00	A+
8	5	55	112.70	A+
9	14	35	185.30	A+++

Table 2. Test point conditions according to EN 14825 for brine/water and air/water HPs and COP terms used in this paper.

Operating Point	High Supply Temperature Level (°C)	Low Supply Temperature Level (°C)	Outside Air Temperature (°C)	COP Terms
E: Full Load	55	35	not defined	COP55
A: Part Load	52	33	-7	COP52
B: Part Load	42	27	2	COP42
C: Part Load	36	25	7	COP36
D: Part Load	30	25	12	COP30

air temperature within the range of -25 °C to 15 °C to calculate the SCOP.

The SCOP is defined as the total reference annual heating load Q_H divided by the total annual power consumption Q_{HE}. Beside the COPs, the Q_{HE} includes the energy consumption in non-active mode, the rated heating capacity and the duration in active mode, again dependent on the climate.

In the following analysis, the temperatures with the highest influence (highest weighting) on the resulting SCOP are identified and the seasonal space heating energy efficiency η_s is calculated from only two temperature values. The results are compared to the EN 14825 (measurement at five temperature levels) in order to analyze the precision of the proposed method. The EN 14825 assigns a reference annual heating load Q_{Hi} for each BIN-temperature, which are summed up to result in the total reference annual heating load $Q_H = \Sigma^i Q_{Hi}$. Figure 2 shows the share of the reference annual heating load $Q_{Hi} = Q_H$ as a function of the BIN-temperature.

The distribution is based on the test results of the tested HPs and the consideration of the three climate zones. The temperatures at which the four COP part load measurements according to EN 14825 are conducted are marked with spots. Figure 2 clarifies that the distribution of the annual heating load is not dependent on the tested HP as there is no deviation within a climate. However, the distribution of the annual heating load is strongly dependent on the climate zones. The green marked spots represent the measurement points of the EN 14825 that have the largest influence on the SCOP for each climate, respectively. This is at outdoor temperatures of 2 °C and 12 °C. The same dependencies as shown for Q_H were observed for Q_{HE}.

In accordance with the 2 °C and 12 °C outside temperatures, the supply temperatures with the largest influence on the SCOP would be the temperature levels of 42 °C and 30 °C for brine/water HPs (see Table 2). However, an in-depth analysis has shown that a combination of 42 °C and 55 °C is the preferable choice as we observed significantly higher deviations between the measurement according to EN 14825 and the two-point-method when using 42 °C and 30 °C compared to when using 42 °C and 55 °C. Since the measurement at 30 °C has the greatest influence on the SCOP only for warmer climate and the measurement at 55 °C has a similar or higher influence on the SCOP for colder and average climate (see Figure 2), 55 °C is given preference over 30 °C. Hence, the measurement for the temperature values of 55 °C and 42 °C are chosen for the two-point-method. The corresponding measurement points for low temperature HPs are at temperature values of 35 °C and 27 °C according to EN 14825. (See Table 2.)

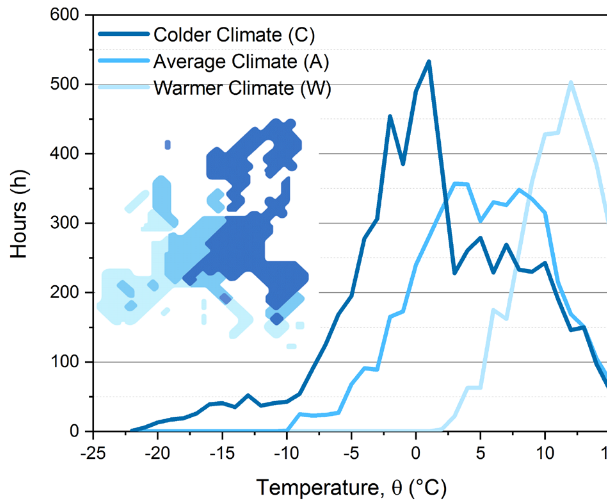

Figure 1. BIN-temperature hours according to EN 14825 (FNKä 2016).

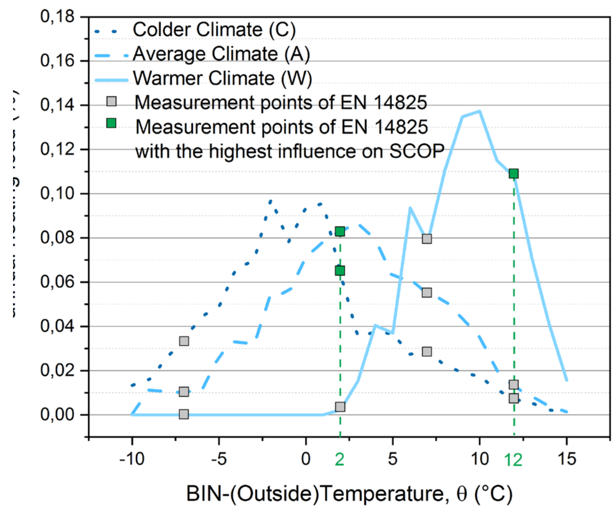

Figure 2. Share of the reference annual heating load as a function of the BIN-temperature.

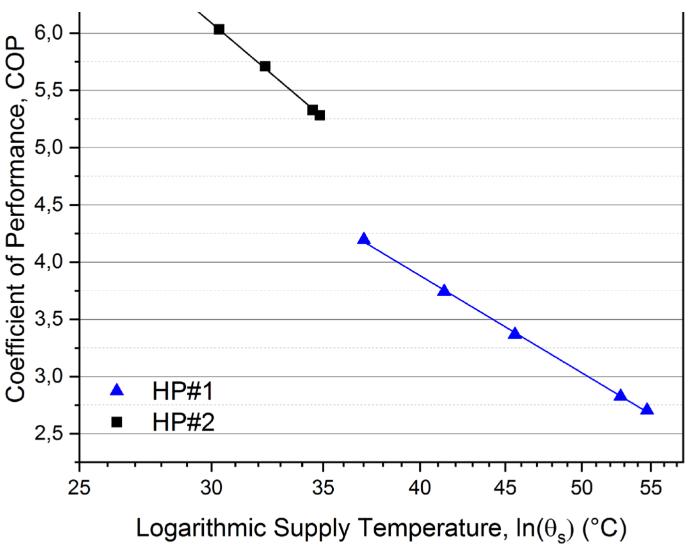

Figure 3. COP as a function of the supply temperature (ln θ).

Results and Discussion

CORRELATION OF THE COP VALUES

Two HPs, HP#1 and HP#2 (see Table 1), were tested according to EN 14825 to determine the COPs for the operating points A–E (see Table 2). The measured COP values were plotted against the logarithmic supply temperature ln θ resulting in a linear function:

$$COP = a - b \cdot \ln \theta \quad (1)$$

Figure 3 shows the results of the COP measurements according to EN 14825.

As the tested units have fixed-speed compressors the supply temperatures have been adjusted according to Annex D of EN 14825 (FNKä 2016)[1], respectively. The straight lines show the linear fit with correlation coefficients R2 higher than 0.99 for both tested HPs. For the COP values the deviation does not exceed 1 %. Hence, the COP of the two-point-method is a logarithmic function of the supply temperature according to Equation 1.

TWO-POINT-METHOD

The previous section clarified the precision of the logarithmic fitting curves. In this section, the two-point-method is introduced and verified. As shown in section "Test standard EN 14825", the supply temperatures 55 °C and 42 °C were selected for the measurements of the two-point-method. In these two operating states measurements with seven HPs, HP#3–HP#9, were undertaken to determine the COPs, COP55 and COP42, respectively. The three other COP values under part load conditions (COP52, COP36 and COP30) were calculated according to equation 1. As a reference, the seven HPs were also tested undertaking the whole testing procedure according to EN 14825.

Figure 4 shows the results of both, the two-point-method (squares) and the measurements according to EN 14825 (circles). The measured COP values from the tests according to EN 14825 are precisely superimposed by the calculated COPs from the two-point-method. The average deviation between the results determined with the two-point-method and the current test standard is 0.63 %. COP values can vary by ±4.44 %, in case that the tolerances for the measurement conditions, such as temperature or volume flow rate, according to the test standard EN 14825 were exhausted. Regarding the given tolerances, the average deviation of 0.63 % between the results determined with the two-point-method and the current test standard seem negligible.

The precision of the two-point-method regarding the seasonal space heating energy efficiency η_s is even of more importance than the COP values as it is used for the classification on the energy label. Thus, from the calculated COPs the SCOP and η_s were calculated according to Equation 2:

$$\eta_s = \frac{SCOP}{CC} - \sum F(i) \quad (2)$$

CC is the conversion coefficient[2] and $\Sigma F(i)$ is the correction factor for an adjustment for further losses. $\Sigma F(i)$ is 8 % for brine- and water/water HPs and 3 % for air/water HPs. The results of η_s from the two-point-method compared to the test standard are shown in Figure 5.

The average relative deviation between η_s (EN 14825) and η_s (two-point-method) is 0.69 % (absolute: 0.87 %). Relative de-

1. The average temperature provided to the heating system $\bar{\theta}_{var}$ is the mean value between inlet temperature θ_{in} and supply temperature θ_s for HPs with variable compressor. For fixed-speed HPs with compressor switched off the average temperature equals the inlet temperature and also the supply temperature ($\bar{\theta}_{fixoff} = \theta_{in} = \theta_s$). To compensate this difference, the supply temperature for fixed-speed HPs with compressor on must be selected at higher values so that their time-averaged temperature equals the average temperature of HPs with variable performance ($\bar{\theta}_{var} = \bar{\theta}_{fix} = (\bar{\theta}_{fixon} + \bar{\theta}_{fixoff})/2$).

2. Conversion coefficient (CC) means a coefficient reflecting the estimated 40 % average EU generation efficiency referred to in Directive 2012/27/EU of the European Parliament and of the Council; the value of the conversion coefficient is CC = 2.5.

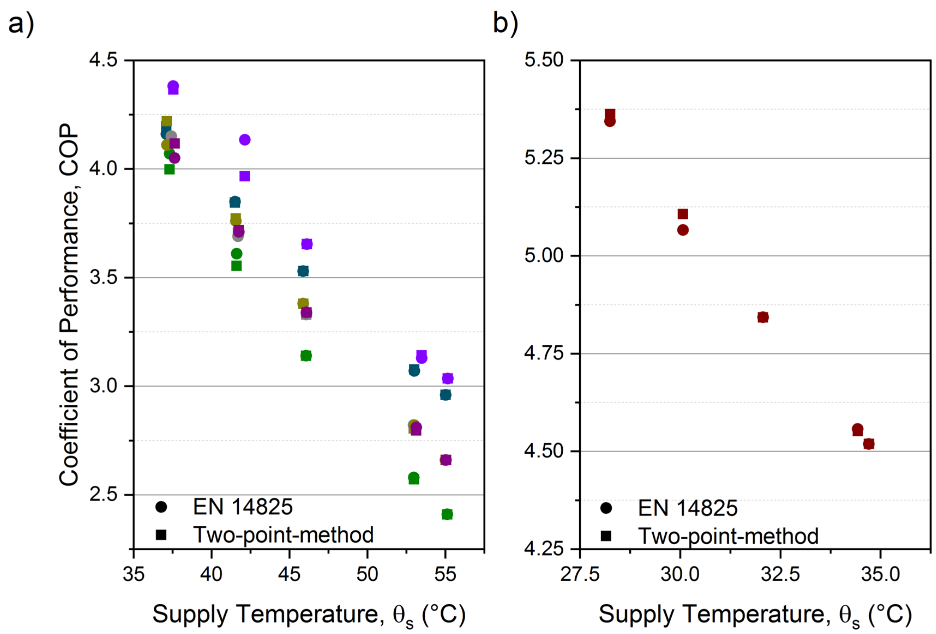

Figure 4. Results of the COP measurements from two-point-measurements (squares) and measurements according to EN 14825 (circles) of a) six HPs at high temperature level and b) one HP at low temperature level.

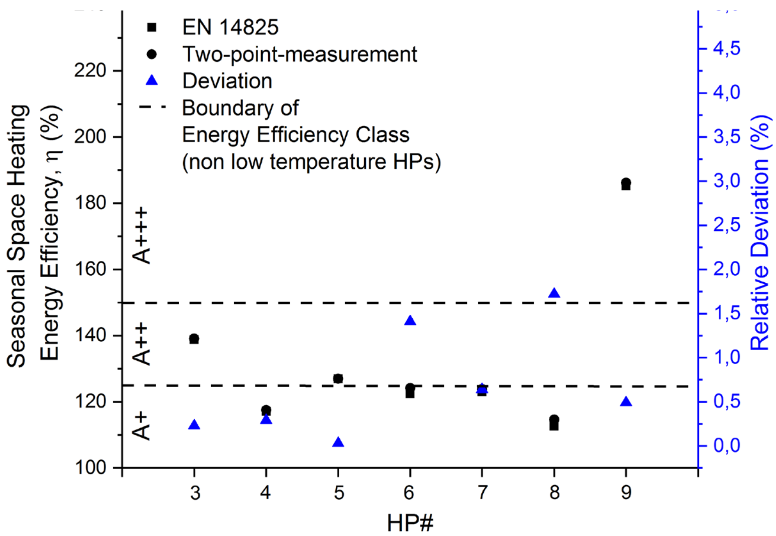

Figure 5. Comparison of the seasonal space heating energy efficiency η_s determined with the EN 14825 and the two-point-method, respectively.

viation values do not exceed values of 1.72 % (absolute: 1.94 %). As the energy classes A+++ to A+ have a range of 25 % or more and market surveillance authorities undertake their activities with a consideration of an 8 % tolerance[3] the maximum absolute deviation of 1.94 % is negligible.

3. The market surveillance authorities shall test one single unit per model. If the results of the seasonal space heating energy efficiency η_s is more than 8 % lower than the declared value, they shall randomly select three additional units of the same model for testing. If the results are not achieved for all units, the model and all other equivalent models shall be considered not to comply with the EU energy labelling regulation. (Annex IV of (European Commission 2013).)

Conclusion

This paper proposes a quick test for the determination of the seasonal performance η_s for HPs as an alternative method to currently used standards, e.g. EN 14825 or ISO 13256. The increasing number of countries which implement energy efficiency standards and the prospective role of HPs in the heating sector implicate the need of a more time-saving and economical test method for the seasonal performance rating.

The proposed two-point-method consists of the two operating points with the highest influence on the seasonal performance, deduced from the calculation part of the EN 14825 with particular regard on the temperature-BIN-method. We tested and verified the two-point-method with tests on seven HPs and compared the results with results of the same units tested according to EN 14825. It appears that the two-point-method delivers the same results with the same degree of precision.

Hence, the two-point-method could be used as a screening procedure or as a full testing procedure for the determination of the seasonal performance of HPs with more than 60 % cost and time improvement. We applied the two-point-method only for ground source heat pumps. The feasibility of the method for air source heat pumps, however, is still not clear and should be part of further investigations.

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