Assessing the performance limits of a variable-speed residential heat pump system

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Abstract. Most of the ducted split-type heat pump systems in the world feature fixed-speed compressors and fans. To meet forthcoming minimum energy rating requirements, reduce operational costs of the heat pump, and increase environmental sustainability, the efficiency of heat pump systems must be improved. Variable-speed equipment offers significant advantages for load modulation and has the ability to increase the seasonal performance significantly. Additionally, novel electrical motor technologies, such as permanent magnet (PM) motors can reduce the power consumption of the drives by up to 25-55% compared to the widely used permanent split capacitor (PSC) motor.

In this study, a ducted fixed-speed heat pump system with a cooling capacity of 17.6 kW and a seasonal coefficient of performance (SCOP) rating of 4.11 is analyzed to quantify the theoretical performance limits that could be obtained by increasing the motor efficiency of the condenser fan, the evaporator fan and the compressor. Furthermore, the performance increase by replacing the fixed-speed components with variable-speed equipment is evaluated. A detailed charge-sensitive system simulation model that was previously developed by the authors and validated using experimental data obtained with the same unit was employed to carry out parametric studies to evaluate the impact of variable-speed compressor and indoor/outdoor fans on the SCOP rating.

The study showed a 0.9% improvement of SCOP with every percentage increase of compressor motor efficiency. The dependence of the evaporator fan and condenser fan motor efficiency on SCOP was lower, but considering the generally low motor efficiencies of these components, a noticeable efficiency gain can be achieved. In variable-speed equipment, the motor efficiency of the component at minimum operational point was the significant factor on SCOP. The motor efficiency at intermediate and maximum speed had only marginal effects on the SCOP. This showed the importance of equipment with high motor efficiencies at low speeds for ducted split-system heat pumps. The change of the fixed-speed system to a fully variable-speed heat pump resulted in a high gain of SCOP, proving the superiority of a variable-speed system. Overall, the model predicted an SCOP gain of 35% when changing the system to a fully variable system with state-of-the-art high efficient motors.

Keywords: Optimization, Variable-speed Compressor, Fan Motor Efficiency, Permanent Magnet Motor
1. Introduction

During the last two decades, the need for more efficient heat pump systems increased significantly due to concerns on energy consumption and awareness of environmental issues including global warming. Moreover, equipment manufacturers are facing challenges with the forthcoming more stringent minimum energy rating requirements for residential heat pumps that will be imposed by the U.S. Department of Energy by 2023. Due to the low cost, most ducted split-type heat pump systems in the U.S. feature fixed-speed components with electric motors in the lower efficiency range [1]. Variable-speed and multi-speed systems can significantly improve the systems seasonal performance due to their inherent ability to adjust the capacity to the needed loads. Fixed-speed systems generally run in an overdesigned condition because the heat pump is chosen for the highest use case, which is only reached a few days a year. Most of the time, a much lower heating or cooling capacity is needed and the unit cycles on-off, which results in inefficiencies. Variable-speed systems can reduce their capacity to the required needs, which leads to an increased efficiency due to less cycling losses.

The use of higher efficiency motors can directly reduce the consumed power consumption due to less motor losses. Especially the compressor, which is the most power consuming component in a heat pump, needs to operate with a high efficiency motor to reduce losses and increase the SCOP. The evaporator fan motor and condenser fan motor have a less significance on the systems efficiency and therefore, manufacturers often choose a less efficient motor. A change of these motors to state-of-the-art motors can significantly reduce the components power consumption. The Permanent magnet (PM) motor is a novel electrical motor technology which is able to reach very high motor efficiencies. PM motors are currently available with efficiencies of over 90% for HVAC equipment [1]. This is a big efficiency gain over current systems, which often use permanent split capacitor (PSC) or electronically commutated (EC) motors, typically with motor efficiencies in the range of 35% to 80% [1].

This study investigates the potential performance improvements of a heat pump system when changing fixed-speed components to variable-speed equipment and increasing the motor efficiency of the compressor, evaporator fan and condenser fan motor.

2. System Description

2.1. Baseline Unit

The unit considered in this study is a commercially available ducted fixed-speed heat pump system. The unit has a cooling capacity of 17.6 kW and is rated at an SCOP of 4.11 using the AHRI Standard 210/240. The heat pump is running with the refrigerant R-410A and uses a fixed-speed scroll compressor, which uses a PSC-motor. Both the evaporator fan and the condenser fan run in single speed. The evaporator fan motor has a power draw of 407 W and runs with an electronically commutated motor (ECM). The ECM is estimated to have a motor efficiency of 0.75. The condenser fan uses a PSC motor and has a power draw of 286 W. The motor efficiency of the condenser fan is assumed to be 0.65.

2.2. Modified Unit

To assess the effect of a variable-speed system, components of the baseline unit are replaced with variable-speed components. As a compressor, the latest commercially available variable-speed R-410A scroll compressor is chosen. This compressor allows to assess the performance limits of current-day high-efficiency compressors. The cooling capacity of the compressor is in a range of 6 kW to 20.9 kW.

To match with the baseline unit, the compressor is modeled for a rated capacity of 17.6 kW, which translates to a rotational speed of 4500 rpm. The motor efficiency is estimated to be at 0.88 at the rated speed of 4500 rpm and 0.85 at lower speeds.

Depending on the configuration of the simulation run, the evaporator fan and condenser fan are also changed to variable-speed. In variable-speed mode, the motors are assumed to have the same motor efficiency as the fixed-speed motors. This translates to an evaporator fan motor efficiency of 0.75 at all speeds and condenser fan motor fan motor efficiency of 0.65 at all speeds. While analyzing the unit with higher motor efficiencies, the motor efficiencies are adjusted accordingly.
3. Methods

3.1. Efficiency Evaluation
In this work, the heat pump is considered to operate in cooling mode. To evaluate the efficiency of the unit, the seasonal energy efficiency ratio (SEER) defined according to the AHRI Standard 210/240 [2] is used. To match with SI-units, the SEER is converted to the seasonal coefficient of performance (SCOP). The standard tries to replicate the use of the heat pump over a cooling season and develop the average COP of the unit within the season. This is a reasonable indicator of the system’s performance as it not only measures the efficiency in one operational point but in many points.

The standard differentiates between the heat pump running with a fixed-speed compressor or a variable-speed compressor. Depending on the mode, the unit is tested at a set of different temperature points which are reported in Table 1 and Table 2. In the test for fixed-speed systems, the compressor and fans run with maximum speed. In variable-speed systems, the compressor and fans run in either maximum speed, intermediate speed or minimum speed, depending on the test condition.

With temperature bins which display the expected temperature within a year of operation and the information of cooling capacity and power consumption at the different operation points, the SCOP is calculated.

| Test Name | Air Entering Outdoor Unit in °C (Dry Bulb / Wet Bulb) | Air Entering Indoor Unit in °C (Dry Bulb / Wet Bulb) | Compressor Speed | Indoor Airflow |
|-----------|-------------------------------------------------------|-----------------------------------------------------|------------------|---------------|
| A\_full  | 35.0 / 23.9                                          | 26.7 / 19.4                                         | Max.             | Max.          |
| B\_full  | 27.8 / 18.3                                          | 26.7 / 19.4                                         | Max.             | Max.          |
| C\_full  | 27.8 / 14.4                                          | 26.7 / 13.9                                         | Max.             | Max.          |
| D\_full  | 27.8 / 14.4                                          | 26.7 / 13.9                                         | Max.             | Max.          |

| Test Name | Air Entering Outdoor Unit in °C (Dry Bulb / Wet Bulb) | Air Entering Indoor Unit in °C (Dry Bulb / Wet Bulb) | Compressor Speed | Indoor Airflow |
|-----------|-------------------------------------------------------|-----------------------------------------------------|------------------|---------------|
| A\_full  | 35.0 / 23.9                                          | 26.7 / 19.4                                         | Max.             | Max.          |
| B\_full  | 27.8 / 18.3                                          | 26.7 / 19.4                                         | Max.             | Max.          |
| B\_low   | 27.8 / 18.3                                          | 26.7 / 19.4                                         | Min.             | Min.          |
| E\_int   | 30.6 / 20.6                                          | 26.7 / 19.4                                         | Int.             | Int.          |
| F\_low   | 19.4 / 11.9                                          | 26.7 / 19.4                                         | Min.             | Min.          |
| G\_low   | 19.4 / 14.4                                          | 26.7 / 13.9                                         | Min.             | Min.          |
| I\_low   | 19.4 / 14.4                                          | 26.7 / 13.9                                         | Min.             | Min.          |

3.2. Simulation Model

3.2.1. ACHP+ Description
The numerical analyses are conducted by employing the simulation framework “ACHP+” which is based on the Python programming language. Such modeling framework is the result of significant efforts by the authors’ research team simulating various vapor compression systems during the last two decades. In a nutshell, ACHP+ is a detailed charged sensitive model, which assesses the influence of heat exchanger sizing, compressor efficiencies, expansion work recovery devices, working fluids, etc. on the
system’s performance. The model has been experimentally validated by various studies, e.g., by Bahman et al. [3], proving a high accuracy of the model.

3.2.2. Compressor Implementation

The fixed-speed commercially available scroll compressor is integrated in the ACHP+ model with a 10-coefficient polynomial map developed by AHRI Standard 540 [4]. The coefficients for power input and mass flow rate are provided by the compressor manufacturer [5]. With the input of suction dew point temperature and discharge dew point temperature, the desired value for power input and mass flow rate at the modelled operation point is calculated.

For modelling the variable-speed commercially available scroll compressor, a modified 10-coefficient polynomial map is used. The compressor manufacturer provides a 20-coefficient polynomial map to additionally account for the rotational speed of the compressor [6]. With the input of suction dew point temperature, discharge dew point temperature and rotational speed, the power input and mass flow rate of the compressor can be calculated.

To model the effect of a changed compressor motor efficiency, the calculated power is multiplied with the ratio of initial motor efficiency to new motor efficiency:

\[
P_{\text{comp,new}} = \frac{\eta_{\text{init}}}{\eta_{\text{new}}} \times P_{\text{comp,init}}
\]

3.2.3. Evaporator Fan Implementation

In the configuration with the evaporator fan in single-speed, the evaporator fan power at a given volume flow rate is taken from experimental data. The data is used from an analysis performed by Salts et al. [7] on the same unit.

For configurations with the evaporator in variable-speed mode, the fan power for different external static pressure \(dp\) and volume flow rate \(\dot{V}\) needs to be calculated. The following equation is implemented in the model:

\[
P_{\text{evap}} = \frac{dp \times \dot{V}}{\eta_f \times \eta_{m,\text{evap}}}
\]

The external static pressure \(dp\) is defined by the AHRI Standard 210/240 for the full load airflow condition [2]. At lower flow rates the minimum static pressure that needs to be reached is calculated according to the standard with

\[
dp = dp_{\text{full}} \times \left(\frac{\dot{V}}{\dot{V}_{\text{full}}}\right)^2
\]

and depends on the Volume flow rate.

The evaporator fan motor efficiency \(\eta_m\) is set depending on the simulation run. For runs in the baseline condition the motor efficiency is set at 0.75 at all speeds. For simulations assessing the impact of a changed evaporator fan motor efficiency, the efficiency is changed, depending on the speed mode.

The fan efficiency \(\eta_f\) is calculated with data from the experimental analysis by Salts et al. [7] and Equation 4.2. In particular, \(\eta_f\) is assumed to be constant at different speeds and is found to be 0.1759.

3.2.4. Condenser Fan Implementation

The condenser fan power consumption at rated speed is calculated by dividing the rated fan power \(HP_{\text{rated}}\) by the evaporator fan motor efficiency \(\eta_{m,\text{cond}}\):

\[
P_{\text{cond}} = \frac{HP_{\text{rated}}}{\eta_{m,\text{cond}}}
\]

In variable-speed mode, the fan motor efficiency at different rotational speed is calculated using the fan laws:

\[
\dot{V}_2 = \dot{V}_1 \times \left(\frac{\text{RPM}_2}{\text{RPM}_1}\right)
\]
Depending on the condenser motor efficiency at certain speed, the power input is calculated with Equation (4).

4. Validation

4.1. System Rating

The ACHP+ model has been validated in several experimental data. Bahman et al. [3] modelled the same heat pump unit with a different variable-speed compressor and validated the results experimentally. The model reached a good agreement with the experimental data for a wide set of operational points. The mean absolute error for cooling capacity and power consumption was under 6%, proofing the high accuracy of the model.

The ACHP+ model for the unit in baseline configuration with the fixed-speed compressor calculated an SCOP of 4.04. This value is just 1.5 % percent lower than the SCOP of 4.11 stated by the manufacturer and hence agrees accurately with the experimental data.

4.2. Evaporator Fan Power in variable-speed mode

The methodology for calculating the evaporator fan power consumption as described in Section 3.2.3 is validated with experimental data of the same evaporator fan collected in a previous experiment by Salts et al. [7]. Table 3 shows the evaporator fan power for different test conditions of the AHRI Standard 210/240 at different volume flow rates. The deviation between experimentally obtained results and calculated results is less than 6% for volume flow rates in the range between 2124 m$^3$/h and 2973 m$^3$/h, which is the range for the analysis in this study. Overall, the agreement is very high, especially considering that the experimental results become more uncertain at lower volume flow rates.

Table 3: Deviation of evaporator fan power between experimental data and calculations in the ACHP+ model

| Test | Evaporator volume flow rate in m$^3$/h | Evaporator fan power consumption in W Experimentally obtained by Salts et al. [7] | Calculated | Deviation in % |
|------|----------------------------------------|---------------------------------------------------------------------------------|------------|----------------|
| B2   | 2973                                   | 406.9                                                                            | 406.7      | 0.0            |
| B2   | 2549                                   | 247.5                                                                            | 248.3      | -0.3           |
| B2   | 2124                                   | 145.8                                                                            | 139.6      | 4.2            |
| B2   | 1699                                   | 95.87                                                                            | 79.5       | 17.1           |
| Ev   | 2973                                   | 403.9                                                                            | 409.5      | -1.4           |
| Ev   | 2549                                   | 238.3                                                                            | 246.9      | -3.6           |
| Ev   | 2124                                   | 149.3                                                                            | 141.7      | 5.1            |
| Ev   | 1699                                   | 93.85                                                                            | 85.2       | 9.2            |
| B1   | 2973                                   | 390.9                                                                            | 404.6      | -3.5           |
| B1   | 2549                                   | 246.1                                                                            | 250.8      | -1.9           |
| B1   | 2124                                   | 152.9                                                                            | 143.7      | 6.0            |
| B1   | 1699                                   | 95.73                                                                            | 86.2       | 9.9            |
| F1   | 2973                                   | 399.9                                                                            | 408.8      | -2.2           |
| F1   | 2549                                   | 243.1                                                                            | 249.8      | -2.8           |
| F1   | 2124                                   | 147                                                                              | 141.3      | 3.9            |
| F1   | 1699                                   | 92.24                                                                            | 85.2       | 7.6            |
5. Parametric Studies

5.1. Compressor Speed Studies
The rotational speed of the variable-speed compressor varies to obtain a high SCOP. The maximum speed is set for the unit to run at the same cooling capacity as the baseline unit. 17.6 kW is reached at a rotational speed of 4500 rpm at test condition A2 of the AHRI Standard 210/240. This is the maximum speed as per standard. The minimum speed can be optimized to increase the SCOP of the system. The intermediate speed is dictated by the minimum speed and maximum speed and is set according to the AHRI Standard 210/240 with the Equation (7).

\[
\text{Speed}_{\text{int}} = \text{Speed}_{\text{min}} + \frac{\text{Speed}_{\text{max}} - \text{Speed}_{\text{min}}}{3}
\]  

(7)

Fig. 1 shows the SCOP at different minimum compressor speeds. An optimum is found at a minimum rotational speed of 2475 rpm, which is 55% of the chosen max speed. For the given minimum and maximum speeds, the intermediate speed is 3150 rpm.

5.2. Evaporator Fan Speed Optimization
The evaporator fan runs in rating condition with a volume flow rate of 2973 m³/h. In variable-speed mode the maximum evaporator fan speed is kept at this rate and the rate for test conditions with lower flow rate are adjusted. Experimental data from Salts et al. [7] showed a high SCOP at an intermediate evaporator fan flow rate of 2549 m³/h and a minimum flow rate of 2124 m³/h. These volume flow rates were transferred to the model.

5.3. Condenser Fan Speed Optimization
At rating conditions in fixed-speed mode, the condenser fan runs at a rotational speed of 1000 rpm, which results in an airflow of 6874 m³/h. To find the optimum speed in variable-speed mode, a parametric study with the condenser running at different fan speeds is conducted. Fig. 2 shows the SCOP with varying fan speeds at intermediate and minimum airflows. The condenser fan speed at maximum airflow is kept constant and the minimum and intermediate fan speeds are varied individually. The curve for the intermediate speed shows only a minor impact on the adjusted airflow. The optimum is reached at a speed of 875 rpm. At minimum airflow, the speed has a bigger impact on the systems SCOP. An optimum is found at a minimum fan speed of 775 rpm.

![Fig. 1: System SCOP for variable-speed mode at different minimum compressor speeds](image)

![Fig. 2: System SCOP in variable-speed mode at different fan speeds.](image)
6. Results

6.1. Efficiency Evaluation on Increased Motor Efficiency in a Fixed-Speed Heat Pump

In this section, the components of the unit run all in a fixed speed condition. The dependence of the compressor motor efficiency, evaporator motor efficiency and condenser fan motor efficiency on the SCOP are evaluated individually.

6.1.1. Compressor Motor

The compressor is generally the most power consuming component in a heat pump system. Therefore, the compressor motor efficiency has a big impact on the SCOP as it directly impacts the compressor power consumption. Fig. 3 shows the impact on increasing the compressor motor efficiency of the baseline single speed heat pump. Due to a lack of detailed information on the initial motor efficiency of the compressor, a study with different motor assumptions is performed. The study shows that the increase of SCOP is fairly independent of the initial motor assumptions in the range between 0.8 and 0.9. A 1% increase of motor efficiency results in an SCOP increase of approximately 0.04 or 0.89%. Increasing the compressor motor efficiency can increase the heat pumps SCOP greatly which speaks for using high efficiency motors in the compressor.

6.1.2. Evaporator and Condenser Fan Motor

The evaporator fan motor and condenser fan motor usually have lower efficiencies than the compressor motor. High efficiency fan motors can increase the systems SCOP. Fig. 4 shows the SCOP improvement potential of fixed-speed fans in a fixed-speed heat pump system. In the study, the motor efficiencies are increased individually while the motor efficiency of the other fan is kept constant.

An increase of the evaporator fan motor efficiency from the baseline motor efficiency of 0.75 to a state-of-the-art motor with an efficiency of 0.9 would result in an increased SCOP of 0.082 or 2%.

The condenser fan motor efficiency has a lower impact of SCOP. For the same SCOP increase of 2%, the motor efficiency needs to be increased from 0.65 to 0.9 or by 0.25.

Fig. 3: SCOP with change of compressor motor efficiency in a fixed-speed system.

Fig. 4: SCOP with change of evaporator fan or condenser fan motor efficiency in a fixed-speed system.
6.2. Efficiency Evaluation on Increased Motor Efficiency in Variable-Speed System

In variable-speed systems, the unit runs at different compressor speeds and fan speeds throughout the AHRI Standard 210/240 tests. An electric motor usually has different motor efficiencies at different rotational speeds. In this paper, the effect of changing the motor efficiency at all speeds, as well as for certain speeds is looked at, to see the dependence of motor efficiency to SCOP. In the following section, the variable-speed scroll compressor is used and the fans are in different speed mode configurations.

6.2.1. Compressor Motor

Similarly to the fixed-speed system, the compressor motor efficiency is changed and the impact on SCOP is looked at. In this parametric study, the compressor runs at variable-speed and the evaporator fan and condenser fan in single speeds.

Fig. 5 shows the SCOP with change of motor efficiency for all speeds and for speeds individually. For simplification, an initial compressor motor efficiency of 0.88 at all speeds is assumed. The motor efficiency assumption is not that significant when looked at the change of SCOP per percentage of motor efficiency increase. A different motor efficiency assumption is expected to result in a shifted curve with the same gradient. In the simulations where the motor efficiency is changed individually, the motor efficiency at all other speeds is kept at 0.88. This allows to see the effect of motor efficiency for certain speeds on the SCOP.

An increase of compressor motor efficiency at all speeds results in an SCOP increase of approximately 0.038 or 0.85%. This result is very similar to the effect of compressor motor efficiency on SCOP in fixed-speed systems. When looked at the compressor motor efficiency at individual speeds, it shows that the motor efficiency change at maximum rotational speed and intermediate rotational speed only have a marginal effect on the systems SCOP. The motor efficiency change at minimum speed has the largest effect on the systems SCOP which shows that the manufacturers of electromotors need to put their focus on increasing the motor efficiency at low speeds.

![Fig. 5: SCOP with change of compressor motor efficiency at different speeds in a variable-speed system.](image)

6.2.2. Evaporator Fan Motor

The configuration in this study is a variable-speed compressor and a variable-speed evaporator fan. The condenser is running in a fixed-speed condition.

The evaporator fan motor efficiency is changed from the initial motor efficiency of 0.75 to higher values individually for certain speeds and for all speeds. Fig. 6 shows the results of the parametric study. Similarly to the compressor motor efficiency study, the evaporator fan motor efficiency maximum and intermediate speed only have a low impact on SCOP while at minimum speed the effect on SCOP is
dominant. A change of evaporator fan motor efficiency at all speeds from 0.75 to 0.9 results in an SCOP increase of 0.075 or 1.5%.

6.2.3. Condenser Fan Motor
The configuration of the heat pump in this analysis is a unit with a variable-speed compressor and variable-speed condenser fan. The evaporator fan is running in fixed-speed mode.

The condenser fan motor efficiency is increased from the initial fan motor efficiency of 0.65 to higher values individually and for all speeds. The results are similar to the evaporator fan motor efficiency, showing a high dependency of SCOP to the motor efficiency at minimum speed and only marginal impact of the motor efficiency at maximum and intermediate speed. An increase of the motor efficiency from 0.65 to 0.9 at all speeds results in an SCOP increase of 0.08 or 1.7%. This shows a slightly reduced effect the condenser fan motor efficiency on SCOP compared to the evaporator fan motor efficiency.

6.3. Comparison of System in Different Speed and Motor Efficiency Configurations
The effect on SCOP of different speed mode configurations is evaluated. In addition, the effect of changing the baseline motors to high efficiency state-of-the-art motors is analyzed. Table 4 shows the initial motor efficiencies of the compressor, evaporator fan and condenser fan motors and the motor efficiencies that can be reached with high efficiency permanent magnet motors.

Fig. 6: SCOP with change of evaporator fan motor efficiency at different speeds in a variable-speed system.

Fig. 7: SCOP with change of condenser fan motor efficiency at different speeds in a variable-speed system.

Changing the evaporator fan to variable-speed mode, configuration 3, further increases the SCOP significantly to 4.96, which is a rise of 0.34 or 7.4% compared to configuration 2.
Lastly, making the system to a full variable heat pump by changing the condenser to variable-speed, configuration 4, the SCOP rises by 0.13 or 2.7% to 5.09. Compared to the fully fixed speed system in configuration 1, this is an increase of 1.2 or 31%.

The heat pumps efficiency can further be improved with the use of high efficiency motors. The systems SCOP with high efficiency motors is represented with blue bars in Fig. 8. In the fully fixed-speed configuration, a significant increase of 0.37 or 9.6% can be achieved by increasing the compressor, evaporator, and condenser motor efficiency. In configuration 2, the SCOP increase with high efficiency motors is similar, at 0.37 or 8.0%. The SCOP improvement in configuration 3 is 0.26 or 5.2% and in configuration 4 0.14 or 2.8%. The results show that with the use of high efficiency motors, the heat pumps SCOP can increase significantly. For full variable systems, the advantage of high efficiency motors reduces slightly, and the highest increase can be seen when increasing the motor efficiency in a heat pump with fixed-speed fans.

### Table 4: Initial and new high motor efficiencies of compressor, evaporator fan and condenser fan used in Section 6.3

| Motor Efficiency [-] | Max. Speed | Int. Speed | Min. Speed |
|----------------------|------------|------------|------------|
|                      | Init. New  | Init. New  | Init. New  |
| Compressor           | 0.88       | 0.93       | 0.85       | 0.85       | 0.85       |
| Evaporator Fan       | 0.75       | 0.93       | 0.75       | 0.83       | 0.75       | 0.83       |
| Condenser Fan        | 0.65       | 0.92       | 0.65       | 0.82       | 0.65       | 0.82       |

**Fig. 8: Performance evaluation of system in different speed and motor efficiency configurations**

### 7. Conclusion

This study quantified the theoretical performance limits of a heat-pump system by changing fixed-speed components to variable-speed and increasing the motor efficiency of the compressor, evaporator fan and condenser fan. For an evaluation of efficiency, the AHRI Standard 210/240 was used, which assesses the systems performance of a full season. The analysis was performed with the simulation model ACHP+, which showed good agreement with experimental data.

In fixed-speed mode and variable-speed mode, the SCOP improved by approximately 0.9 for every percentage of improved compressor motor efficiency. It was found that in variable-speed mode, the compressor motor efficiency at minimum speed has the highest impact on SCOP, while the motor efficiency at intermediate and maximum speed only has low relevance. The same is valid for the motor efficiency of the evaporator fan and condenser fan. This shows that manufacturers of electrical motors need to put their focus on designing motors with high efficiencies at lower rotational speeds. Current day motors mostly have their highest efficiency at maximum speed, with decreasing efficiency at lower
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speeds. Compared to the compressor, the improvement of SCOP of the evaporator fan and condenser fan with an increase of motor efficiency is only marginal. Nevertheless, due to generally low motor efficiencies of the fan motors, a noticeable improvement can be made with high efficiency motors.

Furthermore, it was shown that the change to variable-speed systems can improve the system significantly. Especially, the change of the compressor to a variable-speed compressor showed an improvement gain of 18%. The change to a variable-speed evaporator fan had a reduced but still significant SCOP increase and the condenser fan resulted in the lowest but still not negligible efficiency gain.

An additional change to high efficiency motors, as can be reached with state-of-the-art permanent magnet motors showed high improvement gains, especially in systems with fixed-speed fans. In heat pumps with variable-speed fans, the seasonal performance gain by changing to high efficiency motors was reduced.

Overall, the study showed that by changing a fixed-speed heat pump system to a variable-speed system with high efficiency motors, an overall SCOP improvement of 35% can be achieved.

Although fully variable-speed systems with high efficiency motors require higher initial investment, the big efficiency gain shows that the upgrade is worth the effort. High efficiency heat pumps not only have lower operational costs, which saves costs long term, but also are more environmentally friendly because of a reduced power consumption.

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