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# Efficiency Improvements of Brine/Water Heat Pumps through Capacity Control

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**Abstract**

The increases in efficiency of air/water heat pumps (A/W-HP) for building services through capacity control instead of on/off-control of compressor and fan have been proven theoretically and shown practically on the market. In the presented project, the potential for improvements of brine/water heat pumps (B/W-HP) through capacity control was quantified and an optimal control strategy was developed. Relevant interrelations for planning, designing and controlling efficient B/W-HPs for broad applications are described. The studies showed that for maximizing the efficiency of capacity-controlled B/W-HPs the compressor and the brine mass flow must be controlled whereupon the part-load efficiency of the compressor has a significant influence on the optimum control strategy. The seasonal performance factors (SPFs) of a B/W-HP with capacity control were theoretically and experimentally confirmed to be consistently higher than those of the on/off-controlled HP. The increase in efficiency remarkably depends on the operating conditions. For a heating water supply temperature of 46°C and a geothermal heat probe temperature of 6°C the examined capacity-controlled B/W-HP is 5% more efficient than the on/off-controlled B/W-HP. A heating water supply temperature of 30°C and a geothermal heat probe temperature of 13°C result in the capacity-controlled HP being 11% more efficient.

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Keywords: heat pump; capacity control; control strategy; efficiency; seasonal performance factor; heat transfer; brine-water heat pump;

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## 1. Introduction

The global exploitation of energy and material resources and the concomitant environmental pollution and enrichment of the atmosphere with CO2 are tackled by the so called energy transition [1]. A large portion of the global primary energy demand is used for building heating. By the increasing utilization of heat pumps a significant reduction of the fossil energy demand for building services is expected [2]. A further lever for minimizing primary energy consumption is the increase of efficiencies. Although heat pumps represent a long-standing technology, there is still significant potential for efficiency improvements [3-5]. Advances in compressor, inverter, fan and pump technology in particular open up worthwhile possibilities for sophisticated control strategies and allow efficiencies to be increased substantially. Especially promising in this context is the use of continuous capacity control.

Studies have confirmed that continuous capacity control can result in substantial increases in efficiency for air/water heat pumps (A/W-HPs) assuming that suitable components and the best possible control strategy are used [6]. Studies show that the efficiency of B/W-HPs can also be increased by means of capacity control [7-12], a correlation proved theoretically and experimentally in this study. The findings from the development and implementations of efficient A/W-HPs with continuous capacity control are adapted here to brine/water heat pumps (B/W-HPs) and water/water heat pumps (W/W-HPs), both subsumed hereinafter under the term "B/W-HPs", and are then further developed. Tips are provided on the design and the optimum control of capacity-controlled B/W-WPs. Further, this article discusses the requirements under which capacity-controlled heat pump systems can make the most of their efficiency advantages in field operation.

## 2. State of the Art

The vast majority of A/W-HPs is operated with on/off-control, although the capacity control is increasingly growing [6]. The capacity control of B/W-HPs on the contrary is rare [7-8]. The mechanisms, which improve the HP's efficiency through capacity control, are described in detail for A/W-HPs: the reason for the mediocre efficiency of conventional A/W-HPs with on/off control are the unfavourable operating characteristics resulting from the characteristics of the constant-speed compressor [6]. If the ambient temperature rises, the heating demand and the heating temperature required for the building decline, as given by the heating curve. The A/W-HPs with the constant-speed compressor behave in the opposite way: If the ambient temperature rises, the generated heating capacity and the heating temperature incline.
Today, the generated heating energy is typically adjusted to the required heating energy by means of on/off control, i.e. cyclic operation for A/W-HPs as well as B/W-HPs.
As the ambient temperature rises, the temperature gradients for heat transfer in the evaporator and condenser rise in on/off-controlled A/W-HPs during operation, as shown in fig. 1 on the left.
Moreover, the generated temperature lift, i.e. the difference between condensation and evaporation temperature, decreases less markedly than the ideal temperature lift (Fig. 1 on the right). This results in poor part-load efficiencies, low seasonal performance factors (SPF) and low annual exergy efficiencies [6,13-14].

To have the temperature gradients decreasing instead of increasing or remaining constant when heat is transferred under part-load, the discrepancy between required and generated heating capacity and temperature must be avoided. Consequently, HPs will not operate cyclically (on/off control) but rather continuously (continuous capacity control) – except during off times and during required defrosting processes for A/W-HPs.

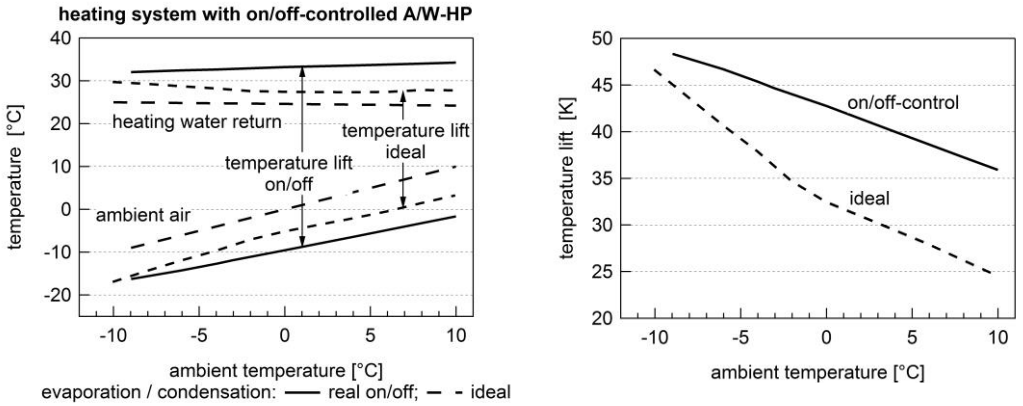



Fig. 1: On the left: Simulated heat source and heat sink, evaporation and condensation temperatures of on/off-controlled and of capacity controlled A/W-HPs. On the right: Simulated temperature lifts of on/off controlled and of ideal capacity controlled HPs. All correlations are shown as a function of the ambient temperature when used in a building complying with the Swiss Minergie standard (SP/RT 30°C/25°C at an ambient temperature of -10°C) [6].

To adapt the generated heating capacity to the required one, the circulated refrigerant mass flow has to be regulated, e.g. by controlling the speed of the compressor. Studies have confirmed the potential for efficiency increases by means of capacity control [6,15-16]. As a result, the attainable coefficients of performance (COP)

and SPFs can be increased markedly for the A/W-HPs compared to classic on/off control. Comparisons of SPFs for typical A/W-HPs with on/off control from field studies show that efficiency increases in the order of 70% can be achieved with capacity control [6].

## 3. Capacity control of brine/water heat pumps

Assuming constant temperatures in the ground for B/W-HPs, the generated heating capacity remains nearly constant during the entire heating period regardless of the ambient temperature, opposed to A/W-HPs.

However, even with B/W-HPs with on/off-control, this also leads to a clear discrepancy between the required and generated heating temperature as the ambient temperature increases. The generated temperature lift is larger than required (Fig. 2) with the corresponding sequence of the unnecessarily low part load efficiency and low SPFs. The temperature lifts can be reduced by variable speed compressors. The part-load behaviour of the compressor and of the entire heat pump system have a significant influence on the optimal control strategy and the HPs efficiency. A mandatory requirement for the attainment of higher COPs and SPFs are therefore compressors with high part-load efficiencies across a broad control range [6,17-18].

Below it will be shown how the part-load behaviour of the compressor affects optimum control and how the optimum settings for the compressor can be calculated while the heat pump is operating at part load. In a further step, the optimum setting for the brine circulation pump (BCP) is discussed. This setting can likewise have a significant effect on the efficiency of capacity-controlled B/W-HPs.

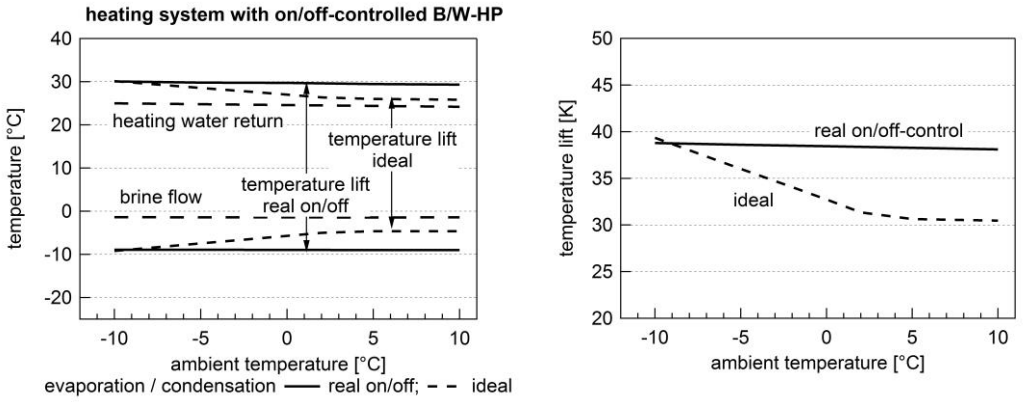



Fig. 2: On the left: Simulated heat source and heat sink, evaporation and condensation temperatures of on/off-controlled and of capacity controlled B/W-HP. On the right: Simulated temperature lifts of on/off controlled and of ideal capacity controlled B/W HP. All correlations are shown as a function of the ambient temperature when used in a building complying with the Swiss Minergie standard (SP/RT 30°C/25°C at an ambient temperature of -10°C).

## 4. Optimum control of the compressor in a capacity-controlled B/W-HP

If the generated heating capacity of the HP is consistently adjusted to the required heating capacity, this can lead to the efficiency falling below the optimum level. To avoid this, the control of the compressor must be attuned as well as possible to the part-load behaviour of the compressor and the entire heat pump system. This requires, that the part-load ratio of the compressor never be allowed to fall below the critical level. Two factors therefore limit the maximum reduction of the part-load ratio of the compressor in part-load operation: One is the heat input required by the building and the other is the maximum attainable efficiency.

Each compressor has an optimum part-load ratio and an optimum compressor speed $n_{opt}$. To attain the best possible COPs in part-load operation, the compressor speed is not permitted to fall below this level, because otherwise, the efficiency would decline (Fig. 3 on the left). If the compressor speed is $n_{match}$, it results in a precise adjustment of the generated heating capacity to the required one. If $n_{match}$ is larger than the optimum compressor

speed $n_{opt}$, the generated heating capacity is allowed to be adjusted to the required heating capacity. In this case ($n_{opt} < n_{match}$), the maximum reduction of the compressor speed is limited by the required heating capacity, which always has to be covered. If the compressor must drop below its optimum speed $n_{opt}$ to adjust the generated heating capacity to the required one (that is: $n_{opt} > n_{match}$), the B/W-HP is subject to on/off-control at a reduced capacity, i.e. at the optimum compressor speed $n_{opt}$, because the exact adjustment of the heating capacity would cause a decline in efficiency (Fig. 3 on the right).

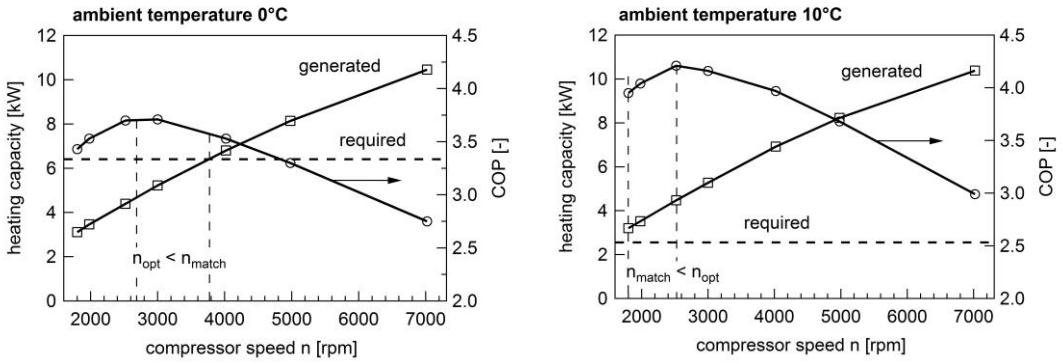



Fig. 3: Required and generated heating capacity as well as the COPs (without BCP) for the B/W-HP prototype with inverter-scroll compressor (Emerson Copeland ZPV36) as a function of compressor speed from measurements for an ambient temperature of 0°C (on the left) and 10°C (on the right), average bore-hole temperature of 6°C, DN32 geothermal heat probe, 100 m depth for the heat exchanger and heating curve of a refurbished older building (SP/RT 46°C/38°C at an ambient temperature of -10°C).

## 5. Determination of the optimum part-load ratio of the compressor

The compressor is not permitted to go below its optimum speed $n_{opt}$ in part-time operation for efficiency reasons. This variable is practically independent of heat source and heat sink operating conditions such as the temperature of the geothermal heat probe (Fig. 4 on the left) and ambient temperature (Fig. 4 on the right).

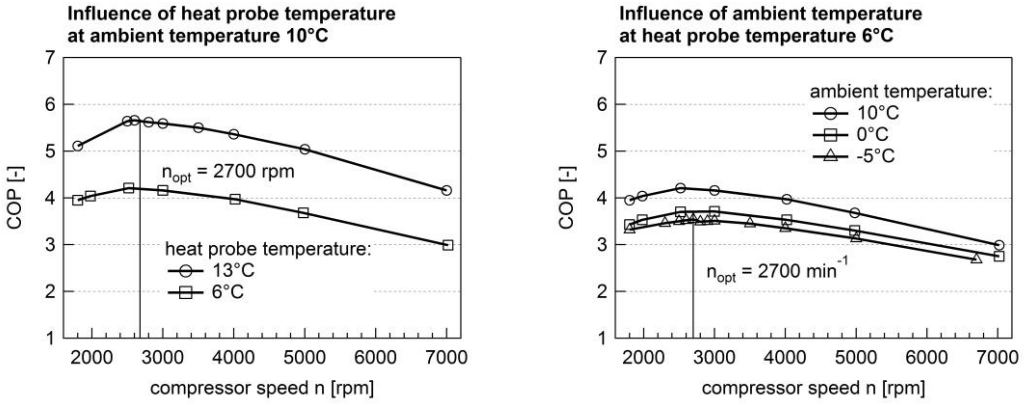



Fig. 4: COPs (without BCP) for the B/W-HP prototype with an inverter-scroll compressor (Emerson Copeland ZPV36) as a function of the compressor speed from measurements for different average heat probe temperatures (6°C and 13°C) and different ambient temperatures (-5°C, 0°C and 10°C). Both figures are valid for the heating curve of a refurbished older building (SP/RT 46°C/38°C at an ambient temperature of -10°C).

The optimum compressor speed for a given compressor can be determined experimentally with relatively little effort and expense practically independent of the source and sink operating conditions of the B/W-HP. This

substantially reduces the cost of developing the optimum control system for B/W-HPs with capacity control.

## 6. Optimum control of the brine circulation pump for a capacity-controlled B/W-HP

To attain the best-possible efficiency for B/W-HPs with capacity control, not only the compressor speed but also the brine mass flow must be selected at every point in time in such a way that the COP is maximized, with account also taken of the BCP (Fig. 5). The studies show however that simultaneous capacity control of the compressor and the BCP is not mandatory. Instead, the control of only the compressor capacity suffices, as long as the best possible brine mass flow is selected. If only the compressor capacity is controlled, however, the selected brine mass flow has a substantial influence over optimum compressor control and the resulting efficiency of the B/W-HP because the pump capacity is correlated with the brine mass flow. In part-load operation, in particular, excessive brine mass flows can have a highly disadvantageous effect on the attainable COPs (Fig. 5 on the left).

Assuming a brine mass flow of 2100 kg/h, the reduced compressor speed increases the COP, with the BCP also considered from 3.0 at full load to a maximum of 3.9 at a part-load ratio of 43% (3000 rpm) (Fig. 5 on the right). Assuming a brine mass flow of 1565 kg/h, the COP can, by contrast, be increased to 4.2 at a part-load ratio of 36% (2500 rpm) (Fig. 5 on the right). Furthermore, excessive brine mass flows reduce the useful range of the part-load ratios of the compressor associated with efficiency increases, i.e. the optimum compressor speed, below which the compressor is not supposed to fall for efficiency reasons, shifts to higher speeds as the brine mass flow increases (Fig. 5 on the right).

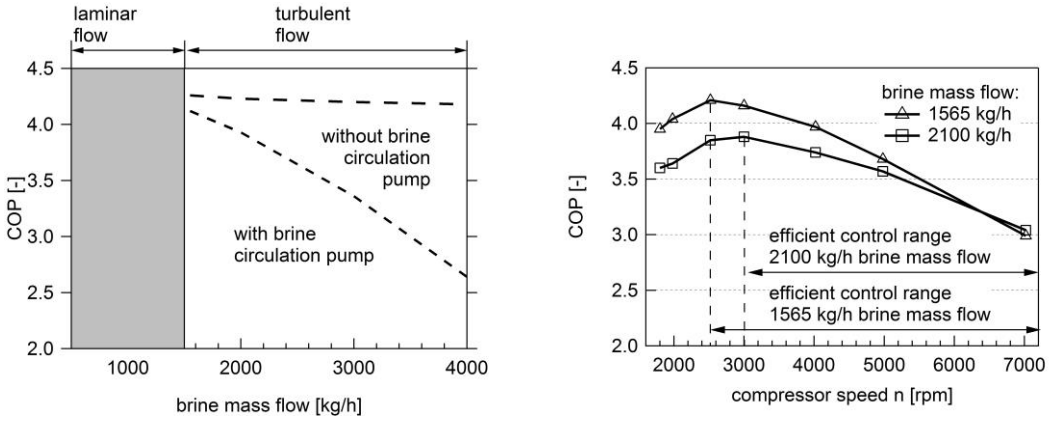



Fig. 5: On the left: COPs with and without account taken of the BCP as a function of the brine mass flow from simulations at 2500 rpm compressor speed (Emerson Copeland ZPV36). On the right: COP with account taken of the BCP, as a function of the compressor speed (Emerson Copeland ZPV36) from measurements at 2100 kg/h and 1565 kg/h brine mass flow. Both figures are valid for 10°C ambient temperature, 6°C heat probe temperature, DN32 geothermal heat probe, depth of 100 m for the heat exchanger, and the heating curve of a refurbished older building (SP/RT 46°C/38°C at an ambient temperature of -10°C).

Experimental studies of the optimum brine mass flow confirm that the BCP does not have to be controlled to attain the best possible COPs and SPFs. In principle, however, it should be selected to be as small as possible. But the important aspect is that the brine mass flow be selected so that the flow in the geothermal heat probe is consistently in the turbulent range. If the flow falls below the turbulent range (laminar flow), the heat transfer in the geothermal heat probe deteriorates severely. For this reason, it is imperative to avoid the laminar flow range in a geothermal heat probe (Fig. 5 on the left) and to set the brine mass flow in such a way as to just barely guarantee a turbulent flow.

## 7. Experimental validation

### *7.1. Heat pump prototype and experimental installation*

Prototypes of an on/off-controlled B/W-HP and a capacity-controlled B/W-HP were developed and built in order

to confirm the potential for efficiency increases with continuous capacity control experimentally and to test the developed control system (Fig. 6). The on/off-controlled B/W-HP prototype is equipped with a ZH09 constant-speed scroll compressor from Emerson Climate Technologies GmbH while the capacity-controlled B/W-HP utilizes an inverter scroll compressor (ZPV36), also from Emerson Climate Technologies GmbH. The inverter scroll compressor enables continuous capacity control across various speeds (1800 rpm to 7000 rpm) using an inverter and is characterized by high efficiencies. Both prototypes are equipped with identical evaporators (Q80Tx40) and condensers (B80Tx30) from SWEP International AB. With these heat exchangers small temperature differences for heat transfer and thus small temperature lifts are possible.



Fig. 6: Capacity-controlled B/W-HP prototype with inverter scroll compressor and heat supply test module in the laboratory of Lucerne University of Applied Sciences and Arts.

### *7.2. Operating characteristics and efficiency*

The experimental testing was conducted for the typical heating curves of a building complying with the Swiss Minergie standard and a refurbished older building. Account was taken of three different average heat probe temperatures (6°C, 9.5°C and 13°C) resulting from the different depths of the geothermal heat probe. Testing focused in each case on monovalent operation (design point for heat pumps at an ambient temperature of -10°C). Results for the heating curves for the Minergie standard and for a refurbished older building are presented below as examples. A geothermal heat probe with an average temperature of 6°C is involved in each case.

Assuming optimum control and the use of the inverter scroll compressor (Emerson Copeland ZPV36), the generated heating capacity can be adjusted continuously to the required heating capacity at an ambient temperature ranging from -10°C to 2°C for the Minergie heating curve or 4°C for the heating curve of a refurbished older building. In this range of ambient temperatures, it is imperative that the compressor does not drop below its optimum speed ($n_{opt}$) for heating capacity adjustment ($n_{match} > n_{opt}$). At higher ambient temperatures, the compressor would have to drop below its optimum speed ($n_{opt}$) for heating capacity adjustment.

**Heating curve "Minergie standard"** **Heating curve "Refurbished older building"**

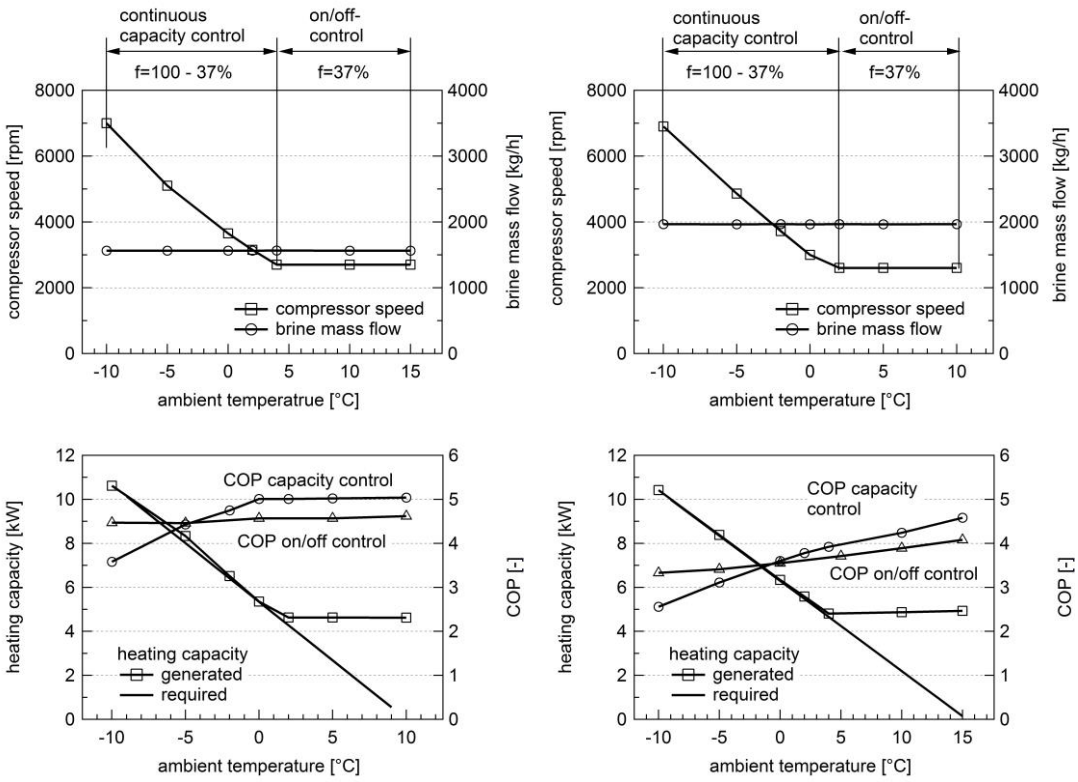



Fig. 7: Optimum compressor speed, optimum brine mass flow, required and generated heating capacity as well as the COPs (with BCP) for on/off-controlled (Emerson Copeland ZH09) and for capacity-controlled B/W-HP prototype (Emerson Copeland ZPV36) as a function of the ambient temperature from measurements for 6°C heat probe temperature, DN32 geothermal heat probe, depth of 100 m for the heat exchanger, constant brine mass flow and the heating curves for the Minergie standard (SP/RT 30°C/25°C at an ambient temperature of -10°C) and for a refurbished older building (SP/RT 46°C/38°C at an ambient temperature of -10°C).

For efficiency reasons, the B/W-HP is subject to on/off-control at ambient temperatures above 2°C (Minergie) or 4°C (rehabilitated older building) with reduced capacity at optimum compressor speed (Fig. 7). If this optimum control strategy is applied, the resulting discrepancy between required and generated heating capacity can be reduced substantially compared to classic on/off control.
If used in a building complying with the Minergie standard, capacity control causes the COP to rise from about 3.6 at an ambient temperature of -10°C to 5.0 at an ambient temperature of 0°C. The COP for the on/off-controlled B/W-HP remains approximately constant at about 4.5 across the whole ambient temperature range. If used in a refurbished older building, capacity control results in lower COPs than conventional on/off control at ambient temperatures below -1°C. At higher ambient temperatures, the capacity-controlled B/W-HP prototype achieves much higher COPs, however. Thus, capacity control can help to improve the SPF when used both in a refurbished older building and in a building complying with the Minergie standard.

Table 1 summarizes the attainable SPFs of the B/W-HP prototype and the on/off-controlled prototype for the heating curves of the Minergie standard and of a refurbished older building for two different heat probe temperatures owing to the geothermal heat probes being at different depths. The SPFs calculated according to the method of v. Böckh [19] were conducted for the cumulative frequency distribution of the ambient outdoor temperatures in Zurich. The efficiency increase resulting from the capacity control ranges from 5% to a maximum of 12% depending on the heating curve, the heat probe temperature resp. the depth of the geothermal heat probe.

Table 1: SPFs with account taken of BCP for the on/off-controlled B/W-HP prototype (Emerson Copeland ZH09) and for the capacity-controlled B/W-HP prototype (Emerson Copeland ZPV36) for the heating curves of the Minergie standard (SP/RT 30°C/25°C at an ambient temperature of -10°C) and of a refurbished older building (SP/RT 46°C/38°C at an ambient temperature of -10°C) as well as heat probe temperatures of 6°C and 13°C from measurements.

| Heat probe temperature/ heat probe depth | Minergie standard SP/RT 30/25°C at -10°C | | Refurbished older building SP/RT 46/38°C at -10°C | |
|---|---|---|---|---|
| | **SPF** On/off control | **SPF** Capacity control | **SPF** On/off control | **SPF** Capacity control |
| 6°C/~100 m | **4.54** | **4.88** | **3.64** | **3.83** |
| 13°C/~320 m | **6.21** | **6.90** | **4.62** | **5.09** |

*7.3. Capacity control for heat pumps in actual practice*

The conducted studies confirm that continuous capacity control can increase the efficiency of both A/W-HPs and B/W-HPs. The consistent application of the control strategies described above is still not a fully sufficient way of attaining the maximum possible efficiency values for these types of heat pumps in field operation.

In the outlined control strategies of capacity-controlled A/W-HPs and B/W-HPs, the compressor speed and any auxiliary units are controlled based on the required heating capacity. That capacity is continuously calculated based on the measured outdoor temperature and the heating curve that has been permanently set. As outdoor temperature usually the average temperature over a 24-hour period is chosen. The heating capacity generated by the heat pump is adjusted at any time according to the required heating capacity from the weather-guided heating controller. Then, the heat pump fulfills the requirements through continuous capacity control or on/off control at reduced capacity in order to attain optimum efficiencies. If such a heating controller is used to determine the required heating capacity, the heating curve has a significant effect on the operational behaviour and efficiency of the capacity-controlled heat pumps. If the heating curve on the heating controller is set at an unnecessarily high level, sufficient heating of the building is ensured, but the advantages of the capacity control are largely lost. Owing to the unnecessarily high setting for the heating curve, the capacity-controlled heat pump operates at too high capacities in cyclic operation even at ambient temperatures above the design point. This leads to unnecessarily low COPs and SPFs. Due to the losses of the inverter, these values can be below the efficiency values of conventional on/off-controlled heat pumps without inverters. If the heating curve is set at the best possible setting for satisfying the effective needs of the building, the heat pump can be operated highly efficiently with continuous capacity control.

## 8. Conclusions

The studies carried out confirm the effectiveness of the control system that was developed and the potential that capacity control has for increasing the efficiency of B/W-HPs. The developed B/W-HP with capacity control achieves up to 12% higher SPFs than the prototypes with on/off control depending on the heating curve and the depth of the heat probe.

A mandatory requirement for achieving efficient heat pumps with continuous capacity control is the use of compressors, pumps, and fans featuring suitable part-load behaviour, broad admissible control ranges and high part-load efficiencies. Another requirement is the use of the right control strategy for the compressor and any auxiliary units. The efficiency of the compressor at part load greatly influences the efficiency and the optimum control of capacity-controlled heat pumps. If the efficiency of a compressor declines sharply at part-load and the compressor is being incorrectly controlled, this can cause the COP in part-load operation with adjusted heating capacity to fall below the COP of a heat pump using on/off control.

If capacity-controlled heat pumps are operated in field operation with weather-guided heating controllers, the setting of the heating curve has a significant influence on the operational behaviour and the efficiency of the heat pumps. In spite of actual capacity control, bad heating curve settings can lead to bad efficiency levels, which can even fall below those of installations with on/off control. Adaptive heating controllers with self-optimizing heating curves could remedy the matter.

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