Investigations of speed controlled heat pumps for NZEB in IEA HPT Annex 49

Lukas Rominger, Carsten Wemhoener, Simon Buesser
IET Institute for Energy Technology, HSR University of Applied Sciences Northwestern Switzerland, Oberseestrasse 10, CH-8640 Rapperswil
carsten.wemhoener@hsr.ch

Abstract. Speed controlled heat pumps are entering more and more the heat pump markets for space heating and domestic hot water (DHW) applications. In this study the design and control of speed controlled air-to-water heat pumps in net zero energy buildings are investigated by simulations of a single family house. The results confirm an increase in efficiency by using a speed controlled heat pump compared to an on/off controlled heat pump both in heating mode and in DHW mode. Further on, the correct sizing and control of a speed controlled heat pump is also important to reach a high efficiency.

1. Aim of research

In IEA HPT Annex 49 concepts for heat pump design and integration in net zero energy buildings (NZEB) are developed with the aim of reducing energy consumption and CO₂-emissions in the new built building sector. Within the framework of this Annex, various system configurations and controls for NZEB with heat pumps are investigated.

The current European Performance of Buildings Directive (EPBD, 2018) [1] stipulates that all new buildings must be nearly zero energy buildings by the beginning of 2021. In Switzerland, this requirement is implemented with the introduction of the new building regulations MuKEn 2014 [2]. In order to achieve the new legal standard, it can be assumed that the already frequent use of heat pumps will increase. Moreover, speed-controlled heat pumps, which promise higher efficiency in part load operation, as described for instance by Gasser [3], are increasingly entering the market. For a future highly efficient building operation in Switzerland, also the speed controlled heat pumps must be well designed and integrated into the building, thus the design and control of speed controlled heat pumps for NZEB application has been investigated by simulations of a single family house.

2. Boundary conditions

2.1. Building definition

NZEBs are already well introduced in the new built residential sector, in particular in single-family houses. Therefore, a single family house is chosen for this study. The building has an energy reference area of 200 m² spread over two floors. The unheated basement is not accounted to the energy reference area, but it is located entirely inside the thermal insulation perimeter. The building has no connection to an underground car park and does not contain a garage. The insulation layer is located outside the supporting structure or between the supporting structure on the pitched roof. With the exception of the pitched roof, all components are of solid construction. The building is oriented to the south. The roof
faces east and west and is equipped with a 3.5 kWp solar photovoltaic system for each direction. The building contains a mechanical ventilation system with heat recovery and an underfloor heating. The heating demand according to SIA380/1:2016 is 23 kWh/(m²a), which is within the limits of MuKEn 2014. The location of the building is Zurich (weather data set Meteoschweiz). The heat pump uses outside air as a heat source.

2.2. NZEB definition
In this study, the complete energy consumption of the building services as well as the household electricity is included in the balancing. The PV electricity produced is also included in the balance at 100%. A delivered energy of 0 kWh/(m²a) is used as the limit value for the annual balance. Thus, a NZEB is achieved. Since it is an all-electric building which uses only electricity as delivered energy no energy weighting factors have been applied, implying a symmetric weighting of generated and consumed electricity.

3. Scientific methodology
For the comparison of different control strategies and design variables, parameter studies by simulations of the defined building and its HVAC system have been performed.

3.1. Simulation model
The simulations are carried out on the Matlab-Simulink [4] simulation platform with the CARNOT Toolbox 6.1 [5] as coupled dynamic system and building simulation.

Since the whole building has a high thermal inertia the temperatures of each room are considered as equal. Therefore, only one zone for the entire building is considered.

3.1.1. Heat pump model. As there is no existing accessible speed controlled heat pump model for the Matlab-Simulink environment, a new model has been developed. The model is based on performance maps of marketable heat pumps taken from manufacturer data and literature [6], see Figure 1 and Figure 2. Different heat pump data were used to evaluate how strong the result depends on the performance map of the heat pump. These performance maps are implemented as look-up tables. The control also uses these tables to ensure that the heat pump is running at the most efficient operating point. All heat pump data used for the modelling are based on inverter controlled heat pumps.

![Figure 1: Performance map of heat pump 1](image1)

![Figure 2: Performance map of heat pump 2](image2)
4. Results obtained

4.1. Speed controlled heat pump vs. on/off controlled heat pump

Figure 3 shows the COP for space heating and domestic hot water (DHW) operation determined by annual simulations. The simulations differ only in the modulation stage of the heat pump. For on/off control, the modulation level is always 1. For speed control, the modulation level is selected which produces the highest COP or the modulation level which can produce the required heating capacity. Here, the term heating capacity refers to the thermal power at the condenser side of the heat pump.

![Figure 3: Speed controlled HP1 vs. on/off controlled HP1](image1)

Figure 4 shows the modulation levels in January. The short peaks of the speed-controlled heat pump can be traced back to domestic hot water operation. It is clear that a speed controlled heat pump achieves a higher COP for heating and DHW operation. Thereby, the degree of improvement depends strongly on the characteristic of the heat pump. Another reason for the better COP in space heating mode is the lower number of starts, as the temperature can be kept constant by modulation. This also promotes thermal comfort in the building. Furthermore, it also prevents the supply temperatures from rising as a result of a too high heating capacity. Figure 4 also shows that there is no need of a heating storage, because with a speed controlled heat pump the consecutive running times without a heating storage are several hundred hours.

Since the desired heating capacity has been kept constant in DHW mode, the heat pump is also modulated there and thus achieves a higher COP. During times when the space heating mode is not active it would also make sense to run the heat pump at the most efficient compressor speed. During winter time, however, the optimised DHW operation may be limited by needed running time of the heat pump for space heating operation to keep comfortable indoor temperatures.

4.2. Sizing of the heat pump

Figure 5 shows the annual performance factors as a function of the heating capacity. The heat pump is the only heat generator. The points shown can all meet the requirements for room and hot water temperature. According to the hydraulic system STASCH 2 [7], taken from the STASCH design guideline, the heat pump should be designed to a heating capacity of 5.5 kW. The performance maps used for the two heat pumps were scaled with a factor for variation. The efficiencies of the two heat pumps have not been changed.

It can be seen that efficiency decreases with increasing heat capacity. This has the following reason: Due to the over-dimensioning of the heat pump, it already starts cyclic operation at higher heat loads. This is also illustrated in Figure 6 with a plot of the performance map of heat pump 1. The cyclic operation starts at an ambient temperature of -4 °C when the heat pump is designed twice as large, whereas with a correct design, this is only the case above an ambient temperature of 2 °C.
Therefore, the smaller heat pump is more efficient. In Figure 6 only the temperatures are considered for the heating curve. But obviously solar radiation is also influencing the heating demand.

The design according to STASCH is in principle still correct even for net zero energy buildings with low heating loads. The design, though, tends to be somewhat too large, as no gains are taken into account. In terms of efficiency, oversizing can help to generate more operating hours with high efficiency. The losses in cyclic operation are, however, decreasing the efficiency. In the simulations, the losses due to cyclic operation are weighted higher than the efficiency gains. However, no start-up data was available for the heat pumps. In addition, the supply temperatures also increase due to the excess heating capacity in cyclic operation, which reduces efficiency. For this reason a deliberately oversizing should be avoided.

4.3. Control strategy and flexibility of the building
To evaluate how the efficiency is influenced by the control strategy, four rather simple control strategies have been compared:

Constant supply temperature: The heat pump is controlled in such a way that the desired supply temperature is reached. For this purpose, the required heating capacity is calculated as enthalpy balance with set point of the supply temperature and the return temperature. If the COP of the heat pump is better at a higher speed, this operating point is selected.

Constant return temperature: With this control, the return temperature is kept constant. The required heating capacity is calculated with the set point of the return temperature. The heat pump is also operated at an operating point which produces a higher capacity, in case of higher efficiency.

Constant supply temperature, maximal running time: The control is analogous to the control constant supply temperature. Only the most efficient operating point of the performance map is not used, but always the operating point which supplies the required heating capacity.

Constant return temperature, maximal running time: The control is analogous to the control constant return temperature. However, the heat pump is always operated in such a way that the required heating capacity is reached.

For all strategies the mass flow is kept constant.

It can be seen that a slightly higher efficiency is achieved with a constant supply temperature than with a constant return temperature. This does not meet expectations, as the lower supply temperature should be achieved with a constant return temperature. However, it should be noted that a constant return temperature leads to a higher supply temperature at the design point, as otherwise the mean temperature in the underfloor heating system is too low at low heating capacity. This results in slightly higher supply temperatures. However, this problem could certainly be solved with a more advanced control system.
Figure 7 shows also that in this case, with the performance map, the COP is higher with a control strategy, which achieves the longest running time. Thus, it is more efficient to run the heat pump at the exact capacity that the building needs than at the capacity which would be most efficient for the heat pump itself. This is due to the fact that the heat pump has more on and off cycles due to the heating capacity surplus. In addition to that the supply temperature increases in times of surplus heating capacity of the heat pump compared to the building load. This increase leads to a lower efficiency of the heat pump. For further work an optimised control should already take this supply temperature increase and the cycling losses into account and thereby always run at the operation point which leads to the highest efficiency of the whole system.

![Figure 7: Comparison control strategies for HP2](image1)

For the next step the most efficient control strategy was taken and improved regarding the reduction of the delivered energy from the grid. Therefore, the simulation was carried out in Figure 8 with including PV production in the control strategy. The heat pump thus runs earlier than necessary, both for heating and domestic hot water, when the production of the PV system exceeds the consumption of the building to a certain extent.

It can be seen that the imported electrical energy decreases with the regulation according to PV electricity. This reduces the PV production impact on the grid. This is generally regarded as positive, as a growing share of renewable energies it is expected that this leads to a higher fluctuation in production. In the simulated case, however, the heating demand increases because the average room temperature increases due to the earlier activation of the heat pump during heating operation. In addition, the heat pump is also switched-on if this is not necessary at all with the standard control, since the building heats up anyway as a result of the solar irradiation. During DHW operation, storage losses also increase because of a higher average temperature in the storage tank. The higher start-up frequency of the heat pump results in even more cyclic losses. On the other hand, there are higher source temperatures due to increased operation during daytime. Moreover, in this case, the reduction of the delivered electric energy from the grid is also comparably low due to the two different orientations of the photovoltaic installation. The heat pump can be used to reduce the interactions with the electricity grid or to have an electricity grid supportive operation mode. A speed controlled heat pump has the advantage that, if desired, it can use a smaller PV output over a longer period of time. However, the actual flexibility of operation seems to be defined by the heat consumers (building and DHW tank). While flexible operation is easier to achieve with the DHW tank, user acceptance must also be guaranteed in the case of the building thermal comfort. The larger heat capacity is naturally in the thermal inertia of the building. Due to the high efficiency of the heat pump and the low consumption of net zero energy buildings, the PV production peaks are also difficult to absorb. Electric mobility offers greater potential in this respect.
5. Conclusion
The simulations carried out show that the recommendations according to STASCH are in principle still applicable. Furthermore, it was clearly shown that a significantly more efficient operation can be achieved with a speed controlled heat pump. The preferable design size is approximately in the range of the STASCH design. A strong over-dimensioning of the heat pump leads to a lower efficiency. The best results were achieved when the heat pump always delivers the required heating capacity and thus achieves the longest possible running time. To decrease the delivered energy from the grid the speed controlled heat pump can be used. However, how effective it can be done strongly on the boundary condition. To further investigate how flexible a building is with a speed controlled heat pump, it has to be looked at other metrics indication numbers. The approach of the IEA EBC Annex 67 [8], which is penalizing grid interactions differently over time, seems to be a good approach in this sense. A heating buffer storage tank is not required for a system with a speed controlled heat pump. The evaluation of the control strategies yielded the result that by a room temperature based control a higher performance of the heat pump can be reached.

Speed controlled heat pumps lead to the problem, that it is hard to tell which heat pump is the more efficient one. Or at least more data have to be considered. However, for numerous speed controlled heat pumps this data are not publicly accessible.

For domestic hot water operation, an efficient operation is achieved by adapting the desired heating capacity to the maximum COP, which occurs in part load operation. In this case, the design size of the heat pump does not affect the efficiency.

All simulations were carried out for single family houses. However, it can be assumed that the general statements are also valid for multi-family houses.

6. Acknowledgements
Gratitude and acknowledgment is expressed for the support and funding of the Swiss Federal Office of Energy for the IEA HPT Annex 49 international research collaboration.

References
[1] European Parliament. 2018. "Directive 2018/844/EU of the European Parliament and of the council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency of the European Parliament and Council of May 19, 2010 on the energy performance of building (recast)." Official Journal of the European Union, L 156/7, 19.6.2018
[2] Konferenz Kantonaler Energiedirektoren. 2018. Mustervorschriften der Kantone im Energiebereich. Bern
[3] Gasser, L., Wyssen, I., Albert, M., Häusermann, M., Kleingries, M., Wellig, B. 2011. Effiziente Luft/Wasser-Wärmepumpen durch kontinuierliche Leistungsregelung. Final report SFOE, Horw
[4] Matlab-Simulink. 2017. Release 17a. the Mathworks.
[5] CARNOT-Toolbox. 2018. Solar Institute Juelich, FH Aachen
[6] De Coninck, R., Baetens, R., Saelens, D., Woyte, A., Helsen, L. 2014. "Rule-based demand side management of domestic hot water production with heat pumps in zero energy neighbourhoods." Journal of Building Performance Simulation, 271-288.
[7] Gabathuler, H.R., Mayer, H., Afjei, Th. 2002. Standardschaltungen für Kleinwärmpumpenanlagen, Teil 1: STASCH Planungshilfen, Final report SFOE, Diessenhofen
[8] Gronborg Junker, R., Ghasem Azar, A., Amaral Lopes, R., Byskov Lindberg, K., Reyners, G., Relan, R., Madsen, H. 2018. "Characterizing the energy flexibility of buildings and districts." Applied Energy (225), 175-182.