FIELD STUDY ON 20 LARGE HEAT PUMPS

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Abstract: Although large scale heat pumps have not been implemented in great numbers, they have the potential to supply a large amount of useable energy. It is thus of interest to ensure they operate with maximum efficiency. They are mostly operated within large heat distribution networks.

Pressure and heat loss, temperature differentials in the distribution network as well as in heat exchangers all have a direct influence on the heat pump's efficiency. The result of this investigation has been to define the influences of these factors.

Large variations were found for domestic hot water supply systems. This report compares two installations as the extremes of the scale. The electrical (charged) energy input per m^3 of domestic warm water varies between 22.5 and 37.3 [kWh/m^3] (by comparison an electric only heating system requires 58.2 [kWh/m^3]). This has a direct influence on the CO_2 emission value.

The auxiliary systems, in particular the source side pumps, hydraulic systems etc. are also important contributors to the overall efficiency of the heat pump. It is not only important to match flows to capacity but also to utilize more suitable systems for domestic water production.

Key Words: ***Large heat pumps, heat distribution networks, energy efficiency, optimization of heat pumps, analysis of heat pumps***

1 INTRODUCTION

Large and complex heat pump installations are gaining territory and market share. In particular where a centralized heat source is used to supply many building types with differing requirements. This paper discusses this type of installation which supplies multiple types of buildings with warm water and heating, which have differing requirements.

In the FAWA project approximately 250 residential heat pumps in the range up to 20 kW heating capacity were investigated. The seasonal performance factor (SPF) of which are shown below (figure 1):

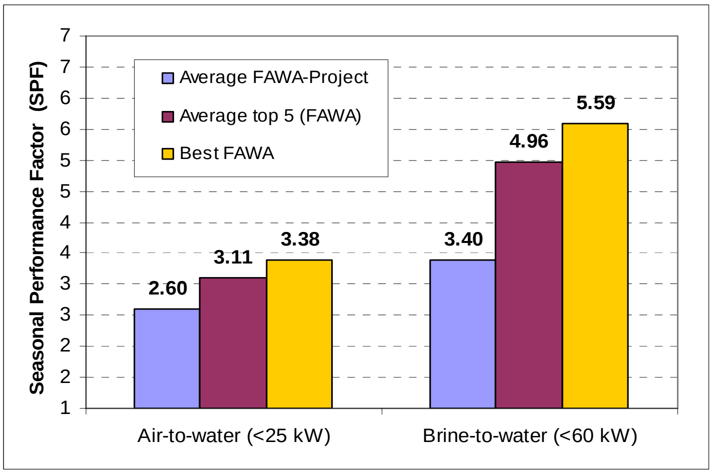

Figure 1: Seasonal Performance Factor for residential heat pumps <20 kW heating capacity [1]

A similar systematic investigation for large heat pump installations is not available. Thus data was analysed from P+D-Installations[1] . In fact, these installations should be better than average. They represent installations where for example efforts had been made to improve energy efficiency. Picture 2 shows the collected results.

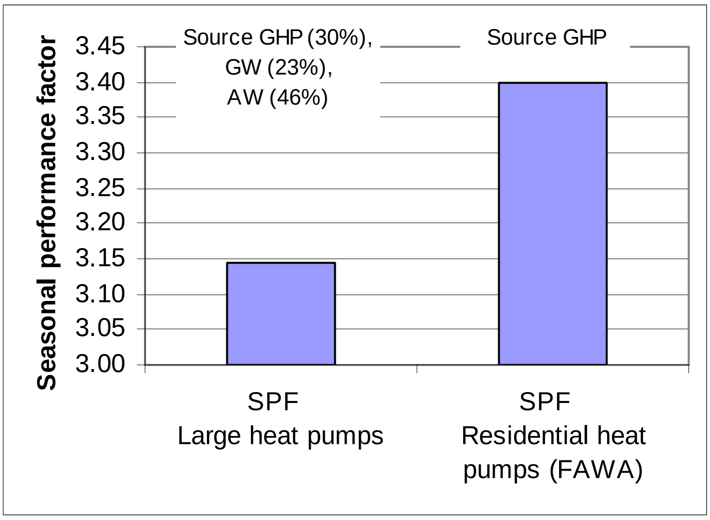

Figure 2: SPF Comparison of Large Heat pump installations from programme P+D and the FAWA project. (GHP=Ground heat probe, GW=Ground water, AW=Waste water)

From the results it is clear that the average SPF of the large heat pump installations is lower than that of the residential installations. This is somewhat surprising and goes against expectations since large systems are in general more sophisticated.

What could be the reasons for this surprising result?

For small scale heat pumps we have the quality assurance programme „ Quality Label for Heat pumps“, from the *Swiss Association for Heat Pump Promotion*. This promotes heat pump efficiency. A similar QA programme does not exist for larger heat pumps. The QA programme has resulted in a demonstrable improvement in efficiency [4].

When multiple locations are fed by a central heat pump, they must be connected by a network of pipes. This network will result in heat and pressure losses which will have a negative effect on the system efficiency.

[1] P+D-Installations: Pilot- und Demonstration Installations, Research Programme Swiss Department for Energy, Bern

Also losses occur in the „sink“ that are non existent or marginal in small installations. If ground water is used as the heat source and a multiple stage pump is used then the source pump should also be multiple staged, having ideally the same number of stages as the heat pump itself. In the worst case scenario, if only one ground water pump is used this will independently of the number of heat pump stages used always supply the maximum water volume and use the maximum amount of electrical energy.

This problem is to be found in all open water systems and also when unfiltered or filtered process waste water is used as the source. In the case of waste water the sewage station is normally at the lowest and thus the remotest point of a network. This results in long networks and – if it is an open hydraulic system - in pressure losses due to frictional and geodesic effects. In these cases the pumps need to be very powerful. In the case of complex heat pump installations with multiple clients for the waste water, decoupling using an intermediate circuit is recommended. In this way the extra heat exchanger increases the efficiency. In addition, a second mixing pump is required for the intermediate circuit.

2 LOSSES IN DOMESTIC HEATING NETWORKS (LARGE NETWORKS)

A disadvantage of a centralised approach to heating multiple buildings is the required heat distribution network. Losses incurred in this network are not to be found in a decentralised solution whereby each building is individually heated. There are four added source of loss that occurs when a centralised solution is used.

- Pressure loss in the local distribution network, i.e. electricity demand for the pumps
- Heat loss of the network outside the buildings
- Temperature drop ΔT_{Leit} of the water along the network requires higher an increase of supply temperature after heat pump condenser, which in turn leads to a reduction of the SPF. (small reduction)
- Temperature gradient $\Delta T_{Gräd}$ of the heat exchanger in the substation (if available). This gradient requires also that the temperature after the condenser is raised.

For the following discussion we only consider networks with a constant flow of water.

2.1 Pressure Loss

We have investigated the pressure loss in 8 large installations with a centralised hot water supply. Using a model we were able to analyse the make up of the pressure losses and compare this with the measured real world values. Accordingly the pressure loss could be described by the following expression:

$$\sigma_p \equiv \frac{E_{el,UP}}{E_{el,WP}} = 0.433 * K_{Plan,p} * K_{Geom,p} * \frac{L_{tot}}{\sqrt{A_{Tot}}} * \frac{1}{\sqrt{\dot{q}_{Ausl}}} * JAZ \qquad (1)$$

An explanation of the variables in the Equation (1) follows

σ_p is the pump’s electricity consumption in the local distribution network referenced to the compressor energy used and is as well equivalent to the relative reduction of the SPF (ΔSPF/SPF) due to the pressure loss in the network. $K_{Plan,p}$ contains all of the factors defining the system, for example the span between supply and return temperatures (design conditions) the pressure loss coefficients, the water velocity etc. The grouping $K_{Geom,p}$*L_{tot}/square root(A_{tot}) is a dimension free value that represents the geometry of the local distribution network. It is similar to the geometrical similarity of thermodynamic and turbulence problems. L_{tot} is the total line length of the local network and A_{tot} is the ground area of all the buildings served by the network. Finally q_{Ausl} is the required heating energy per m^2 of the buildings. It can be seen that the losses are inversely proportional to the root of specific heating requirements. JAZ (SPF) is the Seasonal Performance Factor of the heat pump.

The term $K_{Plan,p}$ contains the designed values for the local heating network:

$$K_{Plan,p} \equiv \frac{\zeta * c_{Ref}^{2.5}}{\eta_{up} * \sqrt{\Delta T_{spr,Ausl}}} * \frac{\Delta t_{UP}}{\Delta t_{VL}} \tag{2}$$

From this equation one can see that the choice of the flow rate has a large influence on the pressure loss. (Δt_{UP} = run time of the pump, Δt_{VL} = number of full load hours, ζ = estimated friction coefficient for the pipes, that contains all pressure losses, η_{UP} = efficiency of the circulation pump, c_{Ref} = flow velocity in main pipe, $\Delta T_{spr,Ausl}$ = Temperature difference (supply and return temperatures at design conditions)

The variable $K_{Geom,p}$ contains the geometry and the connecting pipes of the local network as a dimensionless factor. It represents a dimensionless similarity variable for the network:

$$K_{Geom,p} \equiv \sum_i \frac{L_i}{L_{tot}} * \sqrt{\frac{\dot{Q}_{Ausl,tot}}{\dot{Q}_{Ausl,i}}} * \left(\frac{c_i}{c_{Ref}}\right)^{2.5} \tag{3}$$

The summation occurs for the transported heat of the section that makes up the *longest run*.

In this equation L_i is a network section with $Q_{Ausl,i}$ being the corresponding heat transport volume at the operating point, L_{tot} and $Q_{Ausl,tot}$ are the total length of the network and the total exchanged heat within the network, c_i is the water velocity in section i and c_{Ref} is the water velocity of the main run at the start of the network.

Figure 3: Local Network Schematic.
L_{tot}=1457 m, A_{tot}=38000 m^2 , $K_{Geom,p}$=1.74 , $\dot{q}_{Ausl}$ =13.4 W/m).

The investigation of the 8 installations gave the following results:

Table 1: Factor $K_{Plan,p}$, $K_{Geom,p}$, q_{Ausl} for the 8 investigated installations

Installation	$K_{Plan,p}$	$K_{Geom,p}$	A_{tot}	$L_{tot}/\sqrt{A_{tot}}$	$\dot{q}_{Ausl}$	JAZo	Part load factor[2]	σ_p
			[m2]		[W/m2]			
4000	0.2595	0.294	34000	3.63	12.10	3.30	0.4	0.0456
4001	0.0329	1.402	38000	7.47	13.42	3.41	0.4	0.0555
4003	0.2101	0.414	17500	3.05	71.05	3.61	0.8	0.0394
4004	0.0319	1.438	36450	1.50	9.85	2.74	0.4	0.0104
4006	0.0907	1.395	4770	2.06	24.11	2.75	0.4	0.0252
4007	0.1228	1.256	5880	0.76	6.79	3.50	0.4	0.0216
4009	0.0693	1.013	4500	2.09	19.11	3.20	1.0	0.0467
4010	0.0631	1.128	71800	8.47	41.75	2.64	0.3	0.0320

A large variation in the relative pump power σ_p can be observed.

2.2 Heat Losses

To model the heat losses of the network a similar equation was developed. This network is always outside and thus the heat lost is a total loss.

$$\sigma_w \equiv \frac{Q_{Verl}}{Q_{Trans}} = 0.00346 * K_{Plan,w} * K_{Geom,w} * \frac{L_{tot}}{\sqrt{A_{tot}}} * \frac{1}{\sqrt{\dot{q}_{Ausl}}} \tag{4}$$

The various parameters on the right hand side of the equation have the same meaning as in the pressure loss equations. $K_{Plan,w}$ and K_{Geom} are defined as follows:

$$K_{Plan,w} \equiv \frac{k * (\overline{T_w - T_u})}{c_{Ref}^{0.5} * \sqrt{\Delta T_{spr,Ausl}}} * \frac{\Delta t_{UP}}{\Delta t_{VL}}$$
$$K_{Geom,w} \equiv \sum_{i=1}^{n} \frac{L_i}{L_{tot}} * \sqrt{\frac{\dot{Q}_{Ausl,tot}}{\dot{Q}_{Ausl,i}}} * \left(\frac{c_{Ref}}{c_i}\right)^{2.5} \tag{5}$$

The summation is over all sections of the network. In this case k is the heat transfer number of the insulated pipes, T_w and T_u are the ambient temperature and that of the water or the surrounding (e.g. ground), $\Delta T_{spr,Ausl}$ is the temperature difference between the supply and return temperatures as designed, Δt_{UP} und Δt_{VL} are the operating times of the pump and the duration of the entire heating season, respectively.

Table 2: Variables $K_{Plan,w}$, $K_{Geom,w}$ for the 8 investigated installations

Installation	$K_{Plan,w}$	$K_{Geom,w}$	A_{tot}	$L_{tot}/\sqrt{A_{tot}}$	$\dot{q}_{Ausl}$	σ_w
			[m2]		[W/m2]	
4000	46.23	0.444	34000	3.63	12.10	0.0741
4001	58.36	0.658	38000	7.47	13.42	0.2709
4003	27.87	0.811	17500	3.05	71.05	0.0283
4004	22.79	0.487	36450	1.50	9.85	0.0184
4006	33.83	0.752	4770	2.06	24.11	0.0369
4007	47.88	0.788	5880	0.76	6.79	0.0381
4009	29.74	0.566	4500	2.09	19.11	0.0278
4010	25.45	0.516	72100	8.47	41.75	0.0596

[2] The partial load factor compensates for the lower energy use of modulated pumps versus nominal speed. This value was estimated based on operating requirements of the installation.

The temperature gradient along the transport pipes has not been investigated here, because these are normally only several 10ths of a degree. See final report [2].

The temperature gradient $\Delta T_{Gräd}$ of the heat exchanger in the substation (intermediate heat exchanger, which separates the local network from the house circuit) was shown to have a large influence in the SPF. Because of this gradient the supply temperature after the condenser and the condensation temperature had to be increased to achieve the required input temperature to the house network. Experience shows that the SPF reduces by approximately 1.25% per Kelvin increase in condenser temperature. If the increase is typically 3 K, then the SPF reduces by 3.75%.

2.3 Effect on the Seasonal Performance Factor SPF

The influence of the four loss types on the SPF is simply a linear combination of the four values:

$$\Delta JAZ = -\left[\sigma_p + \sigma_w + 0.0125 * (\Delta T_{Gräd} + \Delta T_{Leit})\right] * JAZ_o \quad (6)$$

For the 8 investigated installations we obtained the following reductions in SPF:

Table 3: SPF Reduction due to losses on local network (Temperature drop along the line ignored)

Installations	σ_p	σ_w	JAZo	Gradient HX substation [K]	ΔJAZ
4000	0.0456	0.0741	3.30	3	-0.519
4001	0.0555	0.2709	3.41	0	-1.113
4003	0.0394	0.0283	3.61	3	-0.380
4004	0.0104	0.0184	2.74	3	-0.182
4006	0.0252	0.0369	2.75	3	-0.274
4007	0.0216	0.0381	3.50	3	-0.340
4009	0.0467	0.0278	3.20	0	-0.238
4010	0.0320	0.0596	2.64	3	-0.341
Average	0.0346	0.0745	3.09		-0.423

The average value for the SPF reduction due to the distribution network is in the range of the difference between residential and large heat pump SPF's shown in figure 2. Without considering the second installation which has a very large distribution network in comparison to the rest and thus larger pressure and heat losses, the average SPF reduction would be 0.325.

3 HOT WATER GENERATION AND DISTRIBUTION

Six of the nine investigated installations were also used to provide warm water to the buildings. The layout and the energy requirements per m³ hot water vary considerably. This is demonstrated by two extreme examples.

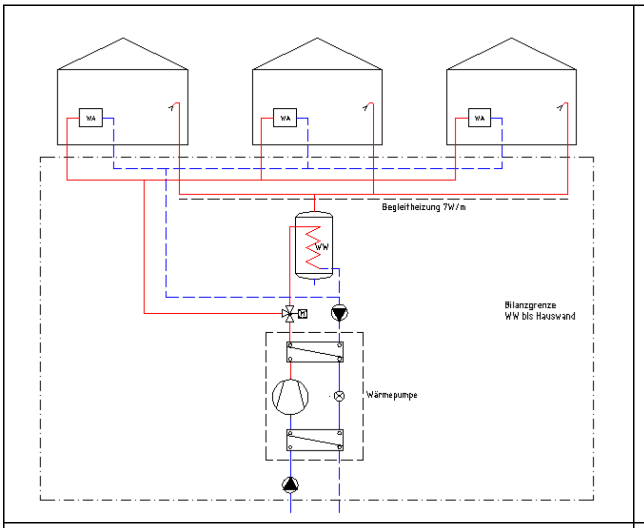

Figure 4: Hydraulic schematic of the warm water supply of the installations 4007[3] und 4004

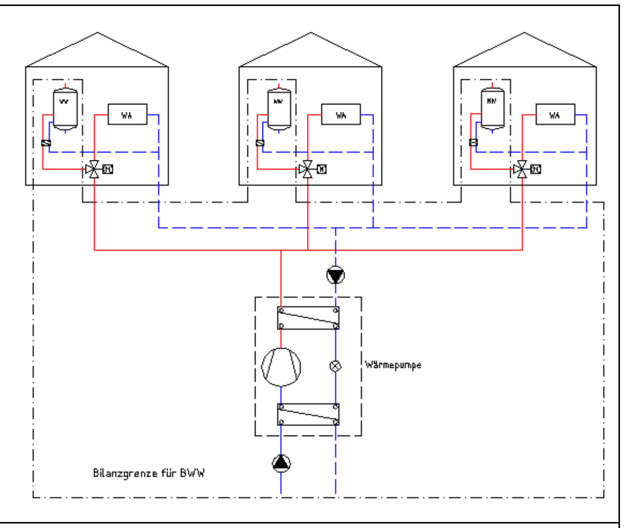

Figure 5: Hydraulic schematic for hot water-preparation in installation 4004

Installation 4007	Installation 4004
In this housing project consisting of 4 buildings, the central heat pump feeds via a switch either the heating or the warm water accumulator. The hot water accumulator is also centralised. The individual taps are fed directly from the central accumulator. At present only 2 of the 4 buildings have been completed. An additional trace heater has been integrated to maintain temperature during consumption free periods.	In contrast this is a „good“ example. The installation serves 8 buildings with a total of 138 apartments. In each building is a warm water boiler which are jointly at defined times loaded through the network.

The energy usage of these installations is described as follows:

Table 4: Electrical energy usage for the hot water generation (Hu = lower calorific value)

	Installation 4007		Installation 4004	
Concept	Final Energy Usage for hot water [kWh/m3]	CO2-Output [kg/m3]	Final Energy Usage for hot water [kWh/m3]	CO2-Output [kg/m3]
This installation	37.3 (Elec.)	17.8	22.5 (Elec.)	10.7
Electro boiler (Efficiency 100 %)	58.2 (Elec.)	21.5	58.2 (Elec.)	21.5
By Comparison:				
Burner, Oil (Efficiency 85%)	68.5 (Hu)	18.1	68.5 (Hu)	18.1
Burner, Gas(Efficiency 95%)	61.3 (Hu)	12.2	61.3 (Hu)	12.2

In the case of installation 4004 one can see a marked improvement in the energy usage and CO_2- release in comparison with installation 4007. The other installations that were reviewed lie between these extremes.

[3] The installation numbers correspond to the anonymous system used in the Final report [2].

4 AUXILIARIES FOR HEATS SOURCES (SOURCE SIDE)

The energy consumption of auxiliary devices can have a major influence on the coefficient of performance (COP) of heat pumps. The large differences in the SPF for the 10 investigated installations can to a great extent be explained by this. A typical situation is now discussed.

A heat pump using ground water as its source has 4 stages. It uses a common source water pump for all four heat pumps and stages.

This installation presents a dilemma. When an auxiliary drive (e.g. pump) needs to supply multiple heat pumps, it is oversized in most cases. This occurs for completed projects and of course during the staged building phases while the heat pump can be oversized for long time.

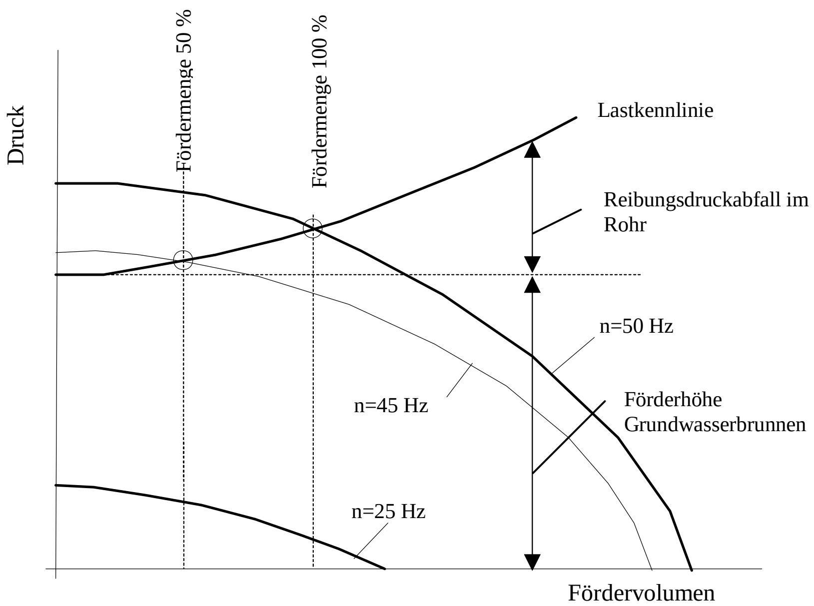

Figure 6: Pump and resistance curve for a constant header with geometric pressure difference

Sometimes the ground water pumps are operated on variable speed to address this problem. However the speed can only be marginally reduced to maintain operation, because of the power of two relationships between pump speed and pumping head. A reduction in 10% of the pump speed reduces the height already by 20%.

Here we have two possibilities to solve this dilemma.

a) Make water reservoirs that are level regulated with a ground water pump and are gravity fed. The heat pumps are then gravity fed or with individual pumps.

b) Add a separate ground water pump for each heat pump (in this case 4)

In the second case we have the following situation:

Four ground water pumps cost more than just one pump. This can be reduced by including only two ground water pumps. These can then pump water volume in a ratio of 1:2 with the same pressure. Thus the smaller pump delivers 1/3 and the larger 2/3 of the required total volume. In this way an almost optimal situation can be achieved.

The energy and water usage of the ground water is approximately 50% less than a single pump. Over a period of 15 years the savings far exceed the extra cost incurred for the second pump.

This concept is also good for a staged development. The ground water supply is not unnecessarily diminished and the energy needed for the ground water pump is better suited to building phase.

This type of problem is found with use of open water or filtered waste water as the heat source. In the case of filtered waste water the sewage plant is normally found at the lowest point in the network. Thus long pipelines are to be found to the heat pump. In addition a height difference between the works and the heat pump is to be expected. Thus the pump must overcome 2 components, the resistance within the pipes and also the height difference. The height difference in hilly regions can be large. In case [5] as a result of this the initially open system was converted to a closed system. This brings the disadvantage that an extra heat exchanger is required between the waste water and the secondary circuit. This change has lowered the evaporation temperature by 3 K.

5 CONCLUSIONS

The analysis of 8 large building clusters with centralised heat pump plants produced a varied picture in terms of energy efficiency and planning skill. Even thought only a few installations were analysed several aspects which lead to design improvement at the planning stage become apparent:

a) The SPF which is important for the energy and the financial justification is not only strongly influenced by the heat pump but also by the nature of the networks used to transport the heat. This must be carefully planned.

b) When heating is to be supplied to buildings in a large project the decentralised solution with individual heat pumps should also be thoroughly investigated.

c) The source installation should be arranged so that the auxiliary device consumption is reduced during heat pump operation in part load.

d) If warm water is to be supplied with a heat pump then a decentralised system is might be more energetically efficient.

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