Part load performance of gas fired absorption heat pumps

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Abstract

The efficiency of a gas-fired absorption heat pump (GAHP) with 40 kW nominal capacity has been examined under transient operation conditions at a test facility at TU Berlin. The GAHP was operated in continuous modulation mode (50% part load), continuous on-off mode (equivalent heat output of 50% of nominal capacity), and discontinuous operation mode (with nominal capacity heating demand for 20 to 70 minutes followed by a cooldown of the entire system). Furthermore, two field applications with hot water storage have been analyzed: One single GAHP and one system of six parallel connected GAHP. For comparison a normalized operational gas utilization efficiency (gue) is applied, which relates the measured GUE of the heat pump to a GUE at maximum heat output conditions for given temperatures.

In modulation mode the efficiency shows a nonlinear increase with increasing gas input. The results show that in this mode, a higher GUE compared to on-off-mode at the same mean heat output is achieved. A strong decrease down to 50 % of the steady state GUE in discontinuous mode for operation periods below 40 minutes has been measured. Compared to continuous on-off mode and modulation mode, the heat pumps perform better in discontinuous operation mode for operation periods exceeding 60 minutes.

As part load operation efficiency affects the overall system performance, its influence on storage sizing and hydraulic design has to be considered in an energy efficient heating system design. The startup and shutdown time is longer than in common systems and has a significant effect on the dynamic behavior of the system. An efficient control strategy has to differentiate between modulation and discontinuous mode.

Keywords: Gas absorption heat pump; part load; annual efficiency; operating strategy; modulation

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1. Introduction

A domestic heating system should be capable to cover the heat load at any time. There is a wide range of the heat load, due to the linear relationship between the heat load of a building and the temperature range from -15 to +15 °C for the heating season in Germany. The mean ambient temperature in the heating season is between 3.6 and 6.8 °C [1], resulting in a low mean heat demand related to the maximum installed. The heat demand during an operation year is usually lower than 50 % of the installed capacity. It is even lower when the system consists of heat pumps: The heating device is chosen to deliver the standard heating load at standard ambient temperature and highest temperature lift and therefore low efficiency. Thus, the heat pump has to be oversized for the rest of the year.

The continuous part load operation of the heating device is limited. Condensing gas burners have a wide modulation range down to 15 % of the gas input, whereas Gas Absorption Heat Pumps (GAHP) used for domestic applications today are able to vary the heat output between 50 % and 100 % [2-4]. Below 50% modulation the cycle losses increase in a way that the operation is no longer reasonable. Measures to increase the efficiency at low part load condition beneath 50% modulation are currently under investigation but not yet market available [5,6].

Control strategies for GAHP are usually, analogous to other typically used heating devices [7], designed for variable hot water outlet temperatures [8]. This temperature, and therefore the GAHP's heat output, is controlled by modulating the gas volume flow and combustion air fan speed of the gas burner [5]. Below the modulation limit the heating device goes into on-off mode. Too many burner starts and stops reduce the lifetime of the device and cause a waste of fuel [9].

Because of this limitation, two modes with discontinuous gas flow are introduced:

- The continuous on-off mode results in an oscillating behavior of the output temperature, originating from switching on and off the gas flow: Typical amplitudes for GAHP are about 5 K for on-off periods between 1 and 10 minutes. The on-off periods are constant and frequent enough so that the GAHP is not considerably cooling off, nor is any function deactivated but the gas input, hence the name continuous on-off mode.

- The discontinuous mode describes heat production under full load conditions for a time period between 10 minutes and 2 hours. This mode can only be used with a storage tank. When the tank reaches the set value, the GAHP shuts down (all electrical and mechanical devices stop and remain in standby) and entirely cools off.

In order to evaluate the part load performance a standard efficiency is used. The standard efficiency for gas burners can be determined according to DIN 4702-8. Five part load conditions are set from 13 to 63 % of nominal capacity which connects heat production duration, inlet/outlet temperatures and energy output in a way to characterize the total annual heating energy ratio. Sorption heat pumps are evaluated according to VDI 4650-2, analogously to the standard efficiency of modulating condensing boilers.

Manufacturers of GAHP advertise efficiencies up to 165 % [2], compared to conventional condensing gas burners with 110 % standard efficiency. Systems in the field are evaluated with 95 % [10] annual efficiency for gas burners and 121 % for GAHP [11]. Manufacturers of GAHP determine the seasonal space heating standard energy efficiency under average climate conditions to 112 % [12]. The method of VDI 4650-2 seems to underestimate the total annual heating energy ratio of GAHP while condensing burners are calculated to be better compared to the field findings.

Field test results show, that there is a potential to increase efficiency by optimizing the design and control strategy in heating systems. In general and especially in systems with GAHP, 10 to 15 % improvement of the annual heating efficiency is possible [13].

The three approaches to heat production below nominal heat capacity are analyzed in this paper and compared to full load operation. The influence of each mode on the efficiency is analyzed and discussed based on the gas utilization efficiency (GUE),

$$GUE = \frac{Q_H}{(H_{i,ref} \cdot V_{gas})} = \frac{Q_H}{Q_{gas}}, \tag{1}$$

where Q_H and Q_{gas} are the heat output and gas energy input of the period under consideration. The energy content of the gas is calculated with the measured gas volume V_{gas} and lower heating value $H_{i,ref}$. The GUE can represent the annual heating energy ratio. In this paper mostly short periods between 10 min and 2 hours are taken into consideration. The maximum GUE (GUE_{max}) can be reached in steady state periods under full load conditions and depends on the external temperatures T_{HP1o} (outlet of heat sink) and T_{HP0i} (inlet of heat source). In order to compare the part load possibilities, the actual measured GUE_{meas} is related to the GUE_{max} for each pair of external temperatures, resulting in a normalized gue:

$$gue = \frac{GUE_{meas}}{GUE_{\max}} \tag{2}$$

Both GUE and gue should be maximized. This paper offers the possibility to determine which effects are crucial to the part load efficiency. Also, the influence of buffer storage on the part load efficiency is presented. For the field systems, the GUE_{max} could not be measured and therefore the manufacturer data is used for the calculation.

The heat input is the third value to fully describe an operating point as it represents the highest temperature of the cycle. When sink and source temperatures of the process are given, consequently the gas input ratio (GIR) is used to describe the part load state. Though the GIR is not equivalent to the heat output it gives information of the free heat capacity.

$$GIR = \frac{\dot{Q}_{gas,op}}{\dot{Q}_{gas,\max}} \tag{3}$$

The gas energy flow of the considered operation point $\dot{Q}_{gas,op}$ is related to the maximum energy flow of gas $\dot{Q}_{gas,\max}$. In another publication, the percentage of part load is calculated with the produced usable heat over a time period $Q_{h,period}$ divided by the amount of heat $Q_{h,nominal}$ that would be produced, assuming a constant nominal heating capacity over the same time period [13].

2. Research methodology

In this paper gas absorption heat pumps of the manufacturer Robur with a nominal heating capacity of approximately 40 kW are examined. The GAHP feature an internal heat exchange between absorber and generator (GAX-Cycle) and are able to use the latent heat of condensation in the flue gas. The working pair is ammonia (refrigerant) – water (absorbent).

The transient behavior of the mentioned GAHP has been examined in two field applications and a test facility at Technische Universität (TU) Berlin.

At TU Berlin an Air-Water-GAHP was monitored in an operating range from -2 °C to 20 °C air temperature, 35 °C to 65 °C water temperature and 15 kW to 40 kW heat load $\dot{Q}_H$. This GAHP can modulate the gas input between GIR = 50 % and GIR = 100 %. The GUE can be determined with an uncertainty of ± 5 % and is considered to be normal distributed. Systematic and statistic measurement errors are not discussed separately.

The diagram in figure 2.1 shows the set-up. The air temperature inside the climate chamber T_{HP0i} is controlled as well as the water input temperature of the GAHP T_{HP1i}. The flow rates are set to nominal conditions. To evaluate the GUE, the flow rates of natural gas and heating water and the temperature difference in the heating water are used. It shall be noted that in this set-up, the hot water temperature directly influences the water inlet temperature T_{HP1i}, making it difficult to keep T_{HP1i} constant in changing heat input conditions (on-off mode). In on-off mode as a consequence the inlet temperature also oscillates. Moreover, the gas flow is influenced by the air temperature T_{HP0i} inside the climatic chamber. Lower temperatures cause a higher density of the gas and therefore higher mass (and energy) flow which is why the GIR = 50 % cannot be reached at operating points with low air temperature.

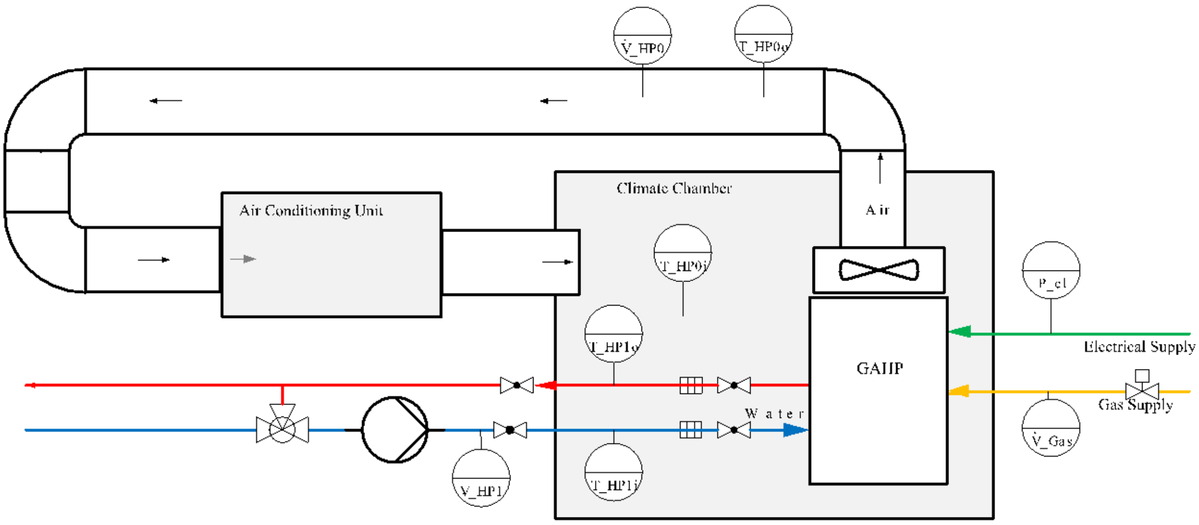

Fig. 2.1: Schematic drawing of the test set-up at TU Berlin

In the second system a GAHP using borehole heat exchangers as heat source has been installed to supply the space heating (heating circles, HC) and domestic hot water (DHW) of a kindergarten. The GAHP can provide either a) 65 °C to the DHW part or b) T<65 °C to the buffer tank (fig. 2.2). This GAHP is also able to modulate the gas input from 50 % to 100 %.

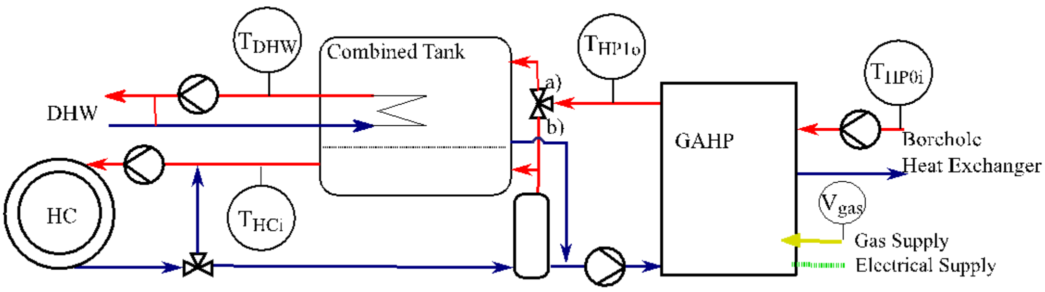

Fig. 2.2: Heating system at field layout kindergarten

In this case the GUE is determined on a weekly base. The quantity of burned gas and the heat given into the system are the values of interest.

The last monitored system consists of six identic GAHPs which are connected parallel. The common heat source are borehole heat exchangers and the heat sink is exclusively floor heating. The GAHPs are switched on one after another when the set temperatures of the buffer system are not reached. When the heat load is lower than the nominal capacity, this type cannot modulate the gas input smoothly but will function in continuous on-off-mode. As in the kindergarten, heat meters and gas quantity meters are the basis for GUE calculation. The metering is online and shorter periods e.g. on a daily base can be analyzed.

In both field systems, the GUE can be determined with an uncertainty of ± 0.1. The measurement equipment used in this paper are the heat meters WMZ1, WMZ2 with the corresponding temperatures T_{HP1o} and the gas meters of GAHP1 and GAHP1…6 seen in figure 2.3. Additionally the temperature of the warm side of WMZ3 is taken for T_{HP0i}.

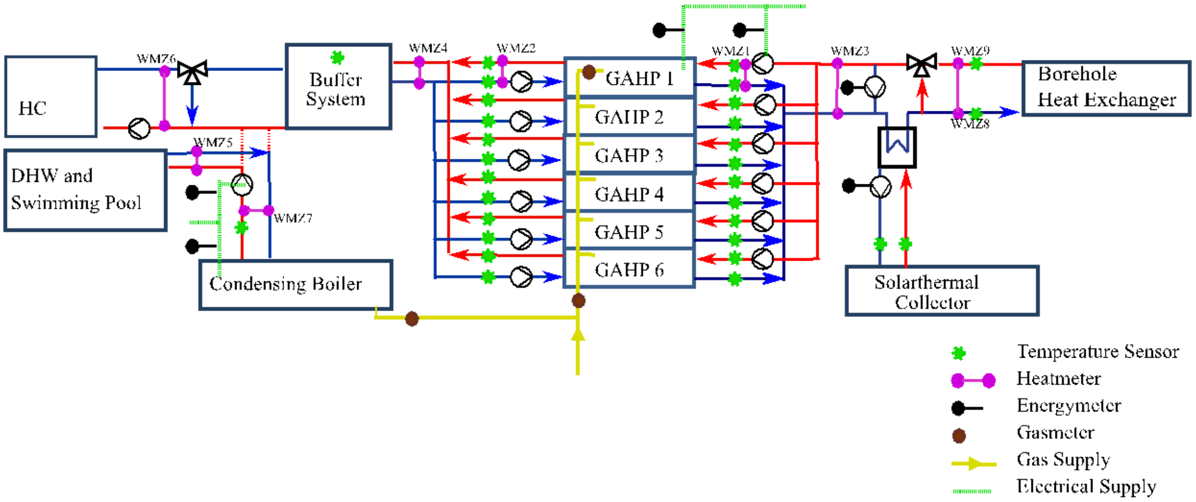

Figure 2.3: Heating System at field layout residential homes

Here two system boundaries can be defined: Firstly the sole GAHP 1 can be balanced and secondly the common energy balance of six GAHPs. Deviations between the GUE of the single GAHP and the common GUE have been observed. The data are shown in fig. 3.2.

3. Results

3.1 Modulation mode

The GAHP at the test facility was operated in steady state operating periods with fixed inlet temperatures of the heat source and fixed outlet temperature of the heat sink. All presented data are produced with nominal flow parameters: For air 11000 m³/h and for water 3.5 m³/h. The GIR was varied in five steps: 100 %, 85 %, 75 %, 65 % and 50 %. This is done 2 times for air inlet temperatures -2 °C, 7 °C and 15 °C combined with water outlet temperatures 35 °C, 50 °C and 58 °C and the gue was determined.

Figure 3.1 shows the behavior of the gue with respect to the given temperatures and the gas input ratio. The different measurement series are characterized by the air temperature T_{HP0i}, the water outlet temperature T_{HP1o} and the temperature lift (e.g. 15/35 (20)). It can be seen that gue depends on the gas input and decreases with it. The slope depends on the temperature lift: The three chosen test series in the diagram of fig. 3.1 show the boundaries of the degradation. When the temperature lift is higher, there is a stronger decrease of the gue by modulating the gas input down to 50 %. The lowest measured gue is 0.73 at 55 % modulation at the temperature pair -2/58 (60). At most operating points with 50 % GIR, the gue are between 0.8 or 0.85 and even under best circumstances a 10 % drop at 50 % modulation is unavoidable.

Aprile et al. concluded in a simulation study for this GAHP that with decreasing gas input from 100% to 50% of the nominal value, the GUE dropped by 6.8% for the operating point 10/50 (40). The Gas Input Ratio influences the highest temperature of the cycle and with a reduction, the heat recovery potential decreases. [14] The efficiency drop found in the test rig is higher as compared to the theoretical cycle analysis by Aprile et al.

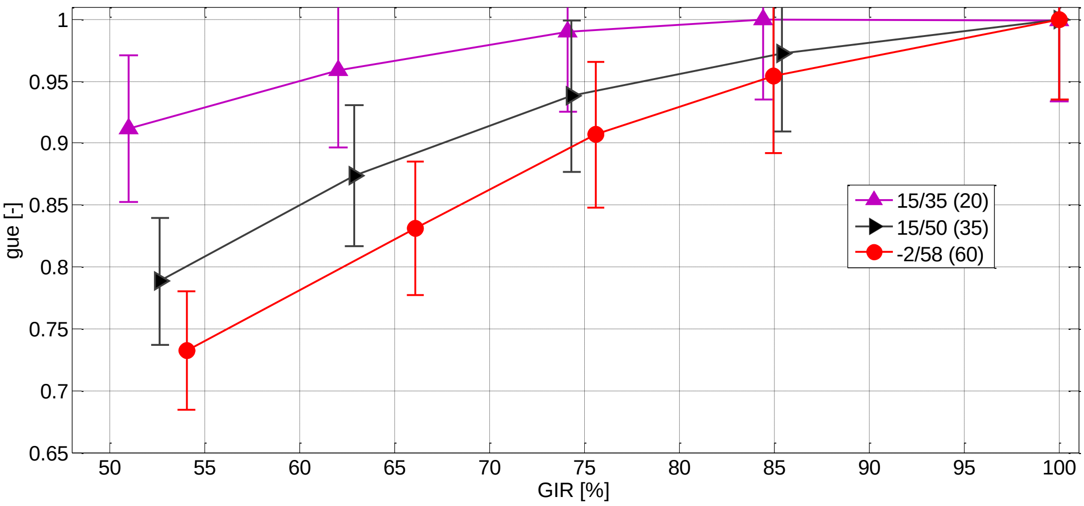

Fig. 3.1: Test rig results for gas input modulation

3.2 Discontinuous mode

In discontinuous operation, cooldown losses reduce the efficiency compared to continuous operation. The maximum GUE cannot be reached. The starting phase takes 10 minutes in this specific type of GAHP and after that, a steady-state phase is developing. At the end of a period the remaining heat above the temperature of the inlet is used, which means about 10 minutes of decreasing heat supply without burning gas.

The shortest evaluated period of 20 minutes only consists of starting phase and cooldown phase. It also has the lowest gue of 0.5 which can be seen in Fig. 3.2. The losses are of the same order as the usable heat. This operation mode is frequent in the system of the residential homes and the results match the findings of the test rig beside some outlier below the test rig curve in Fig. 3.2.

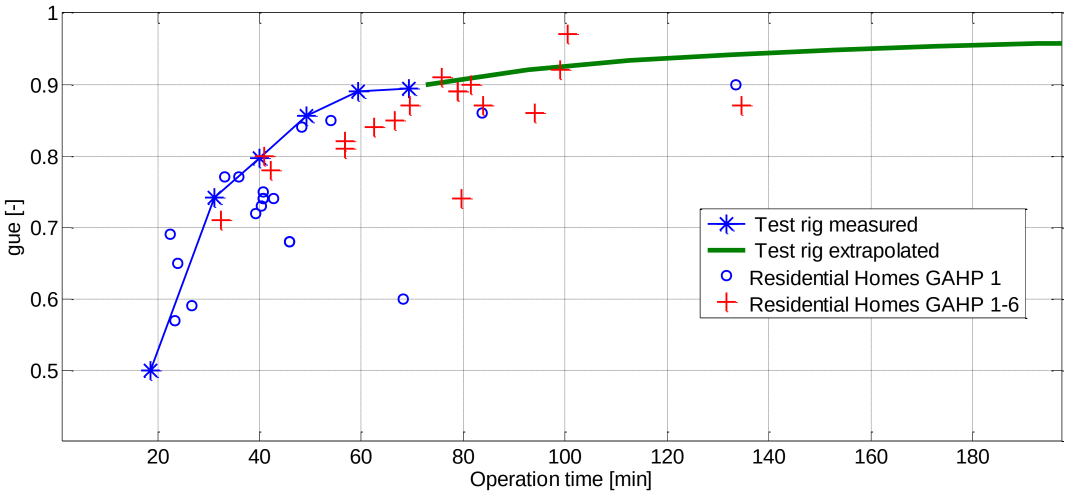

Figure 3.2: Test rig and field results for discontinuous operation

According to Figure 3.2, in order to reach the highest efficiency, the operating time period should be as long as possible. With every starting phase, a specific heat input is necessary to start the process, which cannot be recovered. As a control strategy, a minimum output of usable heat from which the start is worth it can be defined. If heat storage is used to buffer 60 minutes of full capacity heat production, 90 % of the maximum GUE is possible for charging periods without simultaneous heat demand. Compared to modulation mode, in certain operating points, this is better alternative.

For the data of residential homes in Fig. 3.2, GAHP 1 has been evaluated to have a lower gue compared to the balance over all six machines. The reason is that GAHP 1 happened to be the last heat pump being switched on by the control system of the cascade. This means it is operating for shorter time periods than the other heat pumps. When heat demand occurs, an algorithm decides which heat pump is switched on first and when the heat demand appears to be higher than the heat output of the operating GAHP, the second one is switched on and so on.

3.3 Continuous on-off mode

Both field installations typically operate in continuous on-off mode. The GAHP installed in the residential home are not able to vary the gas flow, but modulate the heat by rapidly switching the burner on and off (1/min). Newer versions with modulating burners like the one used in the kindergarten have a starting routine of 4 minutes of full gas input implemented. Nevertheless both operating modes of these different GAHP models are referred to as continuous on-off mode in this paper.

The GAHP of the test rig at TU Berlin was evaluated for one pair of temperatures 7/50 (43) and under mean gas input ratio of 42 % over two hours. The result was a GUE of 0.88 (gue = 0.66). Corrales et al. have estimated that the change from high frequent on-off mode to fewer on-off cycles results in an improvement of 15 % of the GUE. [15]

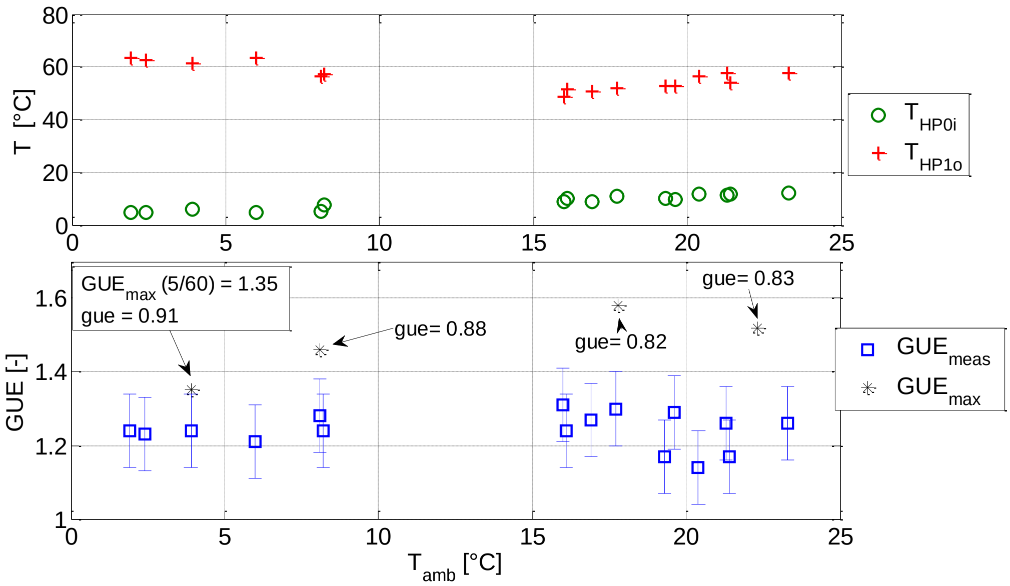

Fig. 3.3: Data from field system kindergarten regarding continous on-off mode

The improvement cannot only be attributed to a reduction of burner starts but several effects play a role: The inlet temperature sinks and the heat output rises which is positive for the GUE. The sole influence of the reduction of burner starts cannot be determined in this work. The test rig has a return flow addition and changes in the outlet temperature strongly affect the inlet temperature. For further investigation a test rig with heat storage is recommended.

In figure 3.3 the monthly mean data of ambient temperature T_{amb}, the temperature of heat sink outlet temperature T_{HP1o}, the temperature of heat source inlet temperature T_{HP0i}, the GUE and the manufacturer steady state GUE_{max} is presented. At times with a low heat demand and high ambient temperatures between 10 and 25 °C, part load losses and dynamic DHW loading phases limit the GUE. High temperature lifts and short heat demands are characteristic for DHW generation. The set temperature and the outlet temperature of the GAHP differ when there is a demand of DHW. The storage is charged at 65 °C. In this case, not only part load demand is the reason for on-off operation. The outlet temperature is limited to 65 °C and the burner stops when this value is exceeded.

As shown in fig. 3.3, the GUEs stated by the manufacturer for the regarded operating conditions are higher than the measured ones. The difference is caused by part load losses and it is smaller at higher loads in winter (e.g. 60/5(55)). The gue varies between 0.8 and 0.9.

Two effects alternate during an operating year and prevent the GAHP in the field from high annual efficiency. In summer periods the benefits of the smaller temperature lifts are overcompensated by high part load loss due to a much lower heat demand resulting in an efficiency reduction. Discontinuous operation mode in combination with on-off operation mode characterizes the operation periods in summer, when only DHW generation takes place. The high temperature lifts in winter periods with higher heat load demands is the predominant factor for the reduced gas utilization rate and because of that higher gue can be reached.

4. Conclusion

In order to evaluate the annual efficiency of a GAHP, it is necessary to know the peripheral system. The result of a standard test procedure for the seasonal efficiency can be exceeded in the field by 10 – 20 %. The use of a thermal storage is an important factor to increase the annual efficiency of the heat pump. Moreover, the efficiency of the evaluated field systems could be improved by approximately 10 % due to the reduction of continuous on-off mode and by the extension of operating time periods. GAHP perform best under continuous, base load conditions which has to be considered in the design of a heating system [15].

It has been shown that the efficiency drop at the highest measured temperature lift can be up to 30 % at GIR = 50 %. In this load condition and below, most of the heat is produced, resulting in low annual GUEs.

Because of that, in the domestic market the modulation range should be lower than 50 % of the nominal heating load of the building. Today this is reached by adding a peak load heating device. Alternatively or additionally, heat storage can be implemented. The operation time is crucial to the GUE and has to be regarded in the planning process. GAHP react slower to changing load conditions compared to gas burners and therefore cannot be seen as a replacement of conventional gas burners without changing the control strategy. An active control of storage charging and discharging with respect to the time is necessary. Continuous on-off mode should be avoided to reduce both flue gas losses and auxiliary energy consumption of continuously working water pumps. For heating demands below the modulation limit, discontinuous mode is preferable in general.

At operation conditions with high temperature lift (winter period) or low heating demand (spring and autumn) discontinuously higher loads raise the efficiency in systems with thermal storage. 50 % of the nominal heat capacity (e.g. at 0 °C ambient temperature) then could be delivered either with a gue of 70 % in modulation mode or with a gue of 90 % in discontinuous mode, provided that the heat pump is working under full load for 60 minutes minimum. The relative optimization potential is higher in the warmer season.

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