INFLUENCE OF HEAT PUMP CONTROL ON PERFORMANCE PARAMETERS

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Abstract
The aim of the verification was to gain knowledge about the energy balance, performance, and operating parameters of gas absorption heat pumps with equithermal heating water temperature control and fixed heating water temperature control. Four ROBUR air-water gas absorption heat pumps (GAHP) A with outputs of 50 kW and 100 kW were tested in operation in various modes. During equithermal control of heat pump operation, 6.5-18.2% higher values of SCOP, SGUE and SPER performance parameters were achieved. The performance parameters SCOP, SGUE and SPER were 8.4-9.1% higher in equithermal control and the requirement of 16-hour active control than in the requirement of 24-hour active control. When using equithermal control, the specific CO_2 production resulting from natural gas consumption was lower by 6.84 kg CO_2/GJ and from electricity consumption by 0.32 kg CO_2/GJ compared to fixed heating water temperature control. A lower defrost frequency of the heat pump evaporator was found during the fixed heating water temperature control.

Key words: *absorption heat pump; natural gas; energy balance; COP; GUE; PER; CO_2 emission.*

INTRODUCTION

Gas Absorption Heat Pump (GAHP) operation control has a major impact on its performance parameters, namely Coefficient of Performance (COP), Gas Utilization Efficiency (GUE), and Primary Energy Ratio (PER). (*Fumagalli, 2017*) indicated that performance parameters determine global performance. However, it is important to analyse performance parameters together with other parameters characterising GAHP operating conditions. They included external conditions (ambient temperature and humidity), operating conditions (heating water temperatures), number of burner ignitions, cycle time, and defrost frequency. They considered PER to be the performance parameter with the highest definition. (*Janssen, 2020*) indicated that the key parameter is the cycle time, which significantly affects the overall efficiency. They supported this statement by the results of verification showing that the start-up time is about 8 minutes. At the 15-minute cycle, the actual efficiency was 22% lower than the steady-state efficiency. When the cycle lasted 35 minutes, the efficiency reached a value higher than 90% of the steady state. (*Corrales Ciganda, 2015*) studied GAHP efficiency in real applications. They observed the poor impact of incorrect design and control strategies, which caused excessive power consumption and frequent ON-OFF cycles (cycling). They also considered the PER performance parameter to be the most important.

(*Famiglietti, 2021*) studied the environmental aspects of GAHP applied to space heating and domestic hot water heating. They carried out evaluations in three buildings located in three representative European climatic conditions. CO_2 emissions were specified per 1 kWh produced by these sources. (*Charlick, 2014*) performed detailed dynamic tests of air/water GAHP at ambient air temperatures of 0 °C and 7 °C and heating water temperatures of 40 °C and 60 °C. CO_2 production ranged from 0.185 kg CO_2/kWh to 0.202 kg CO_2/kWh.

It is indicated in the report for Sustainable Energy Authority of Ireland (*Heat Pumps Technology Guide, 2020*) that the equithermal control is the most commonly used to manage GAHP operations. Equithermal temperature control consists in setting the heating water temperature of the heat source based on the outdoor temperature. At a lower outdoor temperature, a higher heating water temperature is required to balance the supplied heat with the heat loss of the building and vice versa. A set of equithermal curves can be determined for a given building, which describes the interdependence of the heating water temperature, the temperature in the building, and the outdoor temperature. Based on the required temperature in the building, a particular curve can be selected, and the heating water temperature can be regulated according to the outdoor temperature. The disadvantage of GAHP equithermal control is the slow response to rapid changes in outdoor temperatures (*Heat Pumps Technology Guide, 2020*).

The output of systems integrating several heat pumps, or heat pumps containing several cooling circuits, is controlled by switching the individual circuits on or off. This control method reduces the number of starts required, which means getting the system components less worn out and lowering the requirements for the balancing capacity (*Heat Pumps Technology Guide, 2020*).
The verification aimed to gain knowledge about the energy balance and values of the GAHP seasonal performance parameters, i.e., Seasonal Coefficient of Performance (SCOP), Seasonal Gas Utilization Efficiencies (SGUE), Seasonal Primary Energy Ratio (SPER), and values of GAHPs operating parameters (time of one cycle τ_c, total operating times $\Sigma\tau_o$, number of burner ignitions n_c, defrost frequency n_d) at two different control modes. It also aimed to specify the impact of the verified type of regulation on specific CO_2/GJ production resulting from natural gas and electricity consumption.

MATERIALS AND METHODS

The verification was carried out on ROBUR air-water GAHPs A in 4 boiler rooms in a cascade with gas condensing boilers (CB) with outputs of 50 kW and 100 kW in the period of 1.9.2019 to 31.8.2020. The basic description of individual installations is presented in Tab. 1. The column "control" specifies the GAHP and CB operation control method. Abbreviation "Fix." indicates fixed required heating water temperatures. GAHP operation at heating water temperatures of 60/50 °C and 55/45 °C was verified. Abbreviation "Eq." stands for the control of the required heating water temperature based on the outdoor temperature, and the subsequent value indicates the slope of the equithermal curve. The value after the dash indicates the number of hours during the day when the request was active in comfort mode. The note "in" and "out" indicates the position of the reference sensor of the setpoint temperature, i.e., whether the cascade is controlled according to the temperature of the inlet or outlet water from the unit. The following column specifies the heat loss of the building $Q_{\square,h.l.}$ at the calculated temperature of -15 °C. The penultimate column shows the installed capacity of GAHP and peak CB sources, and the last column presents the average ambient temperature t_e during the verification.

Tab. 1 Specification of parameters of verified operations

	Type of building	Type of source control	Heat loss $Q_{\tau,h.l.}$ [kW]	Installed power $Q_{\tau,i.c.}$ GAHP/CB [kW]	t_e [°C]
A	Primary school	Fix. 60/50 - 16 - out	50	1x35/1x30	3.6
B	Primary school	Eq. 1,0 - 16 - in	100	2x35/1x35	3.2
C	Primary school	Fix. 55/45 - 24 - out	50	1x35/1x30	3.6
D	Municipal authority	Eq. 1,0 - 24 - in	100	2x35/1x50	3.0

Heat production Q_C from GAHP condensers, natural gas consumption $Q_{gen.}$ in the generators, and the unit electricity consumption $Q_{e.e}$ in the monitored period were measured. The total operating times of GAHP $\Sigma\tau_o$, average operating times of the cycle τ_c, numbers of ignitions of generator gas burners n_c, and defrost frequency of evaporators n_d were also recorded.
The efficiency of the cycle operation was evaluated by the standard seasonal performance parameters SCOP, SGUE, and SPER, and by the average cycle time τ_c calculated according to the following relations:

$$SCOP = \frac{Q_{C.}}{Q_{gen.} + Q_{e.e}} \quad [-] \quad (1)$$

$$SGUE = \frac{Q_{C.}}{Q_{gen.}} \quad [-] \quad (2)$$

$$SPER = \frac{Q_{C.}}{Q_{gen.} \cdot f_{gen.} + Q_{e.e.} \cdot f_{e.e.}} \quad [-] \quad (3)$$

$$t_c = \frac{St_o}{n_c} \quad [s] \quad (4)$$

Factors of primary energy from non-renewable sources in the sense of the (*Directive EU 2018/844, 2018*) for the Czech Republic are considered $f_{gen.}$ = 1.0 for natural gas and $f_{e.e}$ = 2.6 for electricity.

RESULTS AND DISCUSSION

The verification results are summarized in the graphs in Fig. 1 and 2 and in Tab. 2.

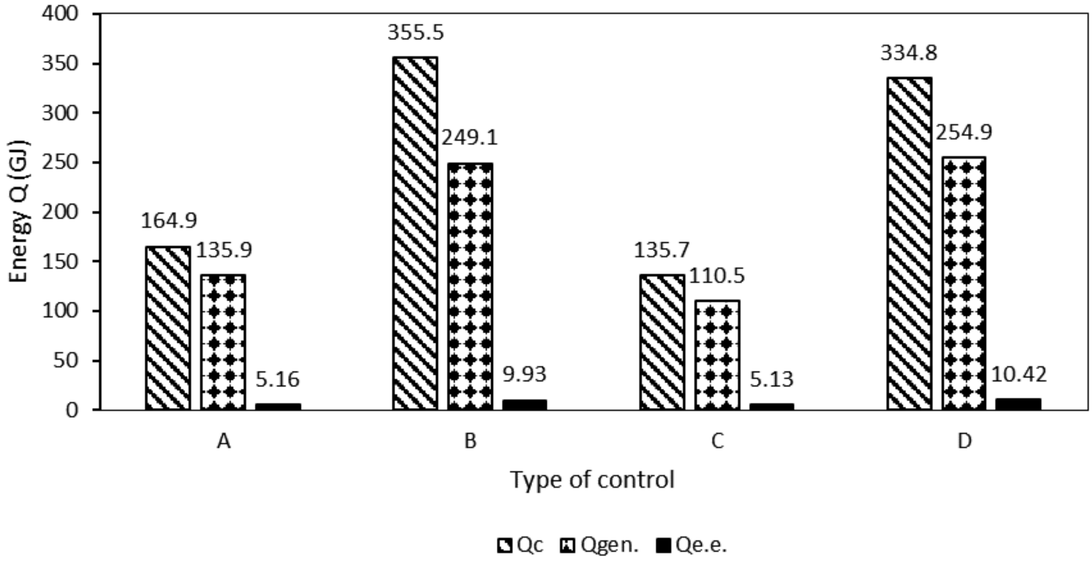

Fig. 1 GAHP energy balance

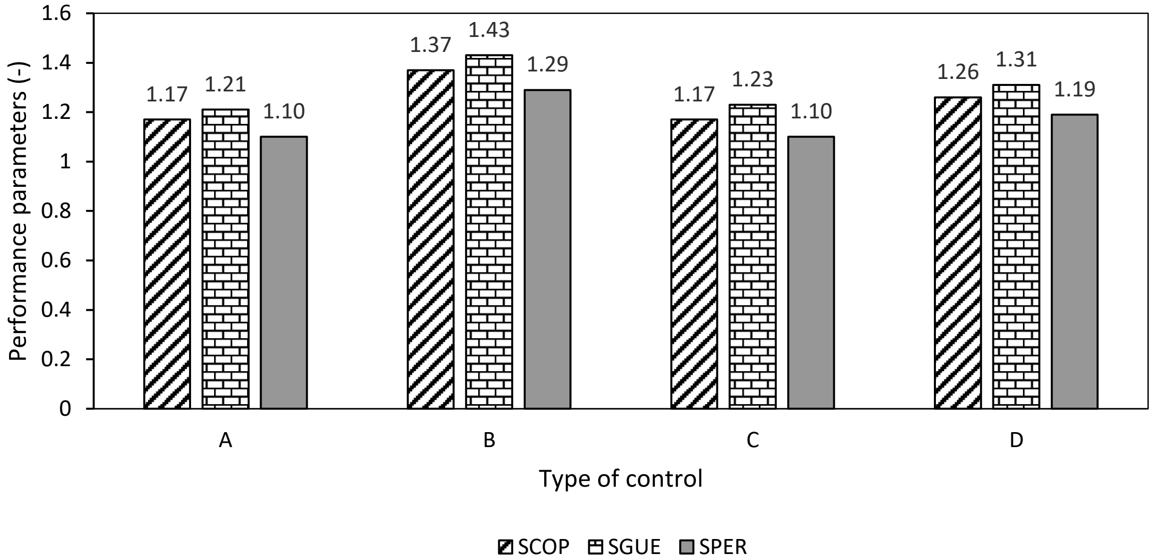

Fig. 2 GAHP performance parameters

Due to different operational and external conditions, the calculated values of SPER performance parameters in the primary school building were 15-25% higher than reported by (*Fumagalli, 2017*). They were in conformity in the municipal authority building.

Tab. 2 Heat pump operating times and switch-on and defrost frequencies

	Type of building	Total operating time $\Sigma\tau_o$ [h]	Average time of cycle τ_c [s]	Number of cycles n_c [-]	Defrost frequency n_d [-]
A	Primary school	1 863	4 132	1 623	59
B	Primary school	1 788/1 795	8 164	742/838	181/140
C	Primary school	1 924	1 399	4 950	0
D	Municipal authority	1 852/1 861	1 538	4 403/4 288	44/39

The verification results confirmed the conclusions reported by (*Corrales Ciganda, 2015*). A higher number of ON/OF cycles caused dynamic losses leading to lower SPER and SGUE values. Higher electricity consumption affected the SPER values negatively.
At the requirement of 16-hour active control, the average cycle times τ_c during control Eq. and Fix. were significantly longer than the cycle time limits specified in (*Janssen, 2020*). It was not the case during the 24-hour active control.

The operational verifications resulted in the following:

1. Despite the significantly higher defrost frequency n_d, higher values of the performance parameters SCOP, SGUE, and SPER were achieved when the control of GAHP operation was based on outdoor air temperature Eq. than when it was based on the fixed outlet water temperature Fix.
2. The average cycle times τ_c were longer during Eq. control, especially when 16-hour active control was required. When 24-hour active control was required, the cycle times were significantly shorter and almost identical for both types of control.
3. Total operating times $\Sigma\tau_o$ did not differ significantly at Eq. or Fix. control. They increased slightly with 24-hour active control.
4. The number of starts (cycling) n_c was higher during control Fix., especially when 16-hour active control was required. When 24-hour active control was required, the number of starts in both types of control increased significantly.
5. The performance parameters SCOP, SGUE, and SPER during Eq. control were higher when 16-hour active control was required than during the 24-hour active control requirement. The performance parameters during control Fix. were almost identical.
6. The number of defrost cycles was significantly higher during Eq. control than during Fix. control.

The seasonal energy efficiency of the device equivalent to our measured SPER value calculated by the manufacturer according to the NK 811/2013 methodology (*Eur-lex, 2013*) indicated its value for Robur GAHP A device 1.13 in average climatic conditions (CR), 1.09 in colder climates, and 1.17 in warmer climates. Higher SPER values were reached during Eq. control, both at the request of 16- and 24-hour active control, and lower during Fix. control.
Tab. 3 presents specific heat consumption in the generator $q_{gen.}$, specific electricity consumption $q_{e.e.}$, and low-potential energy q_{air} in the air fed to the GAHP evaporator needed to produce 1 GJ of energy in the GAHP condenser.

Tab. 3 GAHP specific heat and electricity consumption for the production of 1 GJ

	Type of source control	Heat production in condenser q_C [GJ]	Heat consumption in generator $q_{gen.}$ [GJ]	Electricity consumption $q_{e.e.}$ [GJ]	Heat at the evaporator $q_{air.}$ [GJ]
A	Fix. 60/50 - 16 - out	1.0	0.824	0.031	0.145
B	Eq. 1.0 - 16 - in	1.0	0.701	0.028	0.271
C	Fix. 55/45 - 24 - out	1.0	0.814	0.038	0.148
D	Eq. 1.0 - 24 - in	1.0	0.761	0.031	0.208

The processed verification results indicated the highest specific energy consumption 60/50 - 16 – "out" (A) during Fix. control and the lowest 1.0 - 16 – "in" (B) during Eq. control. The difference between specific heat and electricity consumption was Δq_{gen} = 0.123 GJ and $\Delta q_{e.e.}$ = 0.003 GJ.
According to (*NIR, 2021*), the emission factor 0.2 t CO_2/MWh (55.6 kg/GJ) and the electricity generation factor 0.382 t CO_2/MWh (106.1 kg/GJ) are used to calculate CO_2 emissions from natural gas combustion in the Czech Republic. Average emissions production of 43.78 kg CO_2/GJ was calculated during Eq. control and 49.20 kg CO_2/ GJ during Fix. control. It is evident from the above that the application of control type Eq. 1.0 - 16 – "in" compared to Fix. control 60/50 - 16 – "out" will reduce specific CO_2 production resulting from natural gas consumption by 6.84 kg CO_2/GJ and electricity consumption by 0.32 kg CO_2/GJ. (*Charlick, 2014*) considered emission factors for natural gas 0.1841 kg CO_2/kWh (51.14 kg CO_2/GJ), and for electricity 0.5173 kg CO_2/kWh (143.69 kg CO_2/GJ). For control Fix., they stated average emission values of 0.187 kg CO_2/kWh (51.94 kg CO_2/GJ) for a heating water temperature of 40 °C, values of 0.201 kg CO_2/kWh (55.84 kg CO_2/GJ) for a heating water temperature of 60 °C. The recalculation indicated that the production of CO_2/GJ in our verifications during control Fix. was lower by 16.1%.

CONCLUSIONS

The goals presented in the introduction to the article were achieved. The verification results showed that the Eq. control, i.e., the setting of the heating water temperature based on the outdoor temperature, was more effective than the Fix. control (setting fixed heating water temperatures) in terms of performance and operating parameters of the GAHP.
The results also showed that the heat balance and performance and operating parameters of GAHP achieved better values at the requirement of 16-hour than at 24-hour active control.
Higher performance and operating parameters of GAHP at Eq. control also brought positive environmental aspects of reducing CO_2 emissions.

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