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In situ optimization methodology for the water circulation pumps frequency of ground source heat pump systems: Analysis for multistage heat pump units

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ABSTRACT

In order to optimize the global energy performance of a ground source heat pump system, special attention needs to be paid to the auxiliaries as they stand for a considerable part of the total energy consumption. A new in situ experimental methodology based on the frequency variation of the water circulation pumps in order to optimize the energy performance of the system was previously published by the authors for a ground source heat pump system using a single stage heat pump with ON/OFF regulation. The original single stage heat pump was recently replaced with a multistage unit consisting of two compressors of the same capacity working in tandem. A new experimental campaign was carried out and a new study was performed in order to adapt the in situ optimization methodology to the performance of the tandem compressors unit, and, by extension, to the multistage case. This paper presents the in situ optimization methodology for the water circulation pumps frequency adapted for multistage ground source heat pump systems. Results show that energy savings up to 32% can be obtained by applying this optimization methodology.

1. Introduction

In the current context of global warming concern, special attention should be paid to the efficient use of renewable energies. Ground source heat pump (GSHP) systems, which take advantage of shallow geothermal energy, are widely considered as being among the most efficient and comfortable heating and cooling renewable technologies currently available [1]. They can lead to a 40% savings in annual electricity consumption, in comparison to air to water conventional heat pumps [2].

Over the last years, research has focused on capacity control, mainly by means of variable speed compressors. For instance, Fahlén and Karlsson compared control for ON/OFF compressor with variable speed control for a brine-to-water heat pump ([3] and [4]). In [5], Madani et al. carried out a comparative analysis of three common control strategies for an ON/OFF controlled ground source heat pump system. In [6], Zhao et al. performed both a theoretical and an experimental analysis in order to match the capacity of a geothermal heat pump system, which used as a low temperature heat source the geothermal discharge water, with the actual load requirement by adjusting the compressor rotation speed by means of a transducer.

However, several studies highlighted the important amount of energy consumed by the auxiliaries (such as water circulation pumps) in air conditioning systems ([7–9]) and the necessity of reducing this energy consumption, above all in GSHP systems in which two circulation pumps are required. In [10], Granryd presents analytical expressions for possible optimum flow rates on the secondary loop. In the Ph.D. work by Karlsson [11], a theoretical study shows that there is a potential for applying an optimization method for keeping the compressor and pump speeds at the optimal combination. The key point to find this optimal combination is to consider the pump circulation rates optimizing the total power consumption of the system and not only the heat pump power consumption. The authors previously developed an experimental in situ optimization methodology for the water circulation pumps frequency of ground source heat pump systems when single stage ON/OFF regulation is employed [12].

The present paper is focused on describing and applying a similar methodology, also reliant on in situ experimental measurements, in order to optimize the system energy performance when considering multistage ON/OFF regulation. The study was experimentally carried out for a heat pump unit using two compressors of the same capacity working in tandem, and the methodology was

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Nomenclature

Symbol

COP_{sys}	system coefficient of performance
c_p	specific heat at constant pressure
$\dot{m}$	internal circuit flow rate
n	operation state of the heat pump unit
N	total number of compressors of the heat pump unit
PF_{sys}	system performance factor
$\dot{Q}_B$	instantaneous thermal load of the building
$\dot{Q}_{HP}$	heat pump capacity
$\dot{Q}_{(n)}$	capacity of n stages
$T_{o,ic}$	temperature at the outlet of the internal circuit
$T_{i,ic}$	temperature at the inlet of the internal circuit
T_{SB}	building supply temperature
t_{ON}	duration of the ON cycle
t_{OFF}	duration of the OFF cycle
$\dot{W}_{par}$	parasitic losses of the heat pump unit
$\dot{W}_{comp}$	compressor power consumption
$\dot{W}_{ECP}$	ECP power consumption
$\dot{W}_{ICP}$	ICP power consumption

Greek symbols

α	partial load ratio of the system
α'	partial load ratio of each stage of the heat pump unit
η	electrical efficiency of ICP

Acronyms

GSHP	ground source heat pump
GSHX	ground source heat exchanger
ICP	internal circulation pump
ECP	external circulation pump

adapted to multistage heat pump units with whatever number of compressors.

2. Geothermal experimental plant

The geothermal plant studied in the present work was built in year 2004 during a European project called Geocool [13]. In the framework of another FP7 European project, Ground-med [14], the original heat pump located at the geothermal plant (ON/OFF controlled single stage unit) was replaced with a multistage unit consisting of two compressors of the same capacity working in tandem. Therefore, most of the installation remained unchanged (ground source heat exchanger, hydraulic circuits, etc.) and the main modification was the replacement of the heat pump mentioned above.

The GSHP installation studied in the present work air-conditions a set of spaces in the Department of Applied Thermodynamics at the Universitat Politècnica de València, Spain, with a total area of approximately 250 m^2. All rooms are equipped with fan coils supplied by the GSHP system. The geothermal system consists of a reversible water-to-water heat pump (nominal capacity of 17.2 kW in cooling mode and 19.2 kW in heating mode), a vertical borehole heat exchanger (grid of 2 × 3 boreholes, 3 m separated from each other, 50 m deep) and a hydraulic group, as shown in the diagram of the installation in Fig. 1.

As it can be observed in Fig. 1, the system can be divided into two main circuits: an internal circuit which consists of a series of 12 parallel connected fan coils, an internal hydraulic loop and a water storage tank, and an external circuit which consists of the ground source heat exchanger (GSHX) which is coupled to the heat pump by an external hydraulic loop. A timer controls the overall system operation, which was programed to operate from 7am to 10pm, 5 days per week.

Both circuits, internal and external, are provided with circulation pumps which make the water circulate toward the fan coil units (ICP; nominal values at 50 Hz: 3180 kg/h with 0.63 kW power consumption) and the GSHX (ECP; nominal values at 50 Hz: 2650 kg/h with 0.36 kW power consumption). While the internal pump works continuously during the 15 h per day of system operation, the external pump is controlled by the heat pump controller, which makes it work only when at least one of the compressors is running. Two frequency inverters, one for each circulation pump, were installed in order to vary the internal and external circuit water flow rates. A network of sensors was set up so that the installation is completely monitored: water temperatures (four-wire PT100 with accuracy ±0.1 °C.), mass flow rates (Danfoss flow meter model massflo MASS 6000 with accuracy <0.1%) and power consumptions (Gossen Metrawatt power meter model A2000 with accuracy ±0.5%).

Further details on the system description can be found in previous publications [12,13].

3. Theory and calculation

3.1. Impact of water flow rates on the system energy performance

When optimizing the overall system performance of a GSHP installation, it is important to understand how the increase of the circulating water flow rate affects the performance of the heat pump and that of the entire system. In a given system, the higher the inverter frequency, the greater the circulating water flow rate. A higher water flow rate enhances the heat transfer coefficient through the heat exchanger of the heat pump and diminishes the water temperature variation across it; the same happens at the GSHX. On the heat pump side, the increase of the water flow rate helps to reduce the temperature difference between the water and the refrigerant and, as a result, the temperature lift that the compressor must overcome becomes lower and the heat pump COP increases [12]. This can be observed in Fig. 2, which shows experimental results of the effect of varying the water flow rates (proportional to the frequencies, which were set at the same value when measuring the different experimental points) in both the heat pump COP (COP_{HP}) and the system COP (COP_{sys}). It is clearly noted that the higher the flow rate at both the external and internal circuit, the better the performance of the heat pump (COP_{HP}). Nevertheless, when the whole system is considered, operating at maximum flow rates (maximum frequencies) results in a great reduction of the system COP due to the big influence of the circulation pumps consumption.

In a few words, increasing the water flow rate on both sides of the heat pump (evaporator and condenser) diminishes the compressor consumption but increases the circulation pumps consumption. These two opposite trends on energy consumption result in an optimum frequency for each one of the water loops. This paper describes the in situ methodology to determine those optimum frequencies for a multistage heat pump unit.

3.2. Partial load ratio of the system

When analyzing a multistage heat pump unit, which consists of a specific number of compressors (N) working in tandem, special attention should be paid to the thermal demand of the building, since it will determine the number of stages in operation and thus the compressor consumption. It should be noted that the greater the number of stages switched on, the higher the compressor consumption and the lower the impact of the water circulation pumps