Energy and Buildings 91 (2015) 105–114

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy efficiency in a ground source heat pump with variable speed drives

Davide Del Col[a,*], Marco Azzolin[a], Giacomo Benassi[b], Mauro Mantovan[b]

[a] *Università degli Studi di Padova, Dipartimento di Ingegneria Industriale, Via Venezia 1, 35131 Padova, Italy*
[b] *Hiref Spa, Viale Spagna, 31/33, 35020 Tribano, PD, Italy*

ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form 4 December 2014
Accepted 29 December 2014
Available online 5 January 2015

Keywords:
Ground source heat pump
Model
Experimental data
Control
Variable speed
COP
Seasonal performance

ABSTRACT

A variable capacity heat pump, with variable speed drives on the secondary circuits, needs an adequate control for achieving the maximum energy efficiency. In the present paper, experimental data and a modeling procedure of a ground source heat pump (GSHP) with variable speed compressor, variable speed water pumps and variable speed fans in the coils are reported. Both data and model are used to evaluate the operating conditions that lead to the maximum seasonal coefficient of performance of the system. The control parameters that can be varied are the followings: frequency of compressor, frequency of water pump to the borehole heat exchangers, frequency of the water pump to the user, velocity of the fans, water temperature to the user. From the experimental data, it was possible to define a control variable which is the ratio of compressor electric power consumption to the power absorbed by the water pumps. The model is also the baseline to develop a control strategy that is implemented in the present GSHP system, developed in the framework of the European Project Ground-Med, with the final objective of maximizing the seasonal coefficient of performance of the system.

1. Introduction

Heat pumps operate intermittently in the on/off mode in order to adjust the heating and cooling capacity to the load required by the building. When the heat pump operates in this way, it must supply heat at higher temperature during on time to provide the thermal energy needed during the entire cycle. On the contrary, if a variable speed compressor is used, the heat pump could simply follow the load, taking advantage at partial loads from the "oversized" heat exchangers and thus increasing its efficiency.

Qureshi and Tassou [1] commented that scroll compressors with variable speed drives could be an alternative for refrigeration systems but some problems due to harmonics generated by the frequency inverters, reduction of motor efficiency and proper lubrication and cooling at low speeds required further development.

Regarding the best approach to match the output capacity of a ground source heat pump with the load required by a building, Zhao et al. [2] proposed a theoretical and experimental analysis. They considered several methods for capacity control such as turning on/off the compressor, controlling intake and discharge valves on/off times, varying composition of the refrigerant mixture and varying the compressor speed. After the theoretical analysis they chose the latter method for the experimental analysis. Their tests focused on the influence of the frequency of the compressor speed on the *COP* at different water tank temperatures. While heat and cool capacity increased almost linearly by increasing frequency, *COP* presented different trends depending on water tank temperature. A comparison of the energy performance of variable-capacity geothermal heat pumps against the performance of on/off controlled equipment has been reported in Munari et al. [3]. Three major aspects were taken into account: the temperature level of the heated water, the effect of the performance of the heat exchanger at partial loads and the compressor global efficiency. The electrical efficiency of asynchronous motors at variable speed was compared against the efficiency of permanent magnet brushless motors. The heat exchangers performance at partial loads and compressor efficiency were found as the major aspects in the comparison. A comparison between on/off compressor control and variable speed control for a brine-to-water heat pump was conducted by Karlsson and Fahlen [4]. The main benefit that emerges from the study is that by using a variable speed compressor, the need for supplementary heating is reduced. Recently, the same authors [5] investigated the issue in domestic GSHPs. In their study they compared four heat pumps: two capacity controlled heat pumps specifically designed for this project with one designed for variable speed operations, a

---

* Corresponding author. Tel.: +39 049 8276891; fax: +39 049 8276896.
E-mail address: davide.delcol@unipd.it (D. Del Col).

http://dx.doi.org/10.1016/j.enbuild.2014.12.048
0378-7788/

single speed compressor heat pump available on the market and a fictitious heat pump with a scroll compressor and the same efficiency of the commercial heat pump. From a theoretical analysis the *COP* of the two heat pumps specifically designed should increase but laboratory tests showed that the *COP* increased only for the heat pump designed for variable speed operations if compared with the conventional heat pump. If the seasonal performance factor is considered the standard heat pump gave values higher or equal to the other heat pumps. This is mainly due to lower *COP*s at nominal speed, to the large energy inputs to pumps due to long operating times and to efficiencies and control of variable speed compressors.

Several models of heat pump systems have been developed in literature. Kinab et al. [6] developed and successfully compared with experimental data a system model of an air-to-water reversible heat pump including detailed sub-models of various components. Modeling the compressor, on/off controlled, multiple stage compression and variable speed compressor were taken into account. A model and a year round analysis of a GSHP fitted with a variable speed compressor was presented in Lee [7] and three different locations with different loading profiles and weather data were considered. Three control schemes for the part-load control were applied and compared. With a frequency control a reduction of compressor energy input and an overall energy saving was achieved. A mathematical model for quasi-steady state performance of a water-to-water reversible GSHP working with propane with on/off control system has been presented in Corberan et al. [8]. The model has been validated with experimental data and different control strategies have been tested. Recently Madani et al. [9] developed a model for capacity control in ground source heat pump systems. The model is composed of several sub-models: the variable speed compressor sub-model, the condenser and evaporators sub-models, the building and ground heat source sub-models. The model was developed in order to compare the seasonal performance of different control strategies at different systems layouts finding a balance between complexity and simplifications. For example, the variable speed compressor sub-model is modeled in detail by taking into account electromechanical losses, built-in volume ratio, internal mass leakage coefficient and inverter losses. They also performed a comparison of the model with experimental results from two variable speed GSHP systems, both located in Stockholm. This model was used in Madani et al. [10] to carry out simulations in order to make a comparison of the annual performance and *COP* of on/off controlled and variable capacity systems. They considered five ground source heat pumps, four on/off controlled GSHPs designed to cover different percentages of heat peak demand of the building, and one variable capacity system with variable speed compressor and single speed pumps. At different values of ambient temperature the five heat pumps showed different performance. Considering the seasonal coefficient of performance, this study indicates that if the on/off controlled systems are designed to cover more than 65% of the building peak demand, there is no considerable difference with the variable capacity system. If the on/off controlled heat pump is oversized, covering more than 94% of the building peak heat demand, the annual energy consumption is the lowest but economic constraints prevent the system to be the best option; if the on/off controlled heat pump is dimensioned to cover only the 55% of the peak demand, it gives the highest annual energy consumption due to the large use of electrical auxiliary heaters. The authors pointed out that in the variable speed heat pumps the energy consumptions of the water pumps were 5–30% higher than the on/off controlled heat pumps, due to longer working time of pumps over a year. A steady state model for variable speed heat pump for a wide range of cooling conditions and loads was developed by Zakula et al. [11]. This model was composed by three components (evaporator, compressor and condenser) sub-models within a main solver loop. An idealized expansion valve has

Nomenclature

A	area [m^2]
BHEs	borehole heat exchangers
COP	coefficient of performance [/]
c_p	specific heat [$J\,kg^{-1}\,K^{-1}$]
E	thermal energy [W h]
EER	energy efficiency ratio [/]
f	frequency [Hz]
K	global heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
$k_{p,1}$	proportional constant of the primary regulation [$Hz\,K^{-1}$]
$k_{p,2}$	proportional constant of the secondary regulation of the building water mass flow rate [$L\,h^{-1}\,K^{-1}$]
$k_{p,3}$	proportional constant of the secondary regulation of the BHEs water mass flow rate [$L\,h^{-1}\,K^{-1}$]
$k_{p,4}$	proportional constant of the secondary regulation [K^{-1}]
LUT	look-up table
LR	load ratio (in figure)
m	water flow rate [$kg\,s^{-1}$]
P	power [W]
q	heat flow rate [W]
s	time [s]
$SCOP$	seasonal coefficient of performance (heating) [/]
$SEER$	seasonal energy efficiency ratio (cooling) [/]
SWT	supply water temperature
T	temperature [°C]
VFC	velocity of fan coils [%]

Greek

$\alpha = q_{\mathrm{HP}}/q_{N,\mathrm{HP}}$	load ratio [/]
β	power consumption load ratio [/]
$\tau_{i,1}$	integral time of the primary regulation [$K\,s^{-1}\,Hz^{-1}$]
$\tau_{i,2}$	integral time of the secondary regulation for the building water flow rate [$K\,h\,s^{-1}\,L^{-1}$]
$\tau_{i,3}$	integral time of the secondary regulation for the BHEs water flow rate [$K\,h\,s^{-1}\,L^{-1}$]
$\tau_{i,4}$	integral time of the secondary regulation for the fan coils speed [$s^{-1}\,K$]
ΔT	temperature difference [K]

Subscript

1	primary regulation
2	secondary regulation for internal water flow rate
3	secondary regulation for external water flow rate
4	secondary regulation for fan coils speed
BLD	building
c	condenser
COMP	compressor
ECP	external circuit pump
e	evaporator
ex	exchange
FC	fan coils
geo	geothermal
HP	heat pump
ICP	internal circuit pump
in	inlet
MAX	maximum
ML	mean logarithmic
N	nominal
out	outlet
SET	setpoint
TANK	water tank
w	water