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Capacity control in air–water heat pumps: Total cost of ownership analysis

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ABSTRACT

Adjusting capacity to changing demand by variable speed control is known to offer efficiency improvement over classical on/off control. With a total cost of ownership analysis the economic viability of both control schemes is assessed for residential air–water heat pumps operating in different climate zones. Component sizes are optimized for both control methods individually. Results show optimal compressor displacement volumes to be smaller for variable speed than for on/off control. The optimal ratio of evaporator to condenser size is smaller for the variable speed system. Variable speed control is shown to be uneconomic for space heating in warmer climate while for average climate cost-effectiveness depends on the economic framework. For colder climate variable speed control is the more profitable choice in all considered cases; savings of up to 5000 EUR compared to on/off control can be achieved within 15 years of operation.

1. Introduction

Changes in the control scheme can reduce emissions associated with air source heat pumps operating over a wide range of conditions by more than a third [1]. A control method which improves efficiency especially in part load conditions can reduce the annual energy consumption of air–water heat pumps. When building demand is lower than the capacity delivered by the unit, on/off control is the most common way of balancing capacities. The compressor and sometimes secondary loop fans and pumps are intermittently switched on and off to match building demand. Different on/off control methods are described in detail by Madani et al. [2]. However, Qureshi and Tassou [3] found that adjusting compressor speed to match demand at different operating conditions was a more efficient method.

In practice heat pumps are often designed to cover only a part of the annual building heat demand. At low ambient temperatures the building demand is higher than the heat pump capacity. The gap between capacity demand and delivery is typically closed by an electric backup heater. This need for direct electric heat can be reduced or even eliminated by adjusting the compressor speed. By increasing the speed range towards lower ambient temperatures, higher capacities can be delivered.

Marquand et al. [4] presented an economic comparison between variable speed (VS) and fixed speed on/off (FS) control for air–water heat pumps. They reported payback times of about five years for the increased investment costs of a VS unit. Karlsson and Fahlen [5] listed several researchers who found efficiency improvements of 10–25% comparing variable compressor speed to fixed speed on/off control for air source units. For air–air systems Adhikari et al. [6] reported energy savings of about 13% with VS control. However, savings for air–water units were shown to be closer to the savings gained in ground-water systems of about 9%. For buildings with small heating loads Liu and Hong [7] show a VS air source unit to be nearly as efficient as a FS ground source heat pump while for larger loads the FS ground source heat pump is still more efficient. In an experimental study of a ground-water system by Karlsson and Fahlen [5] it was found both COP and seasonal performance for the variable speed unit to be lower than for the fixed speed unit. Also for a ground source system Madani et al. [8] demonstrated that seasonal performance improvement by VS control strongly depends on the nominal capacity of the baseline fixed speed unit. The performance of the FS unit with electrical backup heat covering less than 5% of the annual demand was the same as the performance of the VS unit.

Jakobsen et al. [9] emphasized the importance of adjusting not only the compressor speed but also the flow rates of secondary

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A	area [m^2]
a	year [yr]
$\dot{C}$	heat capacity rate [J s^{-1} K^{-1}]
COP	coefficient of performance [1]
COP$_c$	coefficient of performance corrected for on/off control [1]
c_c	cycling degradation coefficient [1]
c_{el}	electricity price [EUR kWh^{-1}]
FS	fixed speed on/off capacity control
H	heating hours per year [hr yr^{-1}]
h	specific enthalpy [J kg^{-1}]
I	investment costs [EUR]
i	interest rate [%]
L	normalized length [1]
$\dot{M}$	mass flow rate [kg s^{-1}]
O	operating costs [EUR]
P	power [W]
p	pressure [bar]
$\dot{Q}$	heat transfer rate [W]
s	specific entropy [J kg^{-1} K^{-1}]
T	temperature [K], [°C]
$T_{a,b}$	fixed speed balance point temperature [°C]
$T_{a,l}$	lower variable speed limit temperature [°C]
$T_{a,u}$	upper variable speed limit temperature [°C]
TCO	total cost of ownership [EUR]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
VS	variable speed capacity control
$\dot{V}_{disp}$	compressor discharge volume [m^3 hr^{-1}]
W	work [kWh]

Greek symbols

η	efficiency [1]
ρ	density [kg m^{-3}]

Subscripts

0	baseline
$2p$	two phase
a	air, ambient
bub	at bubble point
c	condenser
d	building demand
dew	at dew point
dis	at compressor discharge
e	evaporator
el	electric
f	fan
g	gas
id	ideal
in	inlet
is	isentropic
j	temperature step [K]
m	mean, middle
out	outlet
p	compressor
r	refrigerant
s	seasonal
suc	at compressor suction
t	total
v	volumetric
w	water

fluids to exploit the full benefit of variable speed control. Granryd [10] discussed the same aspect by showing the strong dependency of efficiency and capacity on secondary flow rates. Madani et al. [11] showed that flow rate optimization of the brine side of ground source heat pumps can increase heat pump capacity at low ambient temperatures.

The goal of this study is to quantify the total cost of ownership (TCO) of VS and FS control in residential air–water heat pumps for different climate zones. Total cost of ownership includes investment costs and operating costs throughout economic lifetime. Air flow rate, compressor displacement volume and heat exchanger sizes are optimized to give minimum TCO of both FS and VS system. Compressor and heat exchangers are the main cost drivers of the heat pump unit and their sizes directly influence investment and operating costs. Individually optimizing their sizes hence helps to prevent biasing the comparison with a random component selection.

2. Methodology

Simulating a heat pump system for a large amount of parameter variations, as typically required both for comparative seasonal performance calculations and for optimization studies, is time consuming and therefore costly. At the same time price information is very volatile, varying with time and also with the business partners involved.

Therefore in the current study a method is chosen which reduces the simulation effort by separating simulation, seasonal performance calculation and TCO optimization. Steady state simulations of the heat pump unit are performed for a limited number of operating conditions. Seasonal performance is calculated by defining different operating hour profiles, interpolating simulated performance parameters and correcting for electric backup heat and losses during on/off control. A quadratic model is used to describe annual power consumption as function of component sizes. This allows calculating a new optimum for changing price information without requiring new system simulations.

Frost and defrost effects are neglected in this study. Only space heating is considered, hot water production is not taken into account. In practice both aspects play an important role for the annual performance of air–water heat pumps.

The model of the heat pump unit is developed using the Energy Equation Solver EES [12]. Post-processing of simulation data for seasonal performance calculation, quadratic regression and optimization is done in Matlab [13].

3. Heat pump model

A one-dimensional steady state simulation model of a typical heat pump cycle is used to calculate COP and $\dot{Q}$. It comprises submodels of the compressor, evaporator, condenser and expansion device. Expansion is assumed to be isenthalpic. R290 (propane) is used as refrigerant. The full set of equations is given in Appendix B.

3.1. Compressor

Seven hermetic scroll compressors of the Danfoss HHP-T4 R407C series, which are optimized for heat pump operation, are modeled. The HHP-T4 R407C series is built for fixed speed operation. For variable speed control an upper and lower speed limit is assumed at 200% and 50% of the nominal speed of 50 Hz, respectively.

In the HHP series the displacement volumes of the compressors range from 5.9 to 17.2 m^3/h. For each compressor, individual polynomials are used to describe evaporator capacity