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Theoretical and experimental investigation of startup and shutdown behavior of residential heat pumps

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ABSTRACT

Standardized efficiency and capacity measurements of residential heat pumps deviate from real time performance due to several factors. While standardized measurements are performed at steady state operation, heat pumps in the field are usually capacity controlled using on-off cycling. In order to determine the difference between these operating modes, laboratory and field measurements were conducted to verify transient models of air-source and geothermal heat pumps. Heat pump performance was then simulated for several operating conditions typical for central European installations. It was shown that air-source heat pumps experience performance losses of only 1–2% for short cycling times. In the case of geothermal heat pumps, the recovery of the ground probe during the off time can lead to efficiency gains of up to 5%. Results of this study help to provide improved control strategies for heat pumps using on-off cycling as capacity control. They also support the conclusion that standardized measurements according to EN14511 accurately represent the efficiency of residential heat pumps both in continuous and in part load operation.

Etude théorique et expérimentale sur le comportement des pompes à chaleur résidentielles lors du démarrage et de l'arrêt

Mots clés : Pompe à chaleur ; Aérothermique ; Géothermique ; Modèle dynamique ; Régulation de la puissance ; Stratégie de régulation

1. Introduction

In several countries of central and northern Europe the number of installed residential heat pump units is rising quickly, reaching a market share of up to 80% in new buildings (IEA, 2010). The vast majority of these small and medium scale heat pumps is on/off-controlled. Several long term field tests, among others Erb et al. (2004), have shown significant reductions in heating capacity and efficiency of heat pumps installed in the field compared to standardized testing methods. These differences can arise due to variations in defrosting, different control strategies, and poor installation methods. Several authors (Erb et al., 2004; Hubacher and Ehrbar, 2001; Ehrbar, 2003) attributed part of the performance loss to the fact that heat pumps are tested at continuous operation according to the test standard EN14511 and operated using on-off cycling in the field.

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Nomenclature

Symbols

A	area, m^2
c_p	specific heat, J kg^{-1} K^{-1}
h	enthalpy, J kg^{-1}
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
p	pressure, kPa
$\dot{Q}$	heat rate, W
T	temperature, °C
TXV	thermostatic expansion valve
$\dot{V}$	volumetric flow rate, m^3 s^{-1}
$\dot{W}$	power, W
Q	heat, J

Greek

α	heat transfer coefficient, W m^{-2} K^{-1}
Δt	time step length, s
η	efficiency, -
λ	volumetric efficiency, -
ρ	density, kg m^{-3}
φ	relative humidity, %

Subscripts

a	air
b	brine
c	condenser
comp	compressor
cond	2-phase fraction of condenser
d	down
desup	desuperheating part of condenser
e	evaporator
E	end
el	electrical
gr	ground
H	high
hg	hot gas
i	in
int	internal
isent	isentropic
L	low
m	metal
mech	mechanical
o	out/outlet
R	refrigerant
s	start
sg	suction gas
st	stored
sub	subcooling part of condenser
sur	surrounding
th	theoretical
u	up
w	water
x	placeholder for numerical index (1, 2, 3,...)

Early research on this topic estimated performance reductions for hydronic air-source heat pumps to be in the area of 5–20% (Hubacher and Ehrbar, 2001). Each start-up process leads to a transient process and a reduction of the heat output until the asymptotic heating performance is reached. On the other hand, the electrical power consumption for water pumps, fans, and compressor reach steady state very quickly. Some measurements and a mathematical model were published by Ehrbar et al. (2003). They found that their approach could describe the measured startup and shutdown process of a heat pump, but needed further refinement to be applicable over a wide range of parameters and heat pump systems. Several other dynamic heat pump models are summarized by Bendapudi and Braun (2002) where they are divided into the topics of overall models, component and subsystem models and applications. Murphy and Goldschmidt (1985) developed a simplified model to investigate the start-up and shutdown transients for air-to-air AC systems using capillary tubes as an expansion device. One of the very few cases of a transient simulation model for a heat pump with geothermal heat exchanger is reported by Safemazandarani et al. (1990). While the model is setup for heating and cooling mode, the evaporator is submerged in water and therefore shows different characteristics compared to a geothermal borehole. The geothermal heat pump model by He et al. (2009) is designed for annual simulations with a time step size of 10 min.

Vargas and Parise (1995) modeled a vapor compression cycle of an air conditioning system with reciprocating compressor. Aim of their study was to compare on/off controlled systems to other methods of capacity control. The study uses a simplified model of the AC-System and assumes instantaneous refrigerant migration after shutoff. While the aim of their study is close to the one presented in this paper, it does not extend to systems with water as a heat sink or to geothermal heat pumps. Results of the current study show that the shutoff period does not lead to instantaneous refrigerant migration. They also neglected the interior heat transfer and thermal inertia of the heat exchangers. Wu et al. (2011) present an experimental analysis of an air-to-water heat pump, optimizing the transient performance using a water storage tank with phase change materials (PCMs). Several other papers were presented on models of heat pump components such as Williatzen et al. (1998) who derived a generic transient model for heat exchangers. Xia et al. (1999) present an evaporator model that focuses on the superheat modeling and the control with an electronic expansion device. Finally Li et al. (2011) show a model that is able to capture the short time transients in a R134a automotive air conditioner in order to study the refrigerant mass migration.

Aim of the current study is to further the understanding of the influence of several parameters on the transient behavior of air-source and geothermal heat pumps. On one hand control strategies can be developed to reduce the loss in heating performance and efficiency due to on/off cycling. On the other hand a fair performance comparison between on-off cycling and variable capacity heat pump units can be achieved. In order to establish the desired results a physics based simulation model of an air-source heat pump was developed based on Bertsch and Groll (2008). The model of the air-source heat pump was then adjusted for geothermal heat pumps including a transient geothermal borehole model. The