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A method for the choice of the optimal balance-point temperature of air-to-water heat pumps for heating

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ABSTRACT

A method for the hourly simulation of air-to-water heat pump systems working in heating mode is developed and implemented through MATLAB. The tool allows to consider both heat pumps with inverter and on–off ones, and takes into account the heat losses from the storage tank. The tool is applied to analyze the seasonal COP of a heat pump system located in Bologna (North-Center Italy), as a function of the bivalent temperature and of the storage volume. The results show that, in the case considered, the optimal value of the bivalent temperature is independent of the storage volume and is lower for heat pumps with inverter. With the optimal bivalent temperature, the highest seasonal COP is obtained without thermal storage.

1. Introduction

In order to reduce the fossil fuel consumption, heat pumps are becoming a widely employed technology for heating and cooling buildings and for domestic hot water production.

Several researches aimed to analyze and to enhance the performance of heat pump systems are available in the literature. Brignoli, Cecchinato, and Zilio (2013) performed an experimental investigation on air-to-water heat pumps, and compared a multiport aluminum flat-tube heat exchanger to a round-tube finned one. Hewitt and Huang (2008) examined, through experiments, the defrost cycle for a residential heat pump with circular shaped evaporator.

A simulation study on an air-to-water heat pump system for building heating was performed by Huchtemann and Müller (2013) in order to analyze the influence of the water supply temperature on the seasonal coefficient of performance (COP) of the system.

A comparison between the energy performance of a ground coupled water-to-water heat pump system and an air-to-water heat pump system for heating and cooling was presented by Urchueguía et al. (2008), with reference to typical conditions of the European Mediterranean coast.

Transcritical CO_2 heat pumps were considered by some authors: Sarkar, Bhattacharyya, and Ram Gopal (2004) presented energy and exergy analyses and optimization studies of a transcritical carbon dioxide heat pump system in order to develop expressions for optimum cycle parameters; Richter et al. (2003) compared, through experiments, a commercially available R410A heat pump and a prototype carbon dioxide system in heating mode. Heat pump systems based on the thermoelectric effect for heating energy-efficient buildings were recently investigated by Kim et al. (2014).

Liu et al. (2013) studied a new kind of heat pump system, which utilizes gray water as heat source and sink for heating and cooling of residential buildings.

An economic COP optimization of air/ground source heat pumps was carried out by Tahersima et al. (2012). In this study the effects of a priori knowledge on weather forecast and electricity price profile are investigated to reduce the total electricity cost subject to constraints on resident's thermal comfort.

Apart from water, also phase change materials (PCM) can be used for thermal storages coupled to heat pumps: for instance, Long and Zhu (2008) performed a numerical study on a heat pump water heater with a PCM-based thermal storage, and validated the numerical results through experimental studies about heat stored and released by PCM. Nkwetta and Haghighat (2014) presented a review of the state of the art on thermal energy storage with phase change materials.

Flach-Malaspina, Lebreton, and Clodic (2004), through experimental tests, demonstrated that air-to-water heat pump systems with controlled capacity are able to reach higher energy efficiency than the ones with a single compressor and an on–off system. Shao

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Nomenclature

a	slope of U function [W m^{-3} K^{-1}]
b	intercept of U function [W/K]
b_U	temperature reduction factor of the storage room
C_c	degradation coefficient
COP	coefficient of performance
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
CR	capacity ratio
E	energy [J]
f	compressor frequency [Hz]
f_{COP}	COP correction factor
FUE	fuel utilization efficiency
H	building heat loss coefficient [W/K]
i	ith hour
P	power [W]
SCOP	seasonal COP
T	temperature [K]
TOL	temperature operative limit [K]
T'_S	storage temperature with the maximum heat pump power
U	storage tank heat loss coefficient [W/K]
V	volume [m^3]

Greeks

η_{EL}	thermodynamic efficiency of the electricity system of the country
ρ	density [kg/m^3]
τ	hour duration [s]
ϕ	fraction of the back-up energy

Subscripts

B	building
BIV	bivalent
BU	back-up
DC	declared capacity
EXT	external air
HP	heat pump
INT	internal air
$LOST$	lost
MAX	maximum
MIN	minimum
$ROOM$	room
S	storage
TOT	total
$USED$	used
w	water
$Z\text{-}L$	zero-load

et al. (2004a) modeled a variable speed compressor for the simulation of an air conditioner and heat pump system with inverter, by utilizing a map-based method to fit the performance curves of the inverter compressor. Zhifang and Lin (2010) developed an analytical model to describe the variable speed compressor characteristics and validated the model experimentally in a water-source heat pump; they provided a control strategy for adjusting the compressor capacity to match the heat pump operating conditions. Park, Kim, and Min (2001) analyzed a multi-type inverter air conditioner with a linear electronic valve as expansion device and a variable speed compressor, and calculated the optimum opening of the expansion valve in order to maximize the COP of the system. Shao et al. (2004b) studied the performance of a heat pump system for air conditioning and domestic hot water production, provided with an inverter compressor and a hot water storage tank.

A topic not yet sufficiently investigated in the literature is the optimal choice of the balance-point temperature and of the volume of the thermal storage tank for heating plants with electric air-to-water heat pumps. The balance-point temperature, or, bivalent temperature, T_{BIV}, is the temperature of the external air at which the heating power required by the building is equal to the thermal power delivered by the heat pump. The value of the storage volume recommended by several manufacturers is, in liters, 60 times the heat pump nominal thermal power, in kilowatts. The European standard EN 14825 indicates a bivalent temperature of −7 °C or lower for the reference heating season C (colder climate), 2 °C or lower for the reference heating season A (average climate) and 7 °C or lower for the reference heating season W (warmer climate). Very recently, Klein, Huchtemann, and Müller (2014) performed yearly simulations of a hybrid heating system composed of an air-to-water heat pump and a gas boiler, through the commercial software Dymola. They analyzed the influence of the heat pump capacity and of the storage-tank volume on the system performance; they found that medium-sized heat pumps attain the highest efficiency, and that the volume of the storage tank has a limited effect. Studies on the optimal choice of the heat pump capacity and of the storage volume, with reference to several climates and heat pump types, are still insufficient.

The aim of this paper is to present a new method for the hourly simulation of air-to-water heat pumps for heating, which can be executed through any programming language and is here implemented in MATLAB. The method can be used to determine the optimal values of the balance-point temperature and of the thermal storage volume of air-to-water heat pumps for heating, and applies both to the case of a system with an inverter compressor and to the case of an on–off system. As an example of application of the method, the MATLAB code is used to determine the optimal values of the balance-point temperature and of the volume of the storage tank for an air-to-water heat-pump heating system located in Bologna (North-Center Italy), operating both with inverter and in on–off conditions. Different values of the balance-point temperature, for the same heat pump, are obtained by considering different values of the building heat loss coefficient.

2. Numerical method

The heating plant considered is composed of an electric air-to-water heat pump provided with a water storage tank and integrated with electrical resistances as back-up system. The hourly thermal losses of the building are evaluated by means of the energy signature, which is determined by the heat loss coefficient, H, and by the external air temperature above which the building thermal losses are vanishing (zero-load external air temperature, $T_{Z\text{-}L}$).

A MATLAB code for the hourly simulation of air-to-water electric heat-pump systems for building heating has been implemented. The input parameters for the MATLAB code are: the vector of the hourly values of the external air temperature for the heating season, $\boldsymbol{T_{EXT}}$; the selected internal air temperature, T_{INT}; the total heat loss coefficient of the building, H; the zero-load external air temperature, $T_{Z\text{-}L}$; the value of the thermal storage volume, V_S; the imposed maximum and minimum value of the water temperature in the thermal storage, $T_{MAX,S}$ and $T_{MIN,S}$; the temperature reduction factor of the storage room according to the European standard EN 12831, b_U; the data on the heat loss coefficient of the storage, U, and those on the heat pump power and COP, given by the manufacturer.

The heat loss coefficient of the thermal storage is expressed as a linear function of the storage volume:

$$U = aV_S + b. \tag{1}$$