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Research Paper

Dynamic simulation during summer of a reversible multi-function heat pump with condensation-heat recovery

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HIGHLIGHTS

- A simulation code for air-to-water heat pumps with heat recovery is obtained.
- While cooling, the heat pump can supply the condensation heat to Domestic Hot Water.
- Traditional heat-pump cooling and gas-boiler DHW is considered for comparison.
- Heat recovery yields 25% seasonal saving in total primary energy.
- Heat recovery yields 30% seasonal saving in non-renewable primary energy.

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ABSTRACT

A numerical code for the hourly simulation of reversible electric air-to-water heat pumps has been implemented. It applies to reversible multi-function heat pumps, which, during summer, are used for both space cooling and domestic hot water (DHW) production, with recovery of the condensation heat to produce DHW while cooling. The method can be used both for on-off heat pumps and for inverter-driven ones, coupled with storage tanks for air-conditioning and for DHW production, and integrated by a gas boiler for DHW. The numerical code has been used to evaluate the summer performance of the multi-function inverter-driven heat pump employed in the retrofit of a residential building in Bologna (North-Center Italy). The results show a 30% seasonal saving in non-renewable primary energy with respect to a traditional solution, where the heat pump provides only air-cooling and the gas boiler provides DHW. A validation of the code by comparison with TRNSYS, in the case of cooling-only operation, is provided.

1. Introduction

Improvement of energy efficiency and reduction in use of fossil fuels are relevant objectives of the European Union. The Directive 2009/28/EC [1] states that the share of renewable energy in the European gross final energy consumption must reach 20% within 2020. The European Directive 2010/31/EU [2] recognizes that buildings are responsible for 40% of the global energy consumption in the Union and states that all new buildings must be nearly zero energy buildings within 2020.

Therefore, the use of heat pumps for air-conditioning and domestic hot water (DHW) production in new constructions and in building retrofits is becoming practically mandatory, since heat pumps employ important fractions of renewable energy, in the form of either aero-thermal, or geothermal, or hydrothermal energy [1]. Several recent studies have been dedicated to heat pumps. Liu et al. [3–5], for instance, analyzed an innovative type of heat pump, which can provide heating, cooling and DHW to residential buildings, and employs both air and gray water as heat source and sink. Richter et al. [6] performed experiments in heating mode to compare a commercial heat pump with R410A refrigerant fluid and a prototype carbon dioxide heat pump. Al-Zahrani et al. [7] simulated with the software TRNSYS the case-study of a water-to-water heat pump, for which the condensation heat is released to a water storage tank to produce DHW, and studied the influence of the storage tank volume on the heat pump performance, when used during night-time, day-time or for the whole day.

In particular, air-to-water heat pumps are widely diffused, because they are relatively cheap and easy to install, and because outdoor air is everywhere. Dongellini et al. [8] presented a numerical model to evaluate the seasonal performance of air-to-water

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Nomenclature

COP	coefficient of performance [-]
c_p	specific heat capacity at constant pressure [J/(kg K)]
E	energy [kWh]
EER	energy efficiency ratio [-]
P	power [kW]
T	temperature [°C]
t	time [h]
U	heat loss coefficient [W/K]
V	volume [m^3]

Greek symbols

η	efficiency, or conversion factor [-]
ρ	density [kg/m^3]

Subscripts

avail	available
b	boiler
bk	back-up
buil	building
c	cold-water tank
cd	cooling + DHW
cool	cooling
d	DHW tank
deliv	delivered
dhw	domestic hot water
eff	effective
ext	external
gain	gained
h	hour
hp	heat pump
lost	lost
max	maximum
min	minimum
prim	primary
res	residual
room	room
s	storage
tot	total
us	used

heat pumps for heating by means of the bin-method, derived from the European standard EN 14825 [9] and the Italian standard UNI/TS 11300-4 [10], while Naldi et al. [11] developed a method for the hourly simulation of electric air-to-water heat pumps for heating.

Traditional reversible electric air-to-water heat pumps, used for air-cooling during summer, reject the condensation heat to the outdoor air. This wasted energy could be recovered to produce domestic hot water at the same time. Gong et al. [12] demonstrated the feasibility and convenience of such a system, testing a heat pump prototype where a water condenser, added to the classic air condenser, is used to recover the condensation heat when the building requires cooling and DHW simultaneously. Byrne et al. [13] performed simulations of a multi-function heat pump for simultaneous heating and cooling, which, during summer, can supply the condensation heat to produce DHW. The authors programmed each component of the heat pump system in FORTRAN and adapted the models to TRNSYS. Simulation results showed a relevant energy saving with respect to a standard reversible heat pump.

Shao et al. [14] simulated a different scheme, where a preheater and a reheater for DHW are placed at the outlet of the compressor and at the inlet of the thermal expansion valve of the heat pump, to recover heat from the superheated gas exhausted from the compressor and from the subcooled liquid leaving the condenser.

Ghoubali et al. [15]. developed a simulation model for an air-to-water heat pump, able to recover the condensation heat to produce DHW, by means of semi-empirical models of the heat pump components.

This paper presents a numerical method for the hourly simulation of reversible electric air-to-water heat pumps, used during summer for air-cooling and DHW production, and able to deliver the condensation heat to DHW. The model is based on heat pump power, *COP* and *EER* data given by the manufacturer, and can be easily employed to evaluate the mean seasonal performance. It applies both to mono-compressor on-off heat pumps and to inverter-driven ones, coupled to storage tanks with cold water (for air-conditioning) and hot water (for DHW production).

The proposed model has been employed to evaluate the summer performance of the multi-function inverter-driven heat pump used in the retrofit of a residential building in Bologna (North-Center Italy). The seasonal results, in terms of primary energy used (renewable and non-renewable), are presented and compared with those of a traditional air-conditioning and DHW production system.

The numerical code has been validated for a simple case-study by means of a TRNSYS hourly simulation.

2. Simulation code

The studied system is composed of a multi-function reversible air-to-water heat pump, used in summer both as a chiller and for DHW production, coupled with a cold-water tank for air-conditioning and a hot-water tank for DHW production. When the building requires cooling and DHW simultaneously, the heat pump condensation heat is released to the hot-water tank (condensation-heat recovery, i.e. cooling + DHW mode), otherwise it is rejected outside (cooling-only mode). If the building requires only thermal energy for DHW, the heat pump extracts heat from the outdoor air and releases it to the hot-water tank (DHW-only mode). The heat pump is integrated with a gas boiler as back-up system for DHW. Fig. 1 shows the plant scheme of the heat pump in cooling + DHW mode.

A numerical code for the dynamic simulation of the heat pump system has been implemented in MATLAB. The code applies in general to inverter-driven heat pumps; mono-compressor on-off heat pumps can be considered as a special case. The main inputs of the code are: the hourly values of the outdoor air temperature for the considered period and location; the hourly values of the energy required by the building for cooling and dehumidifying and for DHW production; the volumes of the storage tanks and their heat loss coefficients; the maximum and minimum temperatures of the storage tanks; the heat pump power data (given by the manufacturer), the *COP* (Coefficient Of Performance) and *EER* (Energy Efficiency Ratio) data (given by the manufacturer); the efficiency of the back-up boiler.

For each hour of the studied period, the code reads the building energy needs and determines the heat pump performance, in order to evaluate the mean seasonal efficiency of the system. In particular, for each hour the code determines the heat pump operation mode (cooling-only, DHW-only, or cooling + DHW) and evaluates the corresponding heat pump power and *COP*, or *EER*, the thermal energy entering the cold-water tank from the storage room and the