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Improvements in the characterization of the efficiency degradation of water-to-water heat pumps under cyclic conditions

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HIGHLIGHTS

- Experimental characterization of a water-to-water heat pump at part load.
- High influence of inertia conditions on start-up losses of water-to-water heat pump.
- Assessment of the validity of parameterizations on efficiency loss at part load.
- New method for improved characterization of water-to-water heat pumps performance.
- Advice for improving the measurement of fixed-capacity heat pumps performance.

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ABSTRACT

This paper presents a study on the characterization of the performance of a water-to-water heat pump of 40.5 kW fixed heating capacity under different cycling conditions scenarios. Semi-virtual laboratory experiments were conducted to analyse the influence of inertia from 1.23 to 24.7 L/kW on the efficiency of the heat pump operating at partial load. Different parameterizations in standards were compared to assess their ability to predict the energy efficiency degradation caused by cycling. Performance deterioration at part load was found to be highly dependent on inertia conditions, with non-negligible start-up parasitic effects detected for the heat pump under study, particularly for decreasing inertia. Results suggest that current standards for characterising the performance of systems at partial load, such as the European EN14825, should be reviewed to account for the influence of inertia on equipment performance and for the potential occurrence of start-up efficiency losses for water-to-water heat pumps. An expression is derived in this study for the start-up losses degradation coefficient C_d and a single parameterization accounting for different sources of efficiency losses is proposed, together with a simple method to determine degradation coefficients from reduced experimentation.

1. Introduction

Global warming concerns are at the forefront of the global energy sector, with the need for cleaner energy sources, recent decades have led to the development of efficient heating and cooling technologies – with an increasing emphasis on the growing renewable energy market. Within this context, water-to-water heat pumps, which are systems that make use of residual heat or natural heat from the ground, are considered a technology that can provide clean energy at a low cost [1,2], thus providing significant energy savings [3].

Although water-to-water heat pumps are efficient energetically, the operation of fixed-capacity water-to-water heat pumps at partial load is subject to undesirable efficiency deterioration effects. While variable capacity equipment adapt to load levels, fixed-speed compressor heat pumps exhibit a cyclic behaviour as they switch from on to off to be able to provide the required set point temperatures. This results in inefficiencies because of the parasitic energy losses associated with cycling [4,5]. The degradation of the performance of HVAC (Heating, Cooling and Air conditioning) systems at partial load is a topic of great interest as it determines the efficiency rating of equipment and ultimately affects buildings energy performance. Significant ongoing research is being performed on characterising the performance of water-to-water ground source heat pumps in different laboratory and testing sites [6,7]. Man et al. [6] investigated the performance of a ground source heat pump in a temperate zone through on site test rig experiments. They found significant influence of the operation mode (cooling or heating) and the intermittent or continuous oper-

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Nomenclature

E	energy (kW h)
Q	heat rate (kW)
Pelec	electrical power consumption (kW)
t	time (s)
V	water storage volume (m^3)
ρ	water density (kg/m^3)
c_p	water specific heat (kJ/(kg K))
ΔT	dead band (K)
C_d	start-up degradation coefficient
C_c	stand-by degradation coefficient
PLF	partial load factor
PLR	partial load ratio
COP	coefficient of performance
a	coefficient
b	coefficient
Z	parameter
τ	exponential time constant (s)
t_{50}	sigmoid time constant (s)
s	sigmoid slope coefficient

Subscripts

cycle	cycling conditions
on	on period
off	off period
sb	stand-by
st	steady state conditions
start-up	start-up period conditions

ation on the coefficient of performance. Montagud et al. [7] analysed the efficiency of a ground source heat pump system, providing heating/cooling to an office building, and developed a model for the fixed-capacity heat pump investigated. While their heat pump model was able to predict the energy consumption with a low error, the largest deviation between model and experiment was found during the dynamic start-up process. Additional recent studies focus on improving the performance of water-to-water heat pumps through control strategies and flow operating conditions [8].

A considerable amount of research has been done to characterise the performance of fixed capacity units at part load, from early work by Parken et al. [9]. Most studies on this topic have primarily been developed for air-to-air and air-to-water systems [10–14]. These early studies detected degradation of the energy efficiency at the start-up of the equipment and as a result of auxiliary systems operation during stand-by phases. Later work by Schibuola et al. [15], Bettanini et al. [16] and Riviere et al. [17] evaluate the influence of partial load on the efficiency of air-to-water systems. In these studies it is shown that degradation of performance for different equipment increases with decreasing load ratios, due to more frequent cycling and longer stand-by periods for low loads. Recent work by Dongellini et al. [18] estimates the efficiency of an air-to-water fixed-capacity heat pump under different load conditions, including consideration of the stand-by degradation losses in comparison with inverter driven and multistage-compressor heat pumps. In their study they showed that the modulation characteristics of the different heat pumps strongly affect the optimal performance.

A frequent approach to characterize the loss of energy performance of a fixed-capacity heat pump at part load conditions is determining the so-called partial load factor (PLF), which is used to correct the coefficient of performance (COP) at full load operation to derive the efficiency at part load [16,4]. The partial load factor (PLF) is the ratio between the COP at cycling and the corresponding steady state COP at equivalent operating conditions, while the partial load ratio (PLR) is the ratio between the load and the capacity of the heat pump [4]. Commonly, a partial load factor equation correction is applied for air conditioning systems, based on the degradation coefficient C_d. This correction is found originally in the North American ARI 210/240 standard [19] and adopted in the ASHRAE 116-1995 standard [20] for rating heat pumps at part load. This parameterization is also considered in the European standard EN14825 for rating air-to-air and water-to-air systems at part load operation [21]. The degradation factor, C_d, is often taken to have a default value of 0.25. According to Henderson and Rengarajan [22] the default value corresponds to a 76 s start-up time and a maximum thermostat cycling rate of 3.125 cycles per hour. However, Bettanini et al. [16] have shown that the ARI standard correction does not always correctly represent the partial load behaviour of space conditioning systems. This is shown for diverse air conditioning and heat pump equipment, for which a non-linear relationship between PLF and PLR is more suitable for modelling the partial load behaviour [16]. As a result, an alternative formulation to the original ARI 210/240 standard has been presented in the Italian standard UNI 10963 [16,23] to model the partial load behaviour of space conditioning equipment. In contrast to the large number of studies focusing on the part load behaviour of air-sourced heat pumps, very few studies focus on studying the partial load efficiency degradation of water-to-water systems. Within this context, Corberán et al. [4] conducted an experimental study on the cycling behaviour and partial load efficiency losses of a residential water-to-water heat pump of 25 kW nominal capacity. They found that stand-by efficiency losses were the only important degradation issue related to water-to-water systems [4]. In contrast, studies by Uhlmann and Bertsch [24], Curtis et al. [25] and Kim et al. [26] suggest a significant efficiency loss during start-up for water-to-water units. Furthermore, Magraner et al. [27] found that deviation between modelled and experimental seasonal coefficient of performance for a water-to-water heat pump reduced from 15% to 5% after applying the partial load factor correction from technical standards that include start-up losses [21]. Safa et al. [5] compared the performance of a fixed capacity ground coupled heat pump and an air to water modulating heat pump under different climate conditions, concluding that the resulting performance of the equipment was highly affected by the cycling exhibited by the fixed capacity unit. The European standard EN14825 [21] for rating equipment at part load considers that only stand-by parasitic losses are of importance for water-to-water heat pump systems. A low significance of start-up parasitic losses in water-to-water units has been attributed to negligible refrigerant pressure equalization effects and the short length of start-up periods [4,21]. However, because some studies point to the potential occurrence of significant start-up losses for water-to-water heat pumps, the validity of methods in current standards needs to be assessed with further experimental studies characterizing partialization losses.

Because of contrasting results in different studies regarding the partial load behaviour of water-to-water systems, sources of partial load losses for water-to-water heat pumps remain unclear. As discussed in the literature survey above, few studies have addressed analysing the part load behaviour of water-to-water heat pump systems; hence, this topic has not yet been clarified completely in the literature and in technical standards. Further