Improved characterization of water-to-water heat pumps part load performance

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In the present paper it is presented a laboratory experimental work performed to evaluate the efficiency of a water-to-water heat pump of 40.5 kW heating capacity at different water storage and load duty conditions. Results on efficiency degradation are compared with predictions from international standards EN14825, ASHRAE 116-1995 (ARI 210/240) and Italian UNI 10963. Results showed a loss of performance with decreasing load ratio for all water storage volumes tested, with a higher detrimental effect for low inertia conditions. A close analysis of the dynamic behavior of the heat pump revealed significant start-up efficiency losses, proving that this effect may be of consideration for water-to-water systems. This behavior is neglected in current standards for rating water-to-water heat pumps performance at part load, such as EN14825. An improved experimental method for characterizing the performance of water-to-water heat pumps at part load is presented and compared with experimental results and standards.

Key words: heat pump, energy efficiency, part load degrdation

Standards for partial load performance rating of water-to-water heat pumps

Due to the lack of modulation available, fixed-capacity heat pumps present the issue that they will cycle between on and off states in order to match the required load demand. This behavior entails parasitic losses during the stand-by and start-up phases of operation of the equipment, thus reducing their energy performance. Commonly, international rating standards estimate a coefficient of performance (COP or EER) at part load for fixed-capacity units using a correction parameter, called partial load factor (PLF), that is applied on the performance coefficient at steady state conditions to obtain its value at part load as:

$$COP\ (part\ load) = PLF\ x\ COP(steady\ state) \quad (1)$$

The American standard ASHRAE 116-1995 [1] characterizes the part load operation of fixed-capacity heat pumps by determining a cyclic degradation coefficient Cd, which is derived in a dynamic test, as defined in the ARI standard 210/240 [2]. In the ASHRAE 116-1995 and ARI 210/240 standards the partial load factor is calculated as:

$$PLF = 1 - C_d(1 - PLR) \quad (2)$$

where the degradation coefficient Cd can be determined experimentally or take a default value of 0.25.

The European standard EN14825 [3], analogously, calculates the efficiency at partial load from the correction of the performance at steady state as obtained with the standard EN14511 testing method [4]. For air sourced systems the partial load factor correction in EN14825 is identical to (2). For the case of water-to-water heat pumps with fixed capacity the efficiency correction is based on energy losses associated to parasitical electrical

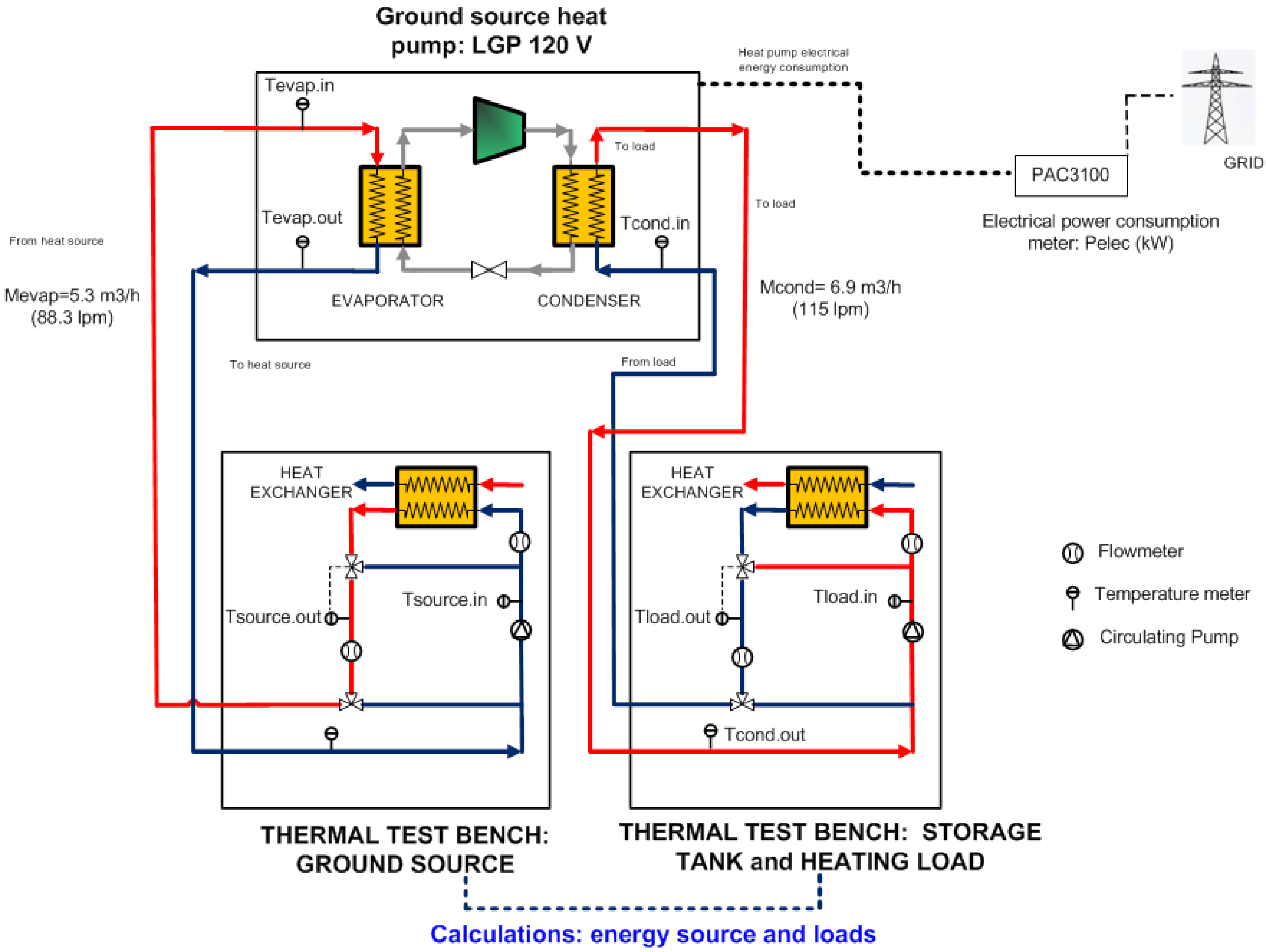

Figure 1. Experimental set-up.

energy consumption at stand-by. The correction for these systems is based on the degradation coefficient Cc and is defined with the following correlation:

$$PLF = \frac{PLR}{C_c PLR + (1 - C_c)} \tag{3}$$

The EN14825 standard allows using the above equation with a default value of Cc=0.9 or with a value determined from the measurement of the electrical power consumption at stand-by.

On the other hand, the Italian standard UNI 10963 [5] proposes an expression for the partial load factor defined as:

$$PLF = \frac{PLR}{Z} = \frac{PLR}{a + b.PLR} \tag{4}$$

The above correlation can be applied with data obtained from a single experiment at part load that allows determining the coefficients *a* and *b* in equation (4). This approach has been tested by Betannini et al. [6] with good results for a number of heat pumps.

The general calculation method in standards ASHRAE 116-1995/ARI 210/240 and EN14825 for deriving heat pump annual performance rating consists on applying the so-called bin method, in which a seasonal coefficient of performance (SCOP or SEER) is calculated for a whole year, under a load profile defined at different climatic conditions.

Laboratory semi-virtual testing of a water-to-water heat pump

Laboratory experiments were conducted to assess the behavior of a 40.5 kW heating capacity water-to-water heat pump in a laboratory setting. The heat pump was tested in a semi-virtual environment that allowed its operation while connected to a virtual storage tank and heating load. The virtual system was created with the software TRNSYS. The temperatures and flows of water circulating to and from the heat pump were emulated in the hydraulic test benches of the laboratory in order to operate the heat pump dynamically as in real conditions (**Figure 1**).

The results of partial load factor obtained from experiments at different water storage volumes and partial load ratios (PLR) are shown in **Figure 2A**. The results show degradation in the energy efficiency for decreasing partial load ratio, with a more important effect for low storage size conditions. The stand-by losses for the heat pump under study were found to be negligible for PLR>0.2, the reason being that the stand-by power consumption for this heat pump is 15 W, only a 0.2% of its nominal electrical power. The main source of efficiency degradation is identified after a close analysis of the transient test data (**Figure 2B**). A significant performance loss is found during start-up, resulting from the thermal capacity reaching its maximum value only after 42–60 s from the onset of start-up, while the electrical power consumption reaches its full value in less than 20 s. This behavior, which was consistently observed at any inertia and load duty conditions, provides evidence that significant start-up losses may occur for this water-to-water heat pump. This efficiency loss, however, is neglected in the European standard EN14825 for fixed-capacity water-to-water systems.

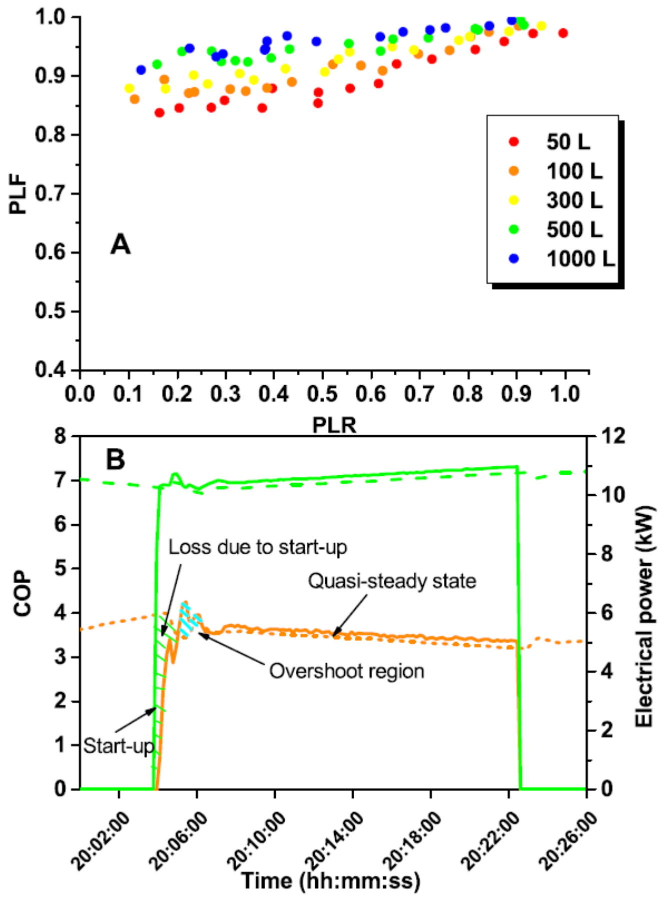

Figure 2. A) Influence of water storage volume on partial load factor B) heat pump start-up (orange: COP, green: electrical power consumption).

Comparison of correlations for partial load factor estimations

Different correlations in the cited standards to estimate the partial load factor were compared with results for the 50 L storage experiment, as shown in **Figure 3**. The predictions from UNI10963 and EN14825 correlations for water-to-water heat pumps substantially deviate from the experiments, while the estimations by the ARI standard (equation (2) is close to the experimental data with Cd=0.22. However, extrapolation of the data to PLR=0 obtained from polynomial fitting analysis (equation fitted to experiments in **Figure 3**) shows that the ARI standard does not account for the drop in the performance for PLR<0.2, produced by stand-by parasitic effects.

New reduced experimentation method for partial load performance estimation

An alternative equation for calculation of the partial load factor is proposed here that is able to account for both stand-by and start-up losses. This equation, which is derived theoretically using the definition of partial load factor by Corberán et al. (2013) [7] is defined as:

$$PLF = \frac{1}{1 + \frac{C_d(1-PLR)}{1-C_d(1-PLR)} + (1-C_c)\frac{1-PLR}{PLR}} \qquad (5)$$

This correlation reduces to equation (2) when stand-by losses are negligible and to expression (3) when start-up losses are negligible. The use of this equation (**Figure 3**) provides a better estimation of the partial load factor when compared with the line fitted to experiments with respect to the other approaches.

Equation (5) can be used to derive the COP value at part load conditions, once the coefficients Cc and Cd are known. A reduced experimentation method is

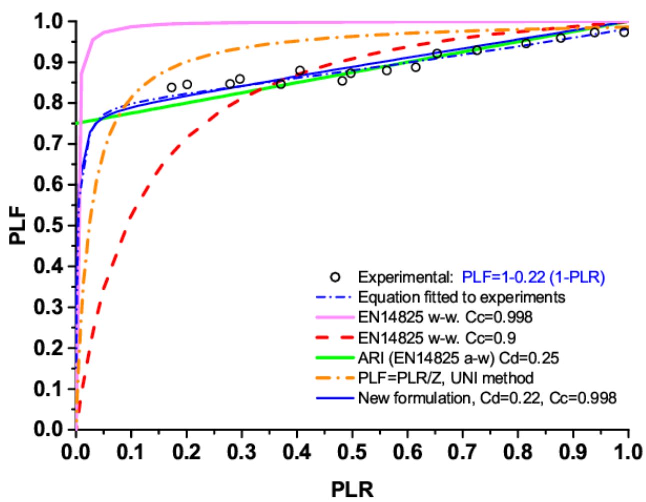

Figure 3. Comparison of experimental data and predictions from parameterizations for 50 L storage inertia conditions.

proposed here to derive these coefficients. The value of Cc can readily be obtained from stand-by measurements as described in EN14825. Then, the value of Cd can be derived from a single experiment at intermediate partial load (eg. PLR≈0.4) by solving equation (5) for Cd, with all the other parameters known.

Figure 4 shows values of partial load factor obtained with this proposed new reduced experimentation method in comparison with the reduced method based on the UNI method and the curve fitted to experiments.

The UNI method achieves good agreement for storage volume of 1 000 L, but it deviates from real degradation as the storage size is reduced. On the other hand, the new method proposed here is able to predict the partial load factor quite closely to the equation fitted to experiments at any inertia conditions.

Improvements in the estimation of yearly COP with standard bin method

In this section the bin calculation method described in the EN14825 standard [3] for estimating the yearly COP is applied to assess the validity of different methodologies determining the heat pump partial load. The bin method is based on the integration of the energy consumed during a year at three different climate conditions with outdoor design temperatures of −22°C (colder), −10°C (average) and 2°C (warmer).

The results of the calculations are presented in **Figure 5**, where the heat pump annual COP (COPnet) is repre-

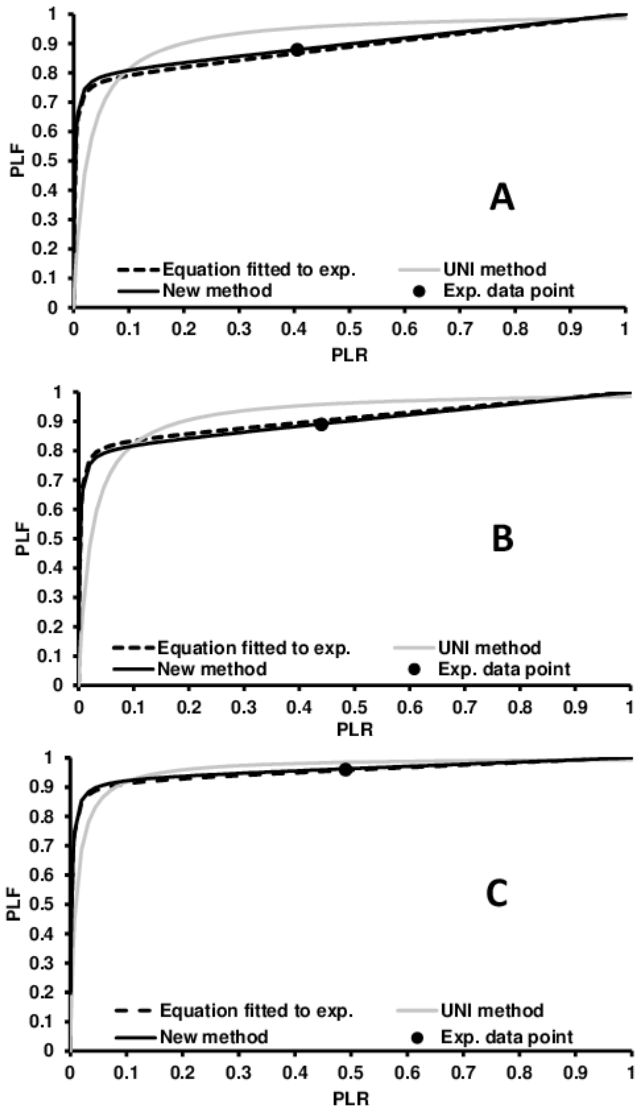

Figure 4. Predictions of partial load factor using the reduced method in UNI standard and the proposed new method for inertia conditions with (A) 50 L, (B) 100 L and (C) 1 000 L.

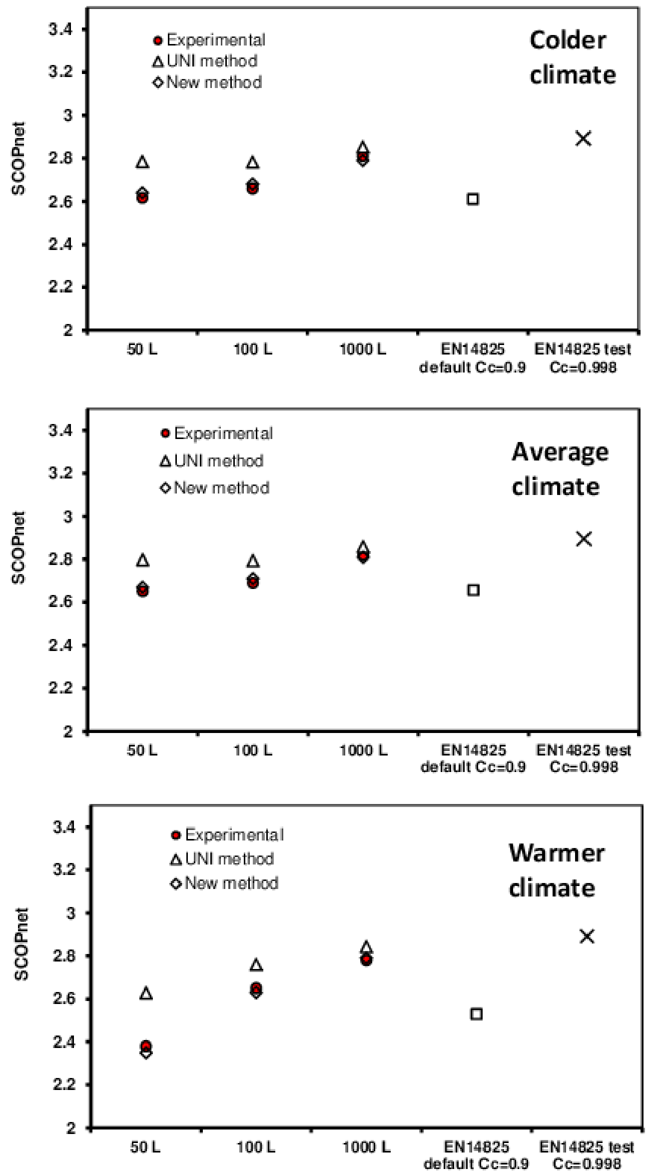

Figure 5. Calculations of SCOPnet with bin method defined in EN14825 standard for different approaches.

sented as obtained from using different methods, namely, 1) the UNI standard reduced experimentation method, 2) the new method proposed in the present study, and 3) the EN14825 standard correlations for water-to-water heat pumps with Cc=0.9 (default value) and Cc=0.998 (as determined from stand-by measurements).

Results in **Figure 5** show that the estimation of the annual COP is sensitive to the storage volume conditions. This implies that the energy performance is dependent not only on the equipment but also on the configuration of a particular system in a building. Hence, similar inertia conditions are required for comparison purposes between equipment. Calculations from using the EN14825 correlations deviate from experiments in as much as 12%, depending on the inertia conditions.

At 1000 L storage conditions the EN14825 standard prediction with Cc=0.998 leads to a small deviation of 3.5%, confirming that this method is reliable for inertia conditions high enough to yield start-up effects negligible. Similarly, the UNI method deviates from real performance as the inertia is reduced, with acceptable predictions for the 1 000 L.

Conclusions

An experimental analysis of the performance at part load of a water-to-water heat pump has shown that these systems may exhibit significant start-up losses and not only stand-by losses as considered in the European standard EN14825. On the other hand, significant sensitivity of equipment performance was found to the water storage configuration. An assessment of existing methods in standards indicated deviations from real part load performance for decreasing inertia conditions. In order to improve this aspect a new reduced experimentation and correlation method is proposed that is able to characterize the real yearly performance of water-to-water heat pumps with inclusion of the inertia conditions and their effects on stand-by and start-up efficiency losses. ■

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