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DECARBONISATION THROUGH INNOVATION

Model based performance prediction of variable-speed heat pumps - an option to reduce certification costs?

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Abstract

Heat pumps are essential for decarbonizing the heating sector, particularly air-water heat pumps, which are favored for their low costs and ease of installation. In case of unrefurbished existing buildings, hybrid heat pumps – combining heat pump and gas boilers – offer the possibility to decouple the replacement of the heating system from further renovation measures to the building envelope.
For tailoring the heat pump capacity to the building demand, manufacturers offer different variants with different nominal capacities that are based on similar hardware, but certification costs quickly add up if each different combination of heat pump and boiler needs to be measured.
To this end, we evaluate the possibility of using standard test data for monoenergetic electric heat pumps to derive operation points required by EN14825 for different hybrid heat pump capacities. To achieve this, we present and evaluate a semi-analytical heat pump model. The model predicts the efficiency (COP) and heat flow rates across various ambient conditions and operating points. When developing the model, care was taken to achieve a good match between measurement and prediction using a minimum of parameters. As a result, the model requires a small experimental dataset of 9 laboratory measurements and only 5 input parameters to fit 5 unknown parameters. Using 50 performance measurements of five commercial machines tested in a certified laboratory, the prediction quality is evaluated and benchmarked against an innovative Machine Learning method.
Initial results indicate that the model can predict COP with an average error margin of 6.6% for norm measurements, and SCOP with a maximum error of 9.2%. The predicted values do not alter the efficiency class of the machines according to the Ecodesign regulation (EU 813/2013).

Keywords: heat pump, hybrid, certification, model, machine learning

1. Introduction

Hybrid air–water Heat Pumps (HPs) are a pathway to decarbonize space heating and can reduce low-voltage grid reinforcement needs, especially in existing, unrefurbished buildings when deployed as hybrids with gas boilers [1]. For tailoring the heat pump capacity to the building demand, manufacturers offer different variants with different nominal capacities that are based on similar hardware. For market introduction each variant requires separate certification with at least five measurements [2], which imposes significant costs on the manufacturer. As an alternative, in this study we evaluate the feasibility of a model-based approach: measure the heat pump variants across a subset of norm measurement points, calibrate a model, and predict performance for the remaining norm measurement points.

This requires accurate performance maps (heat pump capacity and COP versus air/water inlet temperatures and part load ratio). Prior work comprises empirical polynomials, semi-analytical (simplified physical), and

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detailed physical models [3,4]. Empirical polynomials are simple but extrapolation can lead to high deviations; for example, the AHRI-20 polynomial needs ⩾20 parameters and is unreliable outside its calibration range [5–7]. Semi-empirical compressor models reduce parameters to 7–18 while maintaining accuracy [5,6,8]. For heat exchangers, ε-NTU methods offer compact parameterization, whereas moving-boundary approaches increase fidelity at higher complexity [9–12].

Beyond physics-based models, machine learning has been applied to HP performance maps but often requires extensive training data, especially for variable-speed systems [13]. Recently, Hollmann et al. [14] published a tabular foundation model that was applied to HP performance maps by Vadadkar et al. [15], showing accurate performance mapping from minimal measurements and efficient transfer across HP variants.

This work aims to minimize measurement effort while achieving accuracy sufficient to assign the correct efficiency class. We develop a semi-analytical HP model for space heating and, as a comparison, a data-driven strategy based on a tabular foundation model, and we compare their accuracy, extrapolation behavior, and data requirements across a variety of norm measurement points to assess their suitability for model-based certification of hybrid HP variants.

2. Methodology

2.1. Semi-analytical model

The semi-analytical HP model developed and evaluated in this study is based on the modular framework vclibpy by Vering et al. [16] with refrigerant property calculation carried out with CoolProp [17]. The schematics of the HP refrigerant circuit and the corresponding T-s diagram are shown in Figure 1.

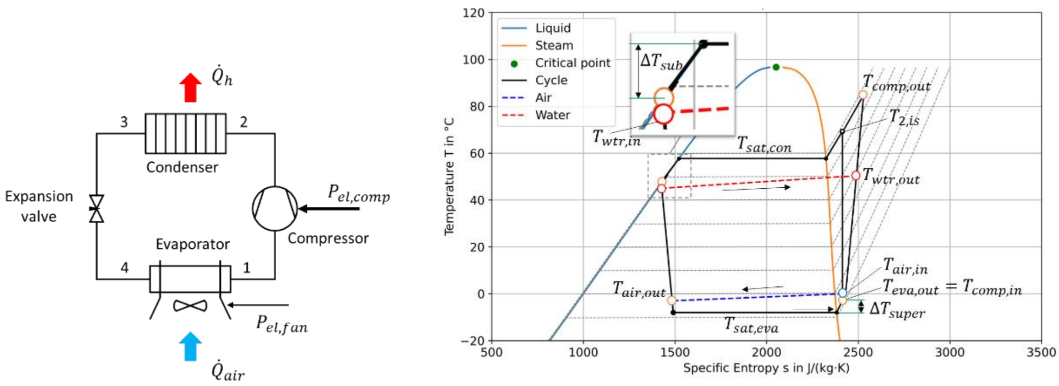

Figure 1: Semi-analytical model. Left: component breakdown of a heat pump. Right: T-S diagram of the refrigerant (Propane) circuit. $T_{wtr,in/out}$: Temperature of water going in/out of the condenser. $T_{air,in/out}$: Temperature of air going in/out of the evaporator. $T_{sat,eva/con}$: Saturation Temperature of the refrigerant in evaporator/condenser.

The efficiency is calculated with equation (1) as the ratio of heat supplied to the heating system $\dot{Q}_h$ and the electrical power consumption P_{el}. The term $P_{el,fan}$ accounts for the electrical power consumption of the fans on air side.

$$COP_h = \frac{\dot{Q}_h}{P_{el}} = \frac{\dot{Q}_{con} - \dot{Q}_{th,loss}}{P_{el,comp} + P_{el,fan}} \tag{1}$$

The heat flow rate at the condenser $\dot{Q}_{con}$ is calculated with equation (2) either with the enthalpy difference and mass flow rate of the refrigerant $\dot{m}_{ref}$ on refrigerant side or with the capacity flow rate of water $\dot{C}_{wtr}$ and the temperature difference on heating circuit side. The term $\dot{Q}_{th,loss}$ accounts for thermal losses.

$$\dot{Q}_{con} = \dot{m}_{ref} \cdot \left(h_{con,in} - h_{con,out}\right) = \dot{C}_{wtr} \cdot \left(T_{wtr,out} - T_{wtr,in}\right) \tag{2}$$

The electrical power consumption of the compressor is calculated with equation (3) out of the enthalpy difference and the mass flow rate of the refrigerant. For simplicity, the mechanical efficiency η_{mech} is assumed to be 1, thus, all electro-mechanical losses are included in the volumetric efficiency.

$$P_{el,comp} = \frac{\dot{m}_{ref} \cdot \left(h_{comp,out} - h_{comp,in}\right)}{\eta_{mech}} \quad (3)$$

The mass flow rate of the refrigerant $\dot{m}_{ref}$ is calculated with equation (4) as the product of volumetric efficiency λ, refrigerant density ρ_{ref}, compressor displacement volume V_{comp} and rotation speed of the compressor n.

$$\dot{m}_{ref} = \lambda \cdot \rho_{ref} \cdot V_{comp} \cdot n \quad (4)$$

The volumetric efficiency λ is calculated with a compressor model suggested by Vogel [8]. The heat transfer between primary and secondary circuits in evaporator and condenser is calculated with the $\epsilon - NTU$ approach according to Shah and Sekulic [10].

2.2. Measurement procedure

The five heat pumps investigated in this study use propane (R-290) as the refrigerant. They are designed for residential applications and targeted for future series production, although ran with a preliminary software at the time of measurements. The first three units will be referred to as “Small Chassis” (SC) and are designed for heating capacities of 4kW, 5kW and 7kW, respectively. The two other larger units will be referred to as “Big Chassis” and are designed for 10kW and 12kW capacity.

All measured and simulated performance values have been scaled by an anonymous factor ranging between 0.8 and 1.2 toensurethat the exact performance characteristics of the heat pumps cannot be directly inferred from the presented graphs.

The 115 measurements points used to parameterize and validate the model were carried out in an accredited test climate chamber at Fraunhofer ISE laboratory, complying with requirements of standards EN14825 [18] and EN14511 [19]. For each heat pump, 10 points have been measured according to the standards: 5 in Low Temperature (LT) application (for floor heating), and 5 in Medium Temperature (MT) application (for radiators). Details about environmental conditions of those measurements are given in EN14825. The other 65 measurements were performed at norm temperatures, but at various compressor speeds, in order to test the model performance on a wider range of performance outside the norm.

2.3. Training strategy for tabular foundation model

As baseline for comparison, the tabular foundation model was trained with the same calibration points of the semi-analytical model as marked in Figure 2 and Figure 3 (basic training). To make use of the possibility to transfer information from one heat pump to the other, an advanced training dataset was defined, including the calibration points plus four full heat pump performance maps of variable-speed HPs of a different manufacturer with similar nominal HP capacities and using R290 as refrigerant [20]. Each performance map comprised between 140 and 175 data points, covering air temperatures from −15 °C to 15 °C, water outlet temperatures from 35 °C to 70 °C, and compressor speeds from 20 Hz to 100 Hz.

3. Results

3.1. Calibration and validation of the semi-analytical model

The model calibration is carried out using a total of 9 out of 30 norm measurement of SC heat pumps (resp. 8 out of 20 of BC heat pumps). Those points are marked in Figure 2 and Figure 3 as training points. The result of the calibration procedure are the values for the 5 unknown compressor equation parameters that yield the best fit between measurement and calculation. The calibration is hence an error minimization problem solved using the python package SciPy [21]. In the objective function, the deviation at each point is weighted according to its relevance in the SCOP calculation, as described in EN14825. After determining the five compressor parameters, all norm measurements are simulated using this calibrated model for validation. The results are illustrated in Figure 2 and Figure 3 which show COPs of measured and simulated points for each of the 50 operating points.

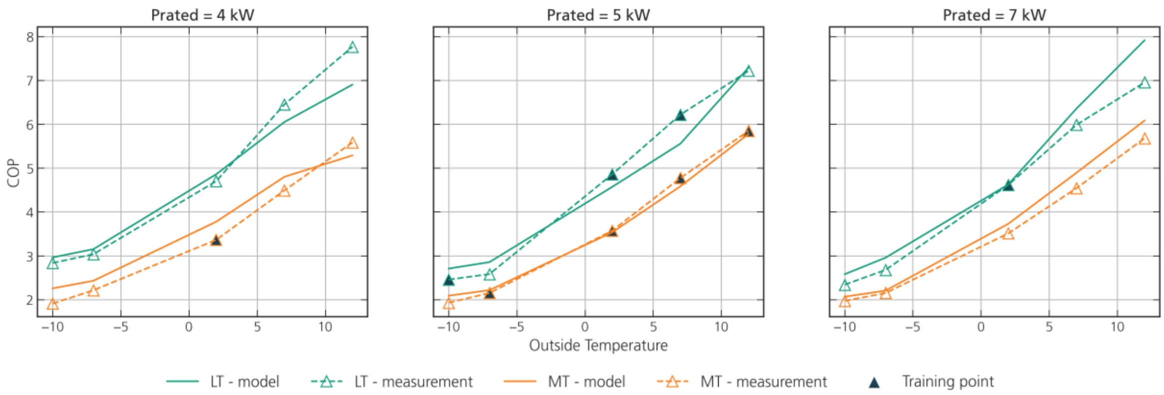

Figure 2: Validation of Norm measurements for SC machines

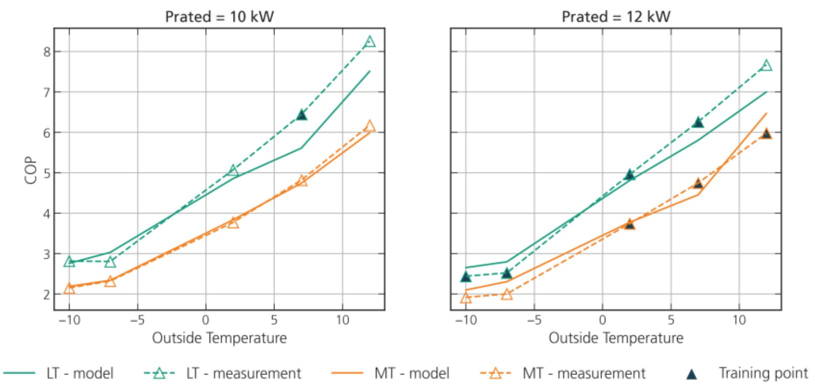

Figure 3: Validation of Norm measurements for BC machines

The model gives good overall result with a mean COP deviation of 8.8% across all 115 measurements, and only 6.6% considering only the 50 norm measurements. The predictions are accurate for outdoor temperatures of 2°C and below but show larger deviations at 7°C and 12°C, which can be explained by the lower weight of these points in the SCOP calculations.

The tabular foundation model reaches very good precision when evaluating solely on norm measurements, however the prediction quality decreases when all operating points are considered, as shown in Table 1. Since advanced training reduces the deviation by approximately 20 to 30%, the transfer of information between different heat pump variants appears promising. For the tabular foundation model, the precision is also higher at 2°C outside temperature points, which can be explained by the larger number of of training samples recorded at that temperature.

Table 1: Comparison of the average and maximum deviation of the COP for all 3 models

	COP mean deviation	COP mean deviation (norm measurements only)
Semi-analytical model	8.8 %	6.6 %
Tabular foundation model (basic)	14.7 %	4.8 %
Tabular foundation model (advanced)	10.7 %	4.0 %

3.2. Prediction of SCOP and efficiency class

Seasonal Coefficient of Performance (SCOP) is a measure to determine the annual performance of a heat pump in heating mode under representative conditions for different defined climates and heating system temperatures. Its calculation, detailed in [18] combines the five standard measurements listed in 3.1 with the frequency distribution of ambient-air temperature bins, plus standby and thermostat-off consumption multiplied by the time t_{SB} and t_{OFF} during which the device is in the respective mode. The total of useful heat delivered is divided by the total electrical energy consumed to obtain SCOP, as shown in equation (5).

$$SCOP = \frac{\sum_i \dot{Q}_{h,i}}{P_{el,SB} \cdot t_{SB} + P_{el,OFF} \cdot \mathrm{t_{OFF}} + \sum_i P_{el,i}} \tag{5}$$

From this value, the seasonal efficiency η_S is derived according to European Regulation [2]. Finally, each heat pump is assigned an energy-efficiency class, based on predefined thresholds, as required by [22].

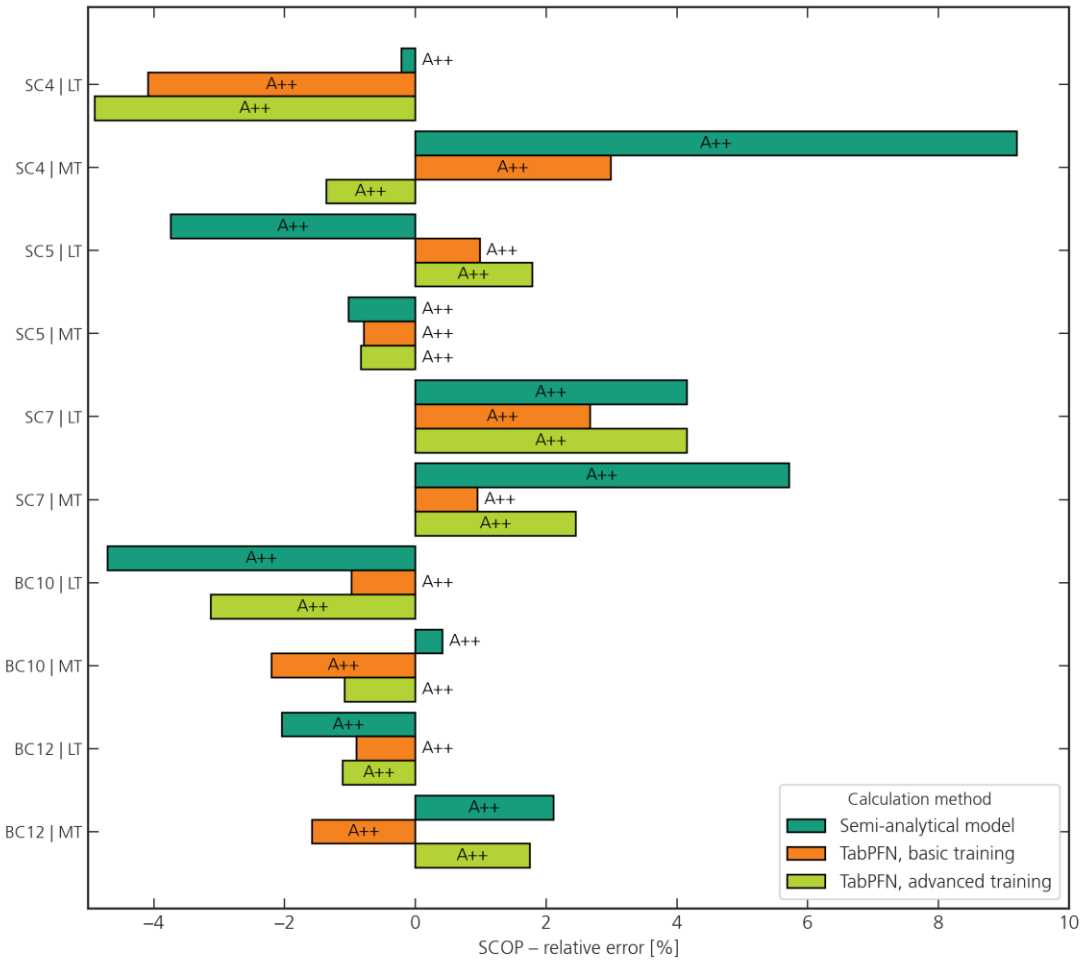

Figure 4: Prediction of efficiency class, comparison of semi-analytical model and tabular foundation model

Using COP predictions by the semi-analytical model and the tabular foundation model trained with two different datasets (basic/advanced), and the SCOP calculation tool provided by the KEYMARK certification organization [23], the seasonal efficiency was calculated for each heat pump variant and model. Comparative results are presented in Figure 4. Although the deviation for the semi-analytical model can reach up to 9.2% (e.g. for SC4 MT), the efficiency class is predicted correctly in every case, since the calculated SCOPs stay inside the defined efficiency class segments. Unexpectedly, the tabular foundation models show smaller SCOP deviations than the semi-analytical model in 7 out of 10 cases, with the basic dataset being in some cases even better than the advanced one. This result stems from the higher weight (50%) assigned to the 2 °C outdoor-temperature test point in the SCOP calculation and the tabular foundation models' strong accuracy at that temperature.

4. Conclusion

Our comparative evaluation indicates that numerical model-based certification of variable-speed air–water heat pumps may be viable using a reduced number of measurements. With a maximum SCOP deviation of 9.2% both the semi-analytical and the tabular foundation model predicted the efficiency class in all studied 10 cases correctly. An in-depth analysis of the calibration process could further decrease the number of required training points. To improve and confirm their robustness, these methods should be further validated using additional heat pumps from different manufacturers.

Acknowledgements

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