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"Experimental and Simulated Assessment of Charge-Optimized R290 Heat Pumps for Residential Heating Applications"

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Abstract

As part of the LCR290 project, three different R290 heat pump solutions for multi-family homes were being planned, simulated, tested, and evaluated. The main area of attention for simulations and measurements in the project were, refrigerant charge, seasonal efficiency and impact of different operation parameters. As part of the project the generated datapoints were used in designing and planning real use cases provided by project partners, representing the German housing industry.
This contribution will show general behavior of the two brine to water heat pumps, with heating capacities of 6kW and 30kw. SCOP55's varied from 3.4-3.8 and additional requirements set by the 12 partnered heat pump manufacturers were met. Brine heat pumps achieved charge efficiencies of <25g/kW. The heat pump performance and qualitative charge behaviors were replicated in the simulation environment IMST-ART, where the comparison with the measurement results yielded valuable insights into the significance of individual component models and parameters.
The main goal of providing market ready <150g R290 brine to water heat pump was achieved, as well as charge reduced larger capacity versions of the most commonly used systems. Furthermore, the comparison can be used to increase the quality of heat pump simulations.

Keywords: Propane, Heat pump, Charge reduction, R290, Brine to water heat pump

1. Introduction

The transition to climate neutral heating technologies in Europe is accelerating, driven by regulatory requirements, rising energy costs, and the need to reduce greenhouse gas emissions from the building sector. Since the implementation of the Montreal Protocol in 1987 [1] and its later amendments, the global phase out of ozone depleting substances and the increasing restrictions on high GWP synthetic refrigerants have strengthened the shift toward natural refrigerants. Propane (R290) has emerged as a strong candidate for residential heat pumps because it combines very low environmental impact with favourable thermodynamic properties and compatibility with high efficiency system designs.

Within this context, the LCR290 project focused on advancing propane heat pump solutions for multi-family residential applications. The project involved 18 industrial partners including manufacturers, component suppliers, energy contractors, and housing companies, who jointly defined research needs and provided continuous feedback during development and evaluation. Three full scale demonstrators were constructed: a 6 kW brine to water system for indoor installation, a 30 kW brine to water system also intended for indoor operation, and a 35 kW air to water system that provides 51 degrees Celsius under nominal conditions. All demonstrators were designed for their respective heating capacities at a sink temperature of 55 degrees Celsius and were successfully operated at sink temperatures up to 75 degrees Celsius during testing.

Each system was thoroughly measured and evaluated under controlled laboratory conditions, and detailed simulations were conducted for all configurations. This contribution presents the experimental assessment of the three R290 demonstrators, provides qualitative comparisons between their performance characteristics, and contrasts the measurements with the corresponding simulation results. The shown results are evidence that the previously shown findings are true for larger capacities, as well as the next generation of smaller capacity components. These findings support ongoing work toward efficient, safe, and scalable propane heat pump solutions for the residential building sector.

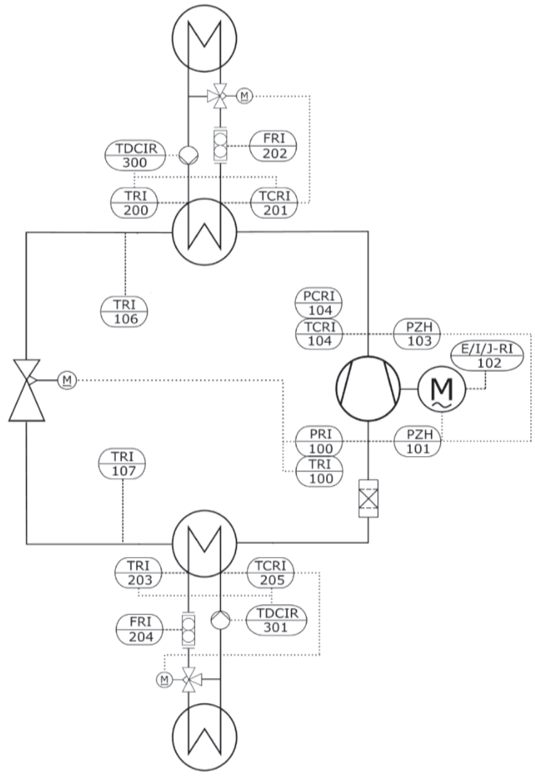

Figure 1:Flow chart of brine to water heat pumps with sensors marked as used

2. Physical demonstrators

All demonstrators were built in the workshop of Fraunhofer ISE, using market available components of a multitude of different component manufacturers. The components of units RC2 and RC3 are outlined in Table 1, it is to mention here the obvious mismatch between heat exchangers of RC2. The mismatch was a deliberate choice to investigate undersized condenser performance. Additionally, all evaluations were performed at Fraunhofer ISE using standardized conditioning modules to emulate the source and sink (secondary circuits). These modules allow control of secondary fluid temperature and mass flow.

2.1. Test set up

Heating and cooling capacities on the secondary sides were determined using Coriolis mass flow sensors and inlet/outlet temperatures recorded by submerged PT100 sensors, using the appropriate specific heat capacities. A detailed flowchart including sensor locations is shown in Figure 1. The electrical input to the driver and compressor was measured between the driver and the grid, so frequency-converter losses are included in all evaluations. The power demand of external secondary-side pumps was excluded of any evaluation.

Table 1 Components units used in LCR290

	Unit	RC2	RC3
Compressor			
Displacement	ccm	17	85
Oil amount	ml	125	2000
Evaporator			
No. Plates	-	20	56
Q_design	kW	6.3	17.5
Port diameter	mm	12.8/28.7	12.7/28.6
Plate profile	-	Dimple	Dimple
Condenser			
No. Plates	-	20	42
Q_design	kW	4	28.5
Port diameter	mm	9.5/22	14/32
Plate profile	-	Fishbone	Dimple

2.2. Measurement procedure

All measurement data and compared values are recorded in steady state operation. For this purpose, the test benches in build during the project LC-150, were used. After steady state operation is achieved, there is a measurement time period in which averages are being taken to create one data point. Multiple data points, for different charges, built a coherent behaviour of the heat pump and are being used to compare to the simulations. In addition to the measured values enthalpies are calculated using the coolprop database and the locally measured pressures and temperatures. Pressures are measure before and after the compressor, no additional pressure sensors in the liquid line or the two-phase line are included

Individual operation points are labelled as Bx/Wy/Fz/SHa/mb, x indicates the brine inlet temperature, y water outlet temperature, z compressor frequency, a desired super heat and b filled charge. Measurement procedures were kept the same between earlier LC150 measurements explained in [2]. The obtained measurements have uncertainties attached to them which will not be discussed in depth in this contribution, since the focus of the evaluation has been qualitative relative performance with variation of charge.

2.3. Charge variation performance measurements

The charge-variation measurements provide a comprehensive dataset illustrating the quantitative performance behaviour of the brine to water R290 demonstrators. All datapoints were measured following the procedures on the testbenches described in section 2.2. The resulting plots visualised in Figure 2 show heating capacity, COP and EEV opening over refrigerant charge, where the fully coloured marked measurements have an increased super heat compared to labelled values. As the plots indicate RC2 and RC3 are the LCR290 demonstrators measured for this project, where the plot indicated as RC821 shows the same data as used in the publication from 2023 [2]. General shape and behaviour of the circuits, match very closely as can be compared in Figure 2 and thus confirming the characteristic response of propane heat pumps to varying refrigerant mass as well as the robustness of the measurement methodology as described in [2, 3]. Notably the behaviour was still observed in a larger capacity heat pump (RC3) as well as a mismatched selection of heat exchangers (RC2).

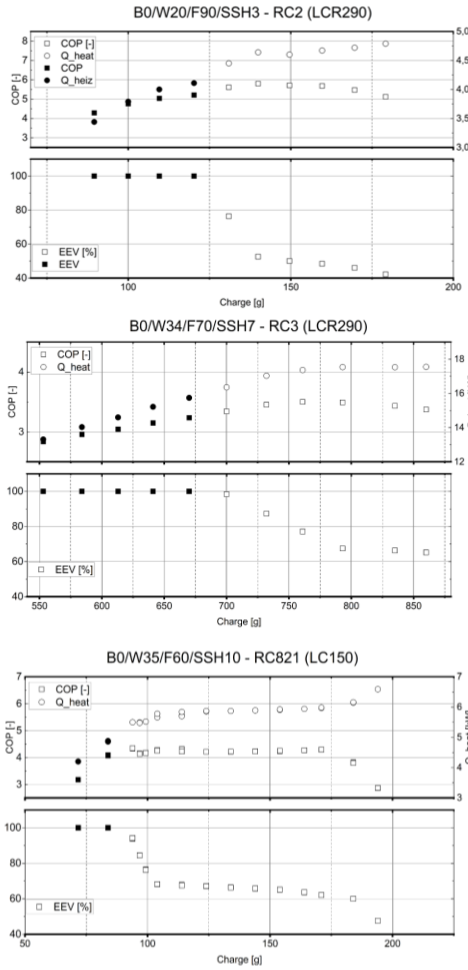

Figure 2: Heating capacity, COP and EEV opening shown over charge for three demonstrators, where solid markers indicate sections with larger than expected super heats.

3. Simulation results

3.1. Simulation Setup

The simulations were carried out using IMST-ART, a steady state simulation tool developed at the Universitat Politècnica de Valencia (UPV) for analysing vapor compression refrigeration systems. IMST-ART represents the cycle through sub models of the compressor, heat exchangers, expansion device, piping, and accessories. Each sub model is formulated through nonlinear algebraic or differential equations, and the heat exchangers are discretized using a finite volume approach. Refrigerant properties are obtained from REFPROP and interpolated during the solution process, which allows the software to compute pressures, enthalpies, and phase conditions at all inlet and outlet points of the cycle [4]. In this work the simulations were used to assess how accurately IMST-ART reproduces the behaviour of the demonstrators and to provide structured feedback to UPV to support further improvements to the modelling.

The simulation models were constructed to replicate the demonstrators, and to ensure direct comparability with the measurement dataset, selected operating conditions were used as inputs for the parametric study in IMST-ART. These included, for example, water inlet and outlet temperatures, compressor speed, and superheat levels. The compressor model was defined using the manufacturer performance map and validated separately against catalogue data. The heat exchangers were then incorporated into the cycle, specified according to the manufacturer data sheets, and validated against the corresponding catalogue data.

3.2. Simulation results

The simulation results were evaluated by comparing IMST ART predictions with the corresponding measurements for the demonstrators AP2 and AP3. For each heat pump a combined set of parity plots is presented, showing heating capacity, compressor power consumption, and coefficient of performance (COP). These indicators provide a consistent basis for assessing the predictive accuracy of the models under the operating conditions used in the measurement campaign.

3.2.1. AP2, brine to water heat pump small capacity

In Figure 3, the parity plots shows that the model reproduces power consumption with good consistency. This indicates that the compressor representation and the imposed boundary conditions are broadly aligned with the behaviour of the real system. COP predictions follow the same trend and match the measurements well across most operating points.

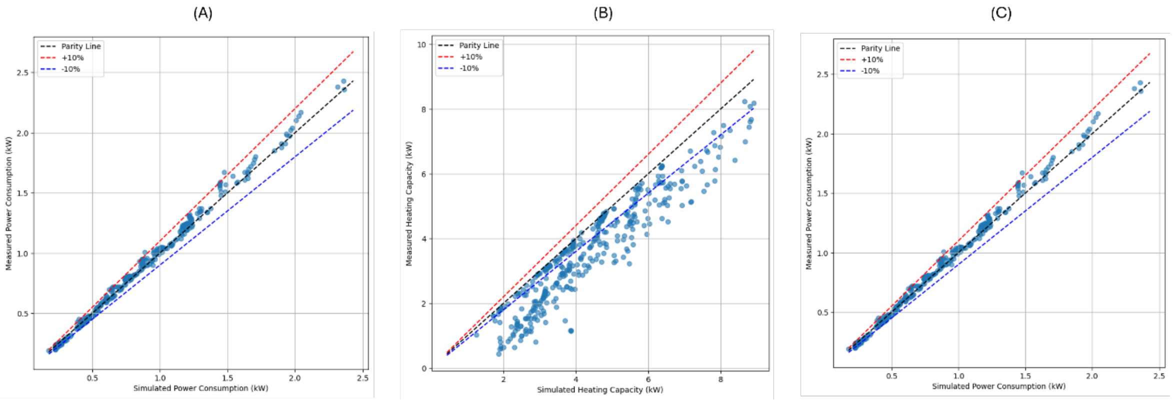

Figure 3: AP2 Parity plots of (A) Power consumption (kW), (B) Heating capacity (kW), (C) COP

However, the heating capacity estimation shows a noticeable and systematic deviation for a subset of conditions. The magnitude of this deviation is larger than what is observed in AP3, and its origin is not yet fully understood. Checks on the heat exchanger definitions, the applied boundary conditions, and the measurement dataset did not reveal an obvious cause, which suggests that additional analysis is needed. Possible sources include measurement uncertainty, due to sub cool temperatures approaching and including 0K, or an inaccurate representation of the compressor volumetric efficiency. If the volumetric efficiency in the map does not capture the real performance of AP2 across the evaluated pressure ratios, the simulated mass flow rate would be biased, which directly affects the heating capacity while leaving the electrical power prediction relatively unaffected.

3.2.2. AP3, brine to water heat pump large capacity

As seen in Figure 4, AP3 shows a generally consistent match between simulation and measurement for heating capacity and power consumption across most operating points. For COP, several operating points show

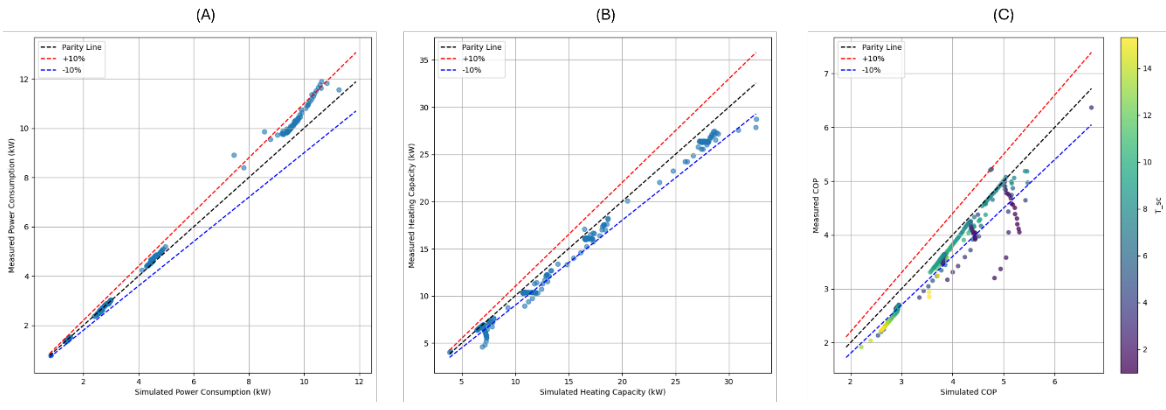

Figure 4: AP3 Parity plots of (A) Power consumption (kW), (B) Heating capacity (kW), (C) COP

noticeable deviations. These points correspond to conditions with very low subcooling, which makes the enthalpy estimation more sensitive and reduces the robustness of the model.

3.3. Key Findings from the Simulation

A clear improvement in the model arises from the updated definition of the heat exchanger port volumes. These refinements were introduced based on the findings of Sanchez, et al. [5] the feedback process with UPV and aim to provide a more realistic distribution of refrigerant within the cycle. The improvement is visible in the charge parity plot for AP3 in figure Figure 5. The visible horizontal clusters of measurements are operation point variations, which lead to varying minimal optimal charges and push the system between undercharge and overcharge operations. The varied operation points are source temperature -12 - 10°C, sink temperature 24 - 75°C, compressor speed 20 – 120Hz and super heat 2 - 15K.

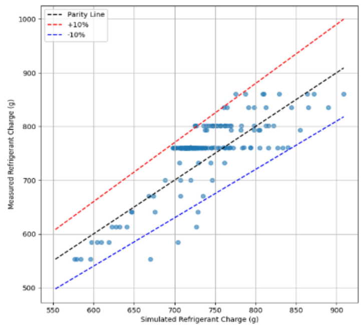

Figure 5: AP3 Parity plots of refrigerant charge (g)

To illustrate the mentioned charge reduction improvements clearly, Figure 6 presents two plots comparing simulated and measured charge in relation to heating capacity, using similar styles. In plot (A) from an earlier publication [6] the measured and simulated curves show a clear separation. In the updated plot (B), generated with the refined port volume definitions, the measured and simulated curves align much more closely across the evaluated range. This improved agreement indicates that the revised port volumes result in a more consistent and accurate refrigerant charge prediction.

AP3 shows clear sensitivity to very low subcooling, which leads to noticeable COP deviations and highlights the need for improved stability of enthalpy estimation near the saturation boundary. In contrast, AP2 exhibits an unexplained deviation in heating capacity that does not follow the same pattern and therefore requires targeted investigation to identify the underlying cause. Together with UPV these findings can be used for further refinement of the IMST-ART models.

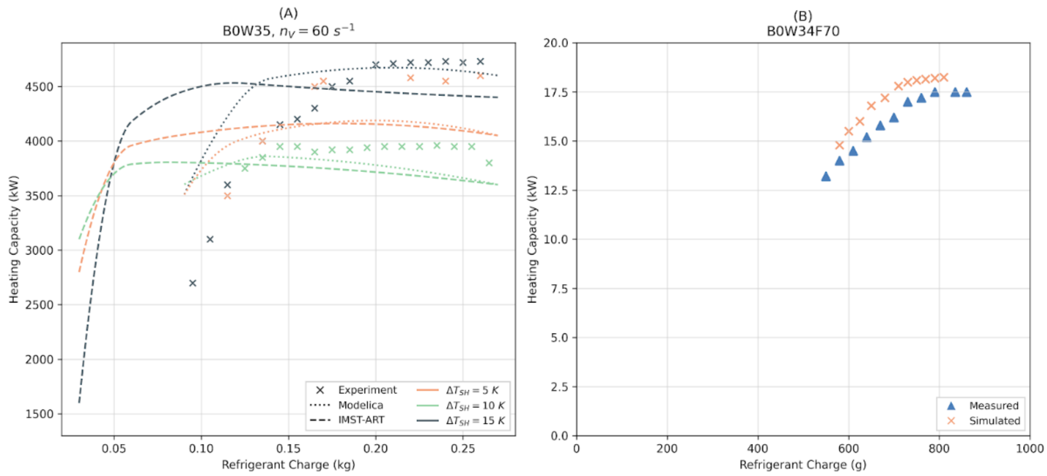

Figure 6: Comparison of charge prediction between earlier and updated IMST ART simulations. (A) Earlier simulation compared with measurements [6]. (B) Updated simulation compared with measurements.

4. Conclusion

Conclusions include the successful repetition of quantitative the results from three years ago [2], as well as the original inspiration for this work [3]. This includes the behaviour of the expansion valve in undercharge region as well as the plateau of the heating capacity as with increasing charge higher than minimal optimal charge. Additionally same correlation was successfully shown for larger capacities.

The validation of the IMST ART models for AP2 and AP3 shows that the simulation framework reproduces the main performance indicators reliably across most operating conditions, while revealing clear sensitivities in low subcooling regions. Compare with LC150 results, the LCR290 results show that simulations are still improving with relatively basic adjustments and provide more information and approaches how to reduce the charge further. The improved charge prediction achieved through refined port volume definitions demonstrates the value of targeted model adjustments, highlights the importance of accurate refrigerant distribution representation. This includes oil distribution since refrigerant absorb in the oil has a significant impact on charge prediction, which increases in importance for smaller systems due to the relative mass between oil and refrigerant. Together, these results provide a solid basis for further refinement of the component models and support ongoing collaboration with UPV to enhance the predictive capability of IMST-ART for low charge heat pump applications.

Dedicated discussions on scaling effects regarding charge per heating capacity on an individual component's basis are ongoing but not focus of the ongoing developments.

Acknowledgement

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