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Propane As Working Fluid For Heat Pump Water Heaters- Opportunities And Challenges

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ABSTRACT

Growing awareness of the potential environmental impacts of various refrigerants has led to the phasedown of hydrofluorocarbon (HFC) refrigerants and initiatives replacing HFCs with hydrocarbons or other environmentally friendlier fluids. This study evaluated the performance of R290 (propane) as a substitute for R134a (an HFC) for heat pump water heating (HPWH). Comprehensive experimentation is performed to predict the performance of propane as a refrigerant for a domestic HPWH. Key performance parameters such as unified energy factor, first-hour rating, condenser discharge temperature, thermal stratification in the water tank, and total refrigerant charge have been established and compared to the baseline system. A drop-in-replacement study indicates that the system can provide reasonable performance with a substantial reduction in refrigerant charge in the system. To further reduce the refrigerant charge in the system, a comprehensive work plan has been developed which focused on individual components including the evaporator, compressor, and condenser. The objective of the study is to develop a roadmap for next-generation heat pump water heaters which are compatible with hydrocarbons as refrigerants and can be deployed safely for domestic applications.

1. INTRODUCTION

Residential and commercial water heating accounts for approximately 10% of all residential and commercial site energy usage in the United States, making it the fourth largest energy end use in homes (*DOE Building Technologies Office 2016 Peer Review*). On a global scale, in 2015 water heating consumed about 15–20% of residential energy for OEDC and non-OEDC countries as shown in Fig. 1.

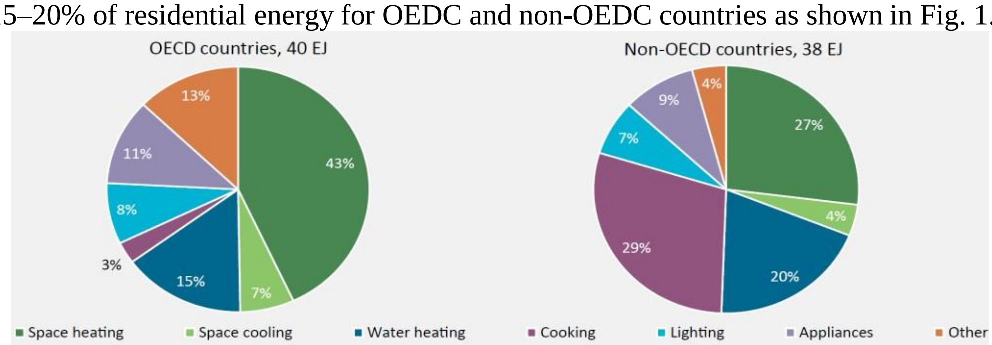

Fig. 1: End uses of residential energy consumed in OECD and non-OECD countries (International Energy Agency, 2016)

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Despite recent advancements in energy efficiency, most residential water heaters are either conventional natural-gas-fired or electric storage heaters. While such systems are quite simple, they have very low system efficiency. Conversely, under appropriate conditions, electrically driven, vapor compression heat pumps, or heat pump water heaters (HPWHs), represent a system opportunity with much higher thermal efficiency than conventional electric water heaters, resulting in significant energy savings.

Similar to conventional refrigeration or air-conditioning cycles, HPWHs use a vapor compression refrigeration cycle to transfer heat from a low temperature ambient to a high temperature reservoir, a hot water tank. A key parameter of interest is the working fluid used in the vapor compression cycle. Conventional HPWH systems deployed R-22, which is being phased down due to the high ozone depletion potential (ODP) associated with this fluid. R-134a emerged several years ago as the potential replacement, and most manufacturers have introduced systems with a reasonably higher unified energy factor (UEF) based on this refrigerant. However, concerns about possible global climate change have led to legislative action all around the world to phase down the use of hydrofluorocarbons (HFCs), including R-134a, in a range of heating, ventilation, air conditioning, and refrigeration (HVAC&R) applications, due to their relatively high global warming potential (GWP). Since HPWH systems are essentially heat pumps relying on the vapor compression refrigeration cycle, the technology has been equally affected (McLinden et al., 2017). Table 1 summarizes some familiar refrigerants with potential impact on the environment.

Table 1 Characteristics and environmental impact of different refrigerants (ANSI/ASHRAE Standard 34, 2013)

Refrigerant group	Refrigerant example	ODP	GWP_{100}	Atmospheric lifetime (years)	Flammability
CFCs	R11, R12, R115	0.6–1	4750–14400	45–1700	Nonflammable
HCFCs	R22, R141b, R124	0.02–0.11	400–1800	1–20	Nonflammable
HFCs	R407C, R32, R134a	0	140–11700	1–300	Nonflammable or mildly flammable
HFOs	R1234yf, R1234ze, R1234yz	0	0–12	-	Mildly flammable
Natural refrigerants	R744, R717, HC (R290, R600, R600a)	< 20	0	Few days	HCs: Highly flammable R717: Flammable R744:Nonflammable

Multiple studies have focused on using HC mixtures as substitutes for conventional refrigerants. Chao and Teng (2014) studied the feasibility of using HC mixtures of R290 and R600a as alternative refrigerants in a small-sized refrigerator originally using R134a. They concluded from a no-load pull-down test that the optimal refrigerant charge for HCs was significantly lower than that for R134a. Rasti et al. (2012) used R436A (56% R290 and 44% 600a) as an alternative to R134a in a domestic refrigerator and concluded that the system's on-time ratio was reduced by 13% and that power consumption was reduced by 5.3% as compared to the original system with R134a. Mani and Selladurai (2008) conducted an experimental study using R290 and R600a (68% and 32% by mass, respectively) as a drop-in replacement for R12 and R134a and found that the HC mixture had a higher cooling capacity. It is important to note that trans-critical CO_2 HPWH technology also relies on a environmental friendly refrigerant, however, issues related to high pressure and variable flow rate pump system along with intermediate heat exchanger makes the technology less feasible compared to HC based HPWH system (Nawaz et al., 2017) .Propane as a working fluid in heat pump water heaters (HPWHs) is an interesting prospect as the fluid has larger volumetric heat capacity than many other refrigerants and has a 20-year Global Warming Potential of 0.072.

Total system charge is a critical parameter that has been the focus of continuous effort toward minimization, not only because refrigerants are expensive but also because class A3 refrigerants present serious safety concerns for any HVAC&R application. Nawaz et al., 2018 analyzed the refrigerant charge in heat exchanger through system simulation and found highly promising outcomes. Fig. 1 compares total system charge in the evaporator and the condenser. Even though there is no significant difference in charge for various design options, it is interesting and encouraging that the charge required for both R290 and R600a is less than half that of the baseline R134a. This can be explained in terms of the lower molecular weights for the R290 and R600a refrigerants which are almost half that for R134a. This shows the potential of HC refrigerants to substitute for R134a and indicates that further development may allow an even smaller charge of flammable refrigerant to be successfully substituted to provide similar performance, thereby reducing safety concerns.

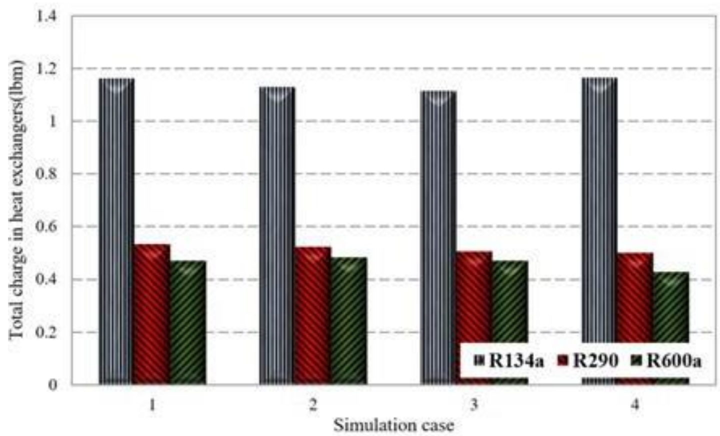

Figure 1 Total charge in condenser and evaporator

Multiple standards could apply to a HPWH using propane as a working fluid depending on the charge level. UL 60335-2-89, 2021 applies to commercial refrigeration systems with > 150 grams of charge. UL 60335-2-24, 2020 applies to appliances with < 150 grams of charge. UL 60335-2-40, 2019 applies to refrigerant systems with < 150 grams of charge. This suggests that the upper limit for a HPWH using R290 will likely be 150 grams. Furthermore, ASHRAE 34, 2019 can be used to calculate the lower flammability limit (LFL) for propane and recommends a maximum charge based on the volume of the room in which the HPWH is installed. When calculating the LFL per the ASHRAE method, the maximum charge in a small closet space would be less than 50 grams of R290. Thus, great care needs to be taken when specifying the installation location of a R290 HPWH.

In the current study a comprehensive experimental evaluation was conducted, and multiple Unified Energy Factor (UEF) tests were performed to determine the optimal charge for 3 different compressors. The tests were baselined against a state-of-art R134a HPWH. R290 is a low GWP replacement for R134a in electric hot-water heating marking carbon footprint reductions would for 2042 in the residential sector alone would be approximately 35 of the 115 Mt/year (Scout, 2022). This amount, which corresponds to a 30% reduction in CO_2 emissions, will be achieved if electric resistance heaters are switched over to HPWHs. Furthermore, this reduction in CO_2 emissions will only increase as large markets (i.e., New York, California) trend towards electrification. Finally, the market potential for this product is large assuming the safety regulations can be met.

2. EXPERIMENTAL PROCEDURES

2.1 Instrumentation

A thoroughly instrumented 50-gallon heat pump water heater was utilized to perform testing on the UEF for baseline and prototype HPWHs with a variety of components and refrigerant. A detailed schematic of the heat pump system with the corresponding measurement instrumentation is displayed in Figure 2. Pressure transducers (Omega PX309) with a reading accuracy of 0.25% were installed in the refrigerant line at the compressor and electronic expansion valve inlet and outlet locations. Externally insulated T-type thermocouples were installed in the refrigerant lines at the same locations. Six thermocouples were positioned evenly across the height of the water tank while two thermocouples were placed at the water heater inlet and outlet locations. Calibration of the thermocouples determined that the fluid temperature measurement uncertainty is 0.5 °C. It was also found that the combined uncertainties propagate to less than 3% relative error in terms of energy associated with the hot water flow.

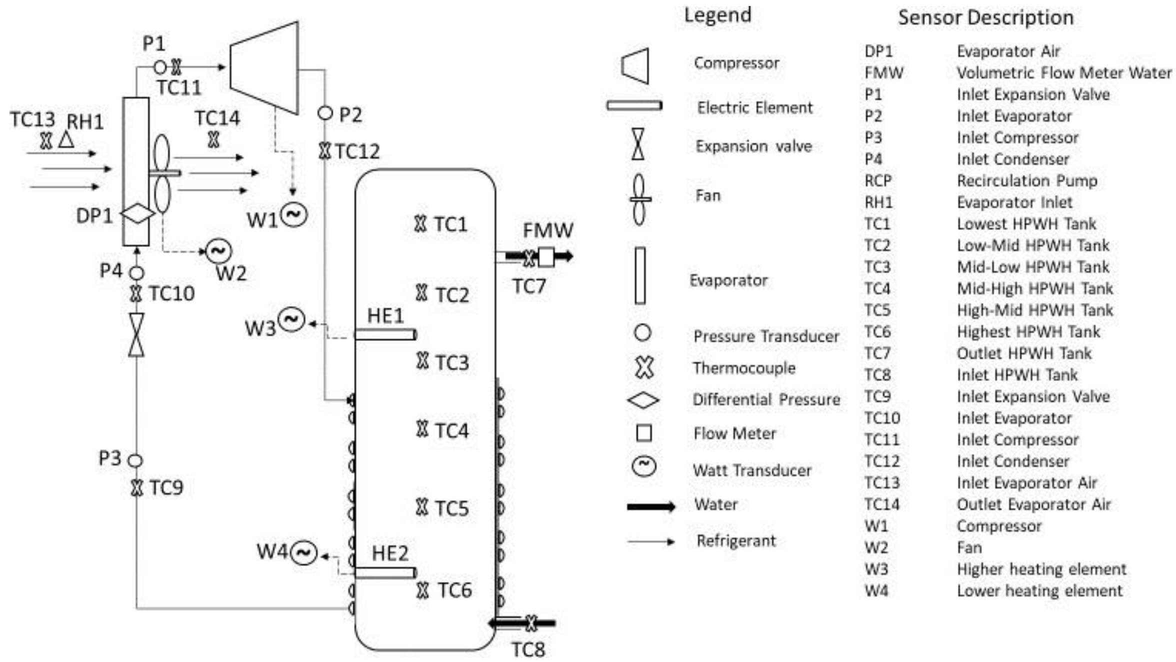

Figure 2 Schematic of the heat pump, hot water tank, and sensor locations.

In total, thirteen UEF tests were performed to determine the optimal charges for the various compressor configurations. Table 2 presents the 4 system configurations which are tested and represented inthe study. Case 1 represents the original HPWH with R290 as a drop-in replacement for R134a. Case 2 represents the baseline with the original refrigerant R134a. Small and Large compressors are prototypes designed mainly for hydrocarbon refrigerants. Due to intellectual property agreement, the compressors specifications can not be disclosed. Baseline refers to the original system components (compressor and condenser coil). Case 3 and 4 represents the modified system with a compressor prototype A and B respectively.

Table 2 Configurations of tested systems.

Case #	Compressor
1	Baseline (R290)
2	Baseline (R134a)
3	Prototype A
4	Prototype B

The experimental campaign goal was to test two compressor prototypes designed for hydrocarbon refrigerants (case 3 and 4) and compare the performance with the baseline performance.

3. RESULTS AND DISCUSSION

3.1 P-h and T-s Diagrams

The results of the initial testing of the R290 unit to that of the R134a unit show significant differences. The heat pump cycle for the R290 and R134a are different due to the properties of the working fluids. As can be seen by comparing the P-h (Pressure-Enthalpy) diagrams in Figure 3, R290 exhibits a larger enthalpy change over the phase change region.

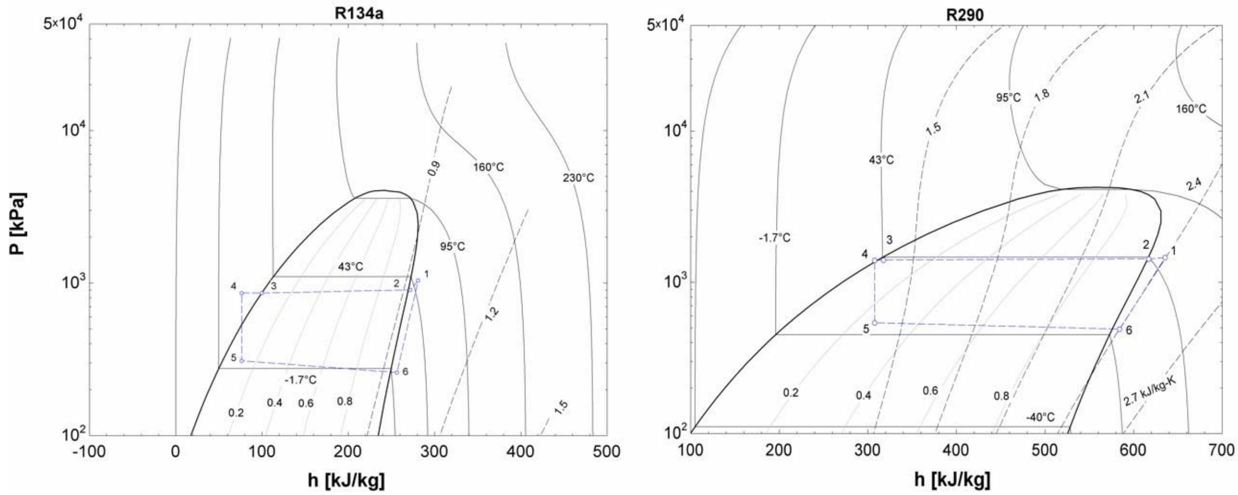

Figure 3 Comparison of Pressure – Enthalpy diagrams for R134a (left) and R290 (right) from experimental data.

The condenser saturation pressure of the R134a system is also below the R290 system by 450 kPa. One must note that the compression of the tested HPWH in not isentropic and the compression efficiency is estimated at 55% from previous modeling work with this system (Rendall et al. 2022).

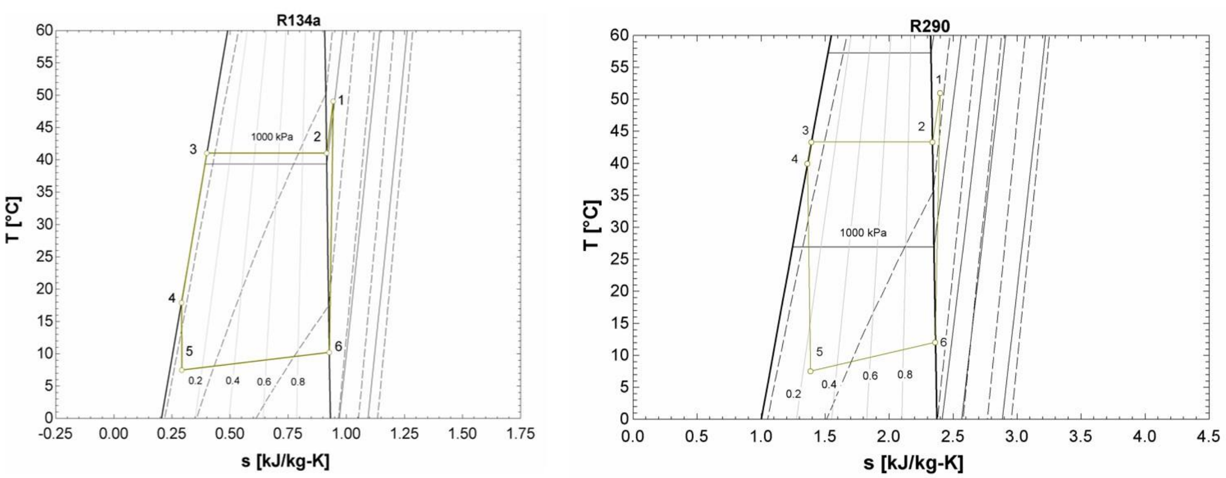

Figure 4 Comparison of Temperature - Entropy cycle diagrams for R134a (left) and R290 (right) from experimental data.

The R290 system also operates at a slightly higher temperature that allows for higher heat transfer coefficients on the inside of the tank as the process of heating the water is dominated by natural convection.

3.2 Compressor analysis

The tests were dedicated to first, find the optimum charge for each configuration. Second, the optimized charge was used for system configurations comparison. The baseline system was tested and used as a reference to assess the modified systems (i.e. 3 and 4). Figure 5 shows the UEF for each configuration in addition to the degree of superheat (SH) at the compressor suction and discharge. Once can see clearly that performance of the tested system configurations are comparable to the baseline.

A noticeable advantage of the compressor prototypes compared to the baseline compressor is shown in Figure 5. SH at the suction and discharge sides of the compressor are lower than that for the baseline system with R290 as a drop-in replacement. Which indicates that utilizing a special compressor designed for Hydrocarbons can reduce the SH degree on both sides of the compressor.

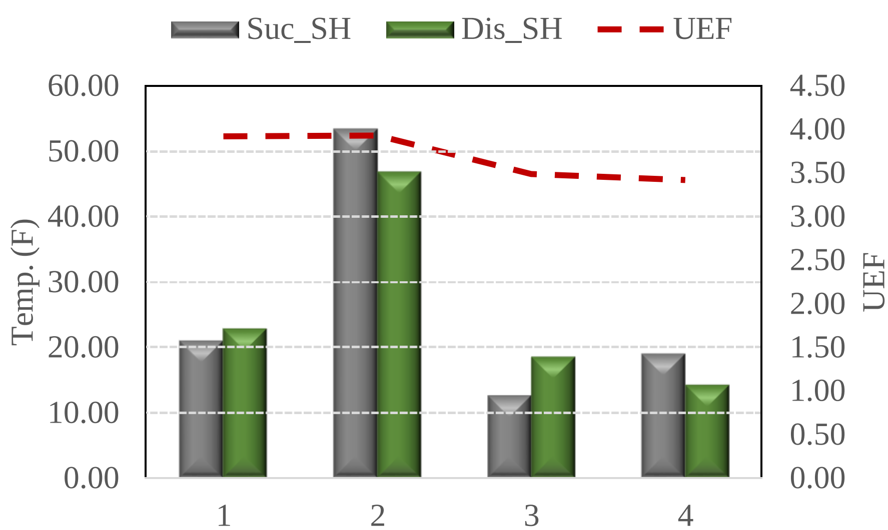

Figure 5 Comparison of super heat degree for all tested systems from experimental data.

The baseline case with the conventional refrigerant has the highest super heat degree among the tested cases. It is clearly seen that all the cases with R290 as the working refrigerant have lower degree of super heat. The figure shows that the degree of super heat is less than half of the degree of superheat for R134a. This observation is important and could encourage the compressor manufacturers in developing new models.

3.3 UEF and FHR Results

To compare the impact of using R290 (low GWP) instead of R134a, three compressors were utilized during a charge optimization test matrix. Figure 6 shows the results of these experiments in which an (X) denotes a noncompliance UEF (i.e., delivering water below the temperature requirements of the UEF test). This noncompliance test is usually associated with a low compressor discharge temperature and low average tank temperature. Each compressor passed the UEF test at a different charge level, as denoted by a darkened circle in Figure 6.

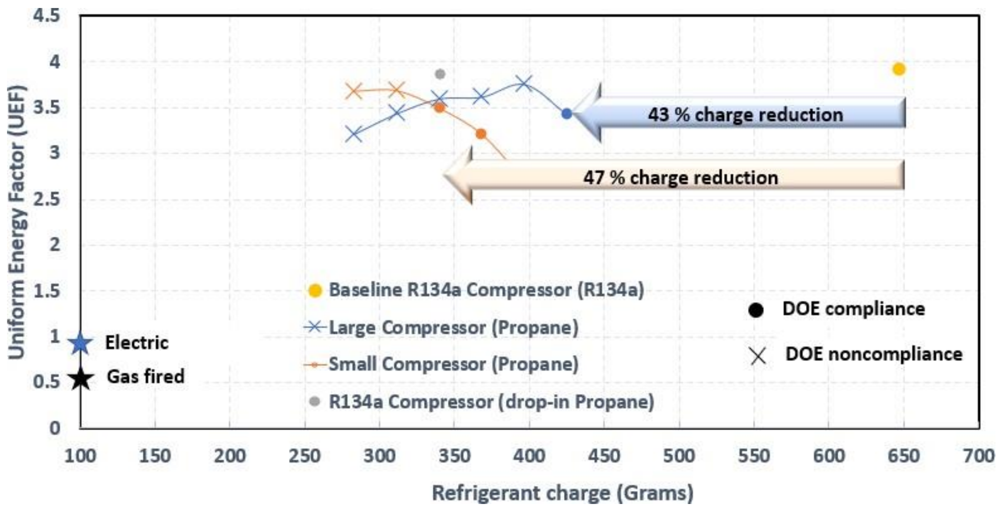

Figure 6 UEF results for three compressors tested with propane. The baseline test with R134a is shown in yellow. The improvements of HPWH over conventional electric resistance and gas system is highlighted. The drop-in replacement of R290 with the current compressor performed the best at a much lower charge.

The baseline test (yellow) with R134a shows a required charge of nearly 650 grams of refrigerant. The charge reductions realized by using R290 are substantial. The larger and smaller compressors required about 425 and 340 grams, respectively.

The reduction methods from switching from R134a to R290 did not degrade the performance of the HPWH significantly (e.g., the UEF was 3.5 at a charge of about 350 grams). This resulted in a 47% charge reduction compared to the baseline system. Furthermore, this embodiment has a 390% increase in UEF over conventional electric resistance storage heaters and an almost 600% increase in UEF over convectional gas storage heaters. Importantly, this result is a factor of about 1,000 reductions in GWP by switching to the new design assuming that the refrigerant is released at the end of life. Since plumbers are not often trained in heating ventilation and air-conditioning technologies, it is easy to assume that the refrigerant will be released into the environment at the end of life. Although the 150-gram limit for UL 60335-2-24 and UL 60335-2-40 was not reached in these experiments, future work will develop a design that can meet this requirement by modifying the condenser without impacting the UEF significantly.

4. CONCLUSIONS

With very low GWP value and large volumetric heat capacity, Propane (R290) presents a good potential to be used as working fluid in HPWHs. However, flammability is one of the risks needs be addressed. In general, a recommended maximum charge in HPWHs needs be met. This study conducts experimental study on the HPWH using R290 as working fluid to determine the optimal charge and improve system and component design to reduce the charge amount. Lab tests have conducted for different HPWH configures with three compressors. According the test results, compared to HPWH with R134a as working fluid, HPWH using R290 as working fluid can reduce the charge by 47%. Future improvement will be conducted on HPWH design, particularly on condenser design, to further reduce the system charge to mitigate the risk of using R290 as working fluid in HPWHs.

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