Experimental Study of an R-407C Heat Pump Water Heater

Vince C. Mei, Ph.D., P.E. **Ronald E. Domitrovic** **Wayne H. Brewer**

Fang C. Chen, Ph.D., P.E.
Member ASHRAE

Titu R. Doctor
Member ASHRAE

ABSTRACT

The purpose of this work was to investigate the possibility that R-407C can replace R-22 in existing heat pump water heaters (HPWHs). Several tests, including baseline tests and system tests with a counter-cross-flow evaporator, were conducted to evaluate the performance of R-407C in HPWHs. The HPWH studied was originally designed for R-22 but was modified for R-407C operation.

The baseline test results indicated that the R-407C HPWH had a much higher water heating capacity than that of the R-22 unit with the same designed capacity. However, the R-407C unit also consumed more power, which resulted in lower COPs at higher water temperature region.

However, when the HPWH was modified with a counter-cross-flow evaporator, the system performance improved. The COP increased by an average of almost 20% and heating capacity by 4% over the baseline case. The improved system COP is slightly higher than that of R-22. It is feasible that R-407C can be used to replace R-22 with improvement in water heating capacity without sacrificing the system energy efficiency.

INTRODUCTION

The aim of this work was to perform baseline and system tests with a new counter-cross-flow evaporator, according to federal standard test conditions, on an R-22 heat pump water heater (HPWH) modified for R-407C operation. The baseline tests were then used to measure the results of the unit after changing the existing evaporator with a new one.

In the United States, at least 6% of all electricity is used for heating water, which is equivalent to 150 trillion Wh/yr and an electric bill of $12 billion a year. A significant portion of this energy is wasted because of inefficient end-use devices, distribution systems, water heating systems, and operational practices. One efficient way to use electricity for water heating is to adopt heat pump water heaters (E-S 1998). According to Meyer and Greyvenstein (1991), heat pump water heaters can save up to 67% of electric energy consumption compared to electric water heaters. A heat pump uses the same vapor-compression cycle as any refrigerator or air conditioner. As the liquid refrigerant evaporates in the evaporator, it absorbs heat from the surroundings and a compressor "pumps" this amount of heat up to a higher temperature. Water is heated as it flows through a condenser, where the hot refrigerant vapor gives off its heat as it condenses back to a liquid. What makes the heat pump water heater more efficient than the electric water heater is that the heat pump absorbs heat at a modest temperature and gives it away at a higher and more useful temperature. Furthermore, HPWHs can be used for dehumidification in residential applications and to dehumidify and cool in commercial applications.

The task to replace R-22 is a difficult one, as there are no pure fluids that have thermodynamic properties close to those of R-22. There are, however, some refrigerant mixtures that may be able to replace R-22. The leading candidates so far are two HFC mixtures, R-407C (Bivens et al. 1994) and R-410A, which are considered environmentally benign. While the use of R-410A requires a thorough redesign of the system because of its high operating pressures, R-407C can be used on the current R-22 systems with minor component modifications and with different oil.

The purpose of the experiment was two-fold. The first was to experimentally examine the validity of R-407C as a replacement refrigerant for R-22 for heat pump application

Vince C. Mei is on the senior research staff and **Fang C. Chen** is a program manager at Oak Ridge National Laboratory, Oak Ridge, Tenn. **Ronald E. Domitrovic** is a senior research associate and **Wayne H. Brewer** is a student research engineer at the University of Tennessee, Knoxville, Tenn. **Titu R. Doctor** is with Crispaire, a division of Airxcel Inc.

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(Smith and Meyer 1998; Spatz and Zheng 1993). The second was to explore the possibility of increasing the efficiency of the system with R-407C over that of the system with R-22. Mei et al. (1998) had shown that taking advantage of the temperature glide that is present in R-407C could increase the system efficiency with an off-the-shelf air conditioner.

TEST STANDARDS

In order to compare the performance of different HPWHs, all units should be tested under the same test conditions. The test conditions specified in the federal heat pump water heater test standard were adopted for this study. Two standard tests, the first-hour rating test and the 24-hour simulated use test, form the HPWH's battery of tests.

TEST CONDITIONS

The ambient dry-bulb temperature was maintained at 19.7ºC ± 0.6ºC (67.5ºF ± 1ºF) and the room relative humidity was maintained between 49% and 51%. The supply water temperature to the water heater was maintained at 14.4ºC ± 1.1ºC (58ºF ± 2ºF) throughout the test. The average temperature of the water within the storage tank was set to 57.2ºC ± 2.8ºC (135ºF ± 5ºF). During the test when water was not being withdrawn, the supply pressure was maintained between 275 kPa (40 psig) or the maximum allowable pressure specified by the water heater manufacturer.

INSTALLATION

The test area was free from draft. A pressure gauge and diaphragm expansion tank were installed in the supply water piping at a location upstream of the inlet temperature sensor.

Six temperature sensors were installed inside the water heater tank with a vertical distance of at least 100 mm (4 in.) between each sensor. If the volume in the tank is divided into six equal volumes (from the top to the bottom), a temperature sensor is positioned at the vertical midpoint of each volume. An ambient air temperature sensor is installed at the vertical mid-point of the heat pump and approximately 0.61 m (2.0 ft) from the surface of the heat pump.

In addition, pressure transducers are used to measure the pressure of the refrigerant line at various positions. Flow meters are installed to monitor the flow rate of the refrigerant and water. Thermocouples are attached before and after every component on the refrigerant line, and a thermocouple is attached to every turn on the evaporator. Relative humidity sensors are installed in the flow zones of the return air and the supply air. To check the validity of the relative humidity sensors, wet-bulb and dry-bulb temperatures are taken at those flow zones. Finally, power readings are taken for the compressor, the fan, and the water pump.

Figure 1 is a refrigerant-side schematic. Figure 2 is a schematic of the hardware components for the HPWH test.

TEST PROCEDURES

First-Hour Rating Test

The first-hour rating test is used to determine how much hot water the heat pump water heater can supply within one hour. The chamber dry-bulb temperature was established at 19.7ºC (67.5ºF) and the relative humidity was set at 50%. After these conditions are met, the heat pump is turned on. A draw was imposed when cut-out occurs or when the compressor no longer draws power. The draw is terminated when the heat pump turns on.

Throughout the first-hour rating test, data are saved to a file with a time interval of five seconds between data points. When a maximum mean tank temperature is observed following cut-out, a draw is initiated. At the beginning of this first draw, the time is recorded and used as the elapsed time of zero. Fifteen seconds after the draw is initiated, the water outlet temperature is observed every fifth second until a maximum temperature (T_{max}) is observed. The draw continues until the outlet temperature decreases by 13.9ºC (25ºF). Every time cut-out occurs, a draw is made in the same way as described above. One hour after the first draw is initiated, the heat pump is turned off. At that time a final draw is imposed. This draw is terminated as soon as the outlet temperature has decreased to the cut-off temperature used for the previous draw.

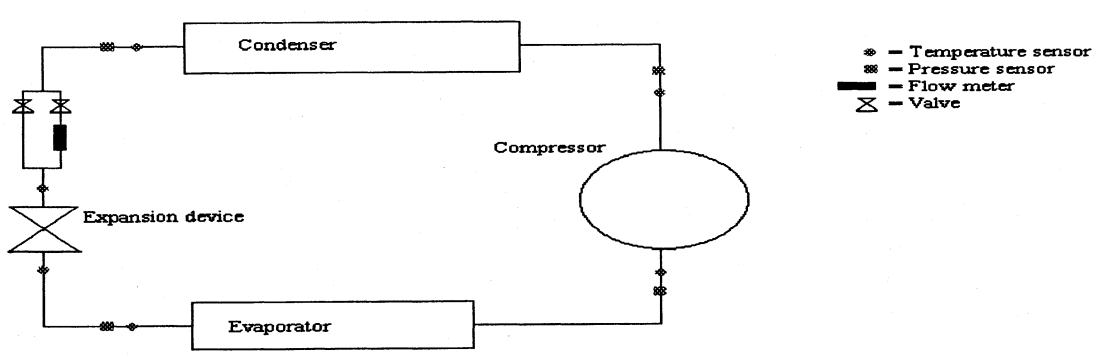

Figure 1 *Refrigerant-side schematic.*

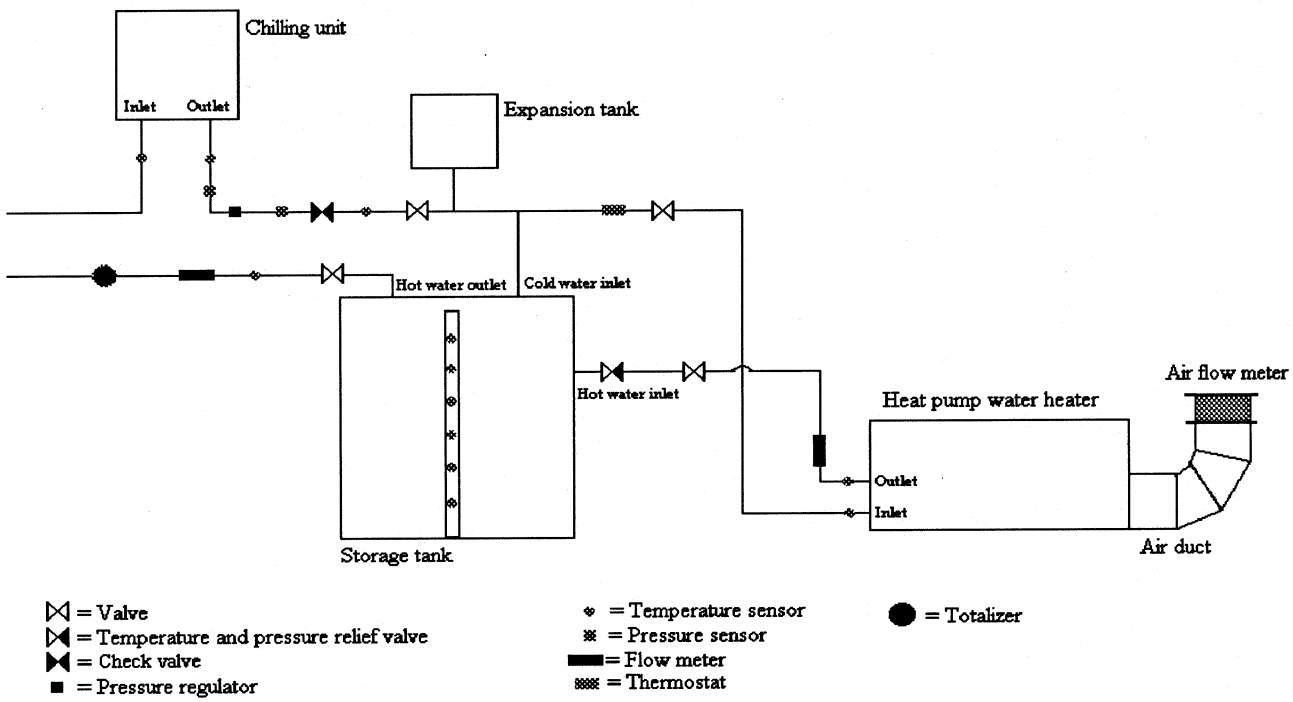

Figure 2 *Hardware schematic.*

In order to compare the R-407C HPWH with the R-22 unit with the same capacity, this test was also ran with the following ambient conditions: the dry-bulb temperature was set to 23.9ºC (75ºF) and the relative humidity was set to 51.6%. These were the test conditions the manufacturer used to test their R-22 units. One hour after the first draw was initiated, a final draw was made. This final draw was terminated when the outlet temperature had decreased by 13.9ºC (25ºF) from the maximum temperature observed at the beginning of the test.

24-Hour Simulated Use Test

During the 24-hour simulated use test, a total of 243.4 L ± 3.8 L (64.3 gal ± 1 gal) is to be withdrawn from the tank. This amount of water is referred to as the daily hot water usage.

Water will be withdrawn six times with a time interval of one hour between each draw. During each draw, one-sixth of the 243.4 L (64.3 gal) shall be removed, that is, 40.6 L (10.7 gal) with a maximum deviation of 1.9 L (0.5 gal). The amount of water being withdrawn during the last draw shall be increased or decreased so that the total volume that has been withdrawn during the test equals a quantity of 243.4 L ± 3.8 L.

Before the test can begin, the room humidity must be set according to the test standards, i.e., the dry-bulb temperature should be established at 19.7ºC (67.5ºF) and the relative humidity at 50%. With the heat pump turned off, the tank is filled with supply water, i.e., water having a temperature between 13.3ºC and 15.5ºC (56ºF and 60ºF). After the tank is filled, the heat pump is turned on. When the thermostat turns off the heat pump, a draw is initiated. The draw is terminated when cut-in occurs, i.e., when the heat pump is turned on by the thermostat. During the first 6 hours of the 24-hour test, data were saved to a file every five seconds.

When cut-out occurs, one-sixth of 243 L (64.3 gal) is withdrawn. At the beginning of the draw, the time is recorded and assigned as the test elapsed time of zero. When one hour has elapsed, another one-sixth of the 243 L (64.3 gal) is withdrawn. This procedure is repeated every hour until a total amount of 243 L (64.3 gal) has been withdrawn from the tank. The volume that is removed during each draw is determined by recording the figures on the totalizer at the beginning and end of every draw. After the recovery period following the sixth draw, the heat pump water heater is left in standby mode. From this time until the end of the 24-hour test, data are recorded every 30 seconds. On the twenty-third hour, the heat pump is turned off in order to prevent the heat pump from beginning a recovery cycle during the last hour of the test.

However, if the heat pump is performing a recovery cycle when the elapsed time reaches the twenty-third hour, the heat pump is allowed to proceed with the recovery and is turned off when cut-out occurs. At the elapsed time of 24 hours, the test is complete.

Baseline Test Results

The first-hour rating test and the 24-hour simulated use test were ran several times and compared to determine the repeatability of the data. The COP of the first-hour rating test, based on refrigerant-side measurements, was calculated as an

averaged value during the recovery period between the first and second draw.

It was found that the system was undercharged at the beginning, which caused a false refrigerant flow rate reading because of the bubbles in liquid refrigerant flow. The heat pump in this project was originally designed for R-22 but was charged with R-407C according to manufacturer specifications for R-22, i.e., the system was charged by weight with the same amount of R-407C as the manufacturer specified for R-22. The refrigerants R-22 and R-407C are very close in their behavior, but the charge should not be the same. The density of R-407C is about 5% lower than that of R-22, which means the system should be charged 5% less with R-407C. Also, additional tubing for instrumentation requires more refrigerant charge too.

When the unit is running, the water gets warmer, which causes the condensing pressure and condensing temperature to increase. Because of this, the heat pump never reaches steady state and this makes it difficult to compare the unit with other units. Instead, a test similar to the one the manufacturer performed when the unit was charged with R-22 was done. The tests were performed with a wet-bulb temperature of 18.3ºC (65ºF) and a dry-bulb temperature of 23.9ºC (75ºF) (heat pump manufacturer's test conditions). The water in the tank was chilled to 21.1ºC (70ºF), then the heat pump was operated until the water in the tank had reached a temperature of 51.7ºC (125ºF). The data from this test were compared with the system performance of R-22 in the same kind of HPWH. Figures 3 and 4 show the comparisons for heat pump COP and water heating capacity.

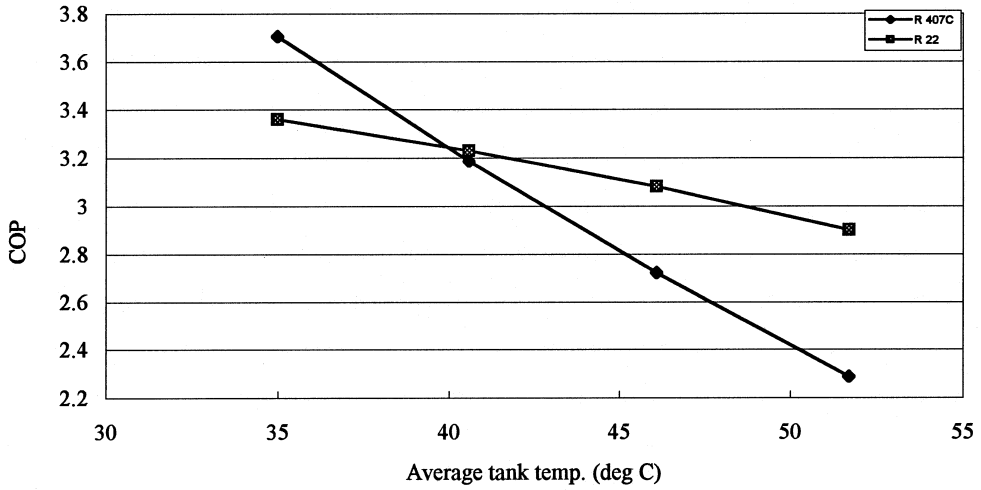

Figure 3 *Water heating COP, R-407C baseline vs. R-22 (at manufacturer's test conditions).*

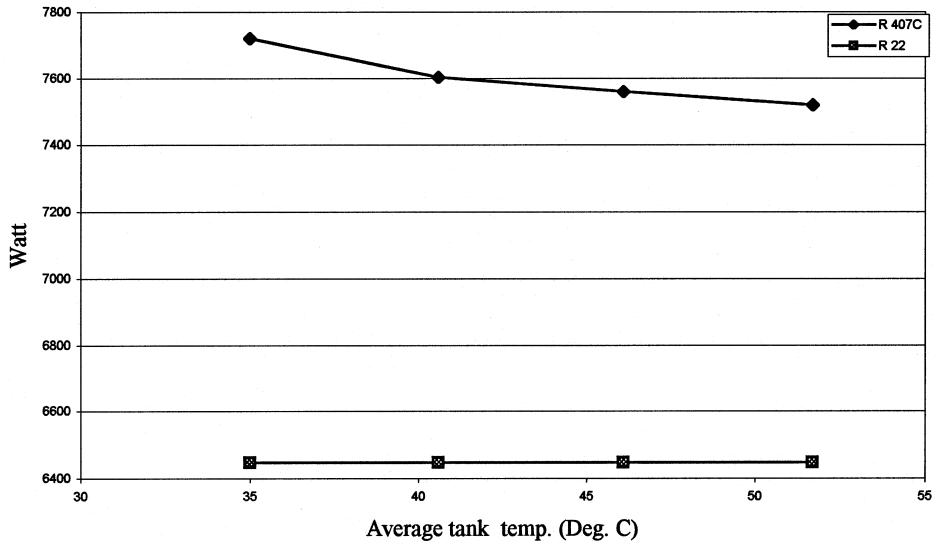

Figure 4 *Heating capacity, R-407C baseline vs. R-22 (at manufacturer's test conditions).*

COUNTER-CROSS-FLOW EVAPORATOR TESTING

Setup and Test Conditions

Prior to the second phase of testing, a counter-cross-flow evaporator was installed to take advantage of the temperature glide present in the R-407C. The original evaporator was a three-row coil with three passes. One pass was counterflow, one was right in the middle, and one was in parallel flow. The new evaporator was a four-row coil with four passes but with the same frontal area. From the previous experience on an R-407C air conditioner computer simulation, it was found that the effect of temperature glide would be marginal for a three-row coil. The results would be much better for a four-row coil. Therefore, a four-row coil was used. Otherwise, the unit was left exactly as it was for baseline testing.

Discussion of Test Results

As expected, the unit responded well with the counter-cross-flow evaporator installed. An increase in heating-side capacity and in the coefficient of performance over the baseline test results was observed. A comparison of the counter-cross-flow evaporator and the baseline capacity is illustrated in Figure 5.

A comparison of the baseline and counter-cross-flow evaporator coefficients of performance is shown in Figure 6. According to Figure 5, the increase in capacity varies with the mean tank temperature. The increase in the coefficient of performance, however, is approximately 20% over the operating temperature range of the heat pump.

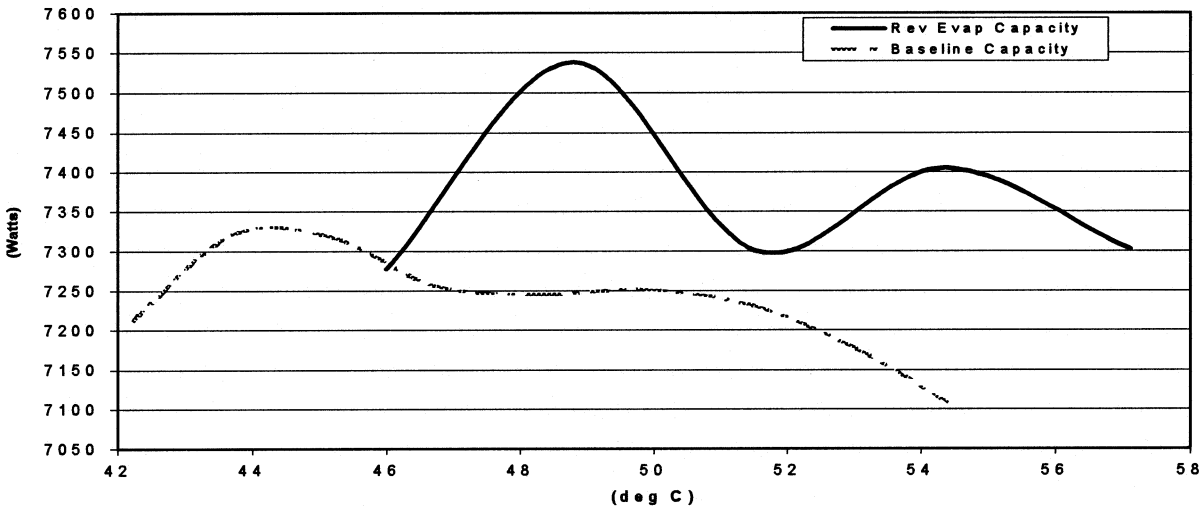

Figure 5 *Capacity, baseline vs. counter-cross-flow evaporator (at federal standard test conditions).*

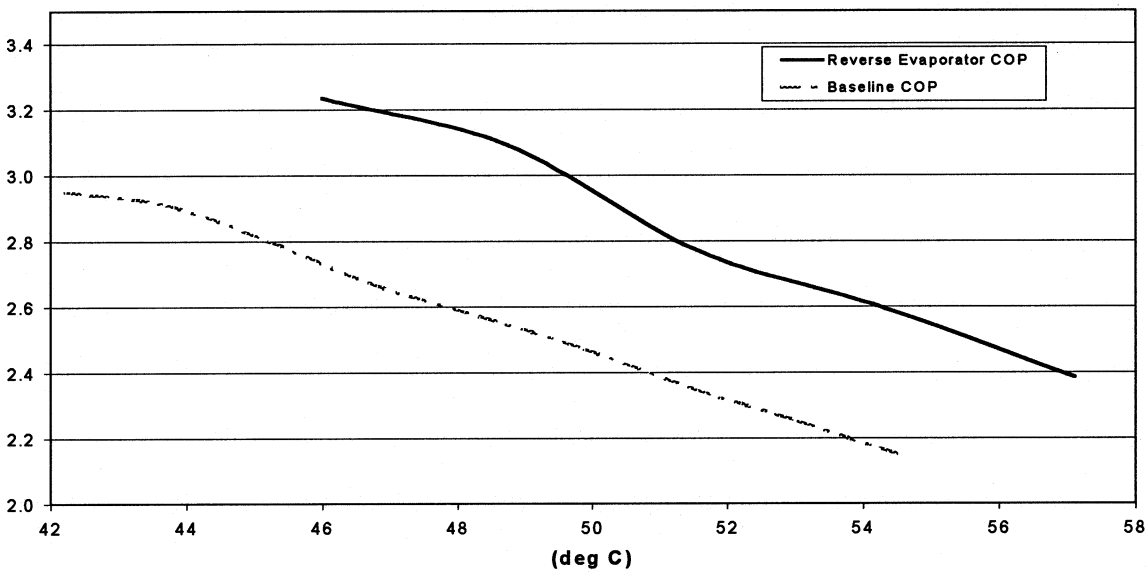

Figure 6 *COP, baseline vs. counter-cross-flow evaporator (at federal standard test conditions).*

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this project was to investigate the viability of R-407C in replacing R-22 in the existing heat pump water heaters with improved system performance. The conclusions that can be drawn when comparing these tests with the tests performed by the manufacturer are that both the heating capacity and the energy consumption are higher when using R-407C. The heating capacity is higher due to the higher condensing pressure, which also causes the energy consumption to increase.

However, when the HPWH was modified with a counter-cross-flow evaporator, the system performance improved. The COP increased by almost 20% over the baseline case and is equal to, or slightly better than, that of R-22 over the water temperature range of 35ºC to 52ºC (95ºF to 126ºF). (R-22 system test data were provided by the heat pump manufacturer. Manufacturer's test specification called for an ambient temperature of 75ºF and the federal test standard called for an ambient temperature of 67ºF). The average heating capacity also improved by about 0.29 kW (1000 Btu/h) at 50.6ºC (123ºF), an improvement of 4%. The average COP actually is higher than that of R-22, except at very high tank water temperature. The test data indicated that it is feasible to replace R-22 with R-407C in HPWH application. It is also obvious that the future design of R-407C HPWHs should have counter-cross-flow evaporators.

ACKNOWLEDGMENTS

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