A Study of a Natural Convection Immersed Condenser Heat Pump Water Heater

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ABSTRACT

This study reports the finding of an energy-efficient heat pump water heater with no water pump. The condenser is directly inserted into the tank for water heating purposes. An experimental setup of a direct exchange vapor compression heat pump water heater was used to test and characterize several immersed condenser styles in a simulated domestic water heater. The condensers were of two primary designs—bayonet style with annular flow and U-tube style. A nominal 1-ton heat pump was affixed to an insulated 55-gallon water tank in such a way that the condenser, which was immersed in the water tank, could be easily changed. Tests were performed with eight types of condensers: one circuit, two circuit and three circuit bayonet, and three through seven circuit U-tube styles. The circuits were connected in parallel. Because of the double-wall requirement, outer tube with rifle lines were used, and smooth inner tubes were adopted. The rifle lines served as the vent channels in case there was a crack of the inner tubes. Each of the eight condenser configurations was tested by using the heat pump to heat 460 pounds of water from a starting temperature of ~57°F (14°C) up to a final temperature of at least 130°F (54°C). A variety of measurements were taken both within the water tank and throughout the heat pump in order to chart relative performance. The straight vertical geometry of the single-circuit bayonet condenser caused temperature stratification within the water tank. The other seven styles had non-vertical components and caused no discernable stratification because the non-vertical section of the condenser provided enough convective heat transfer to break the water thermal stratification. This non-vertical copper tube configuration should not be difficult or expensive to manufacture. Current design without a water pump is a major improvement over the current heat pump water heaters (HPWHs) because a major moving part has been eliminated. The U-tube style condensers generally outperformed the bayonet condensers as judged by the heating coefficient of performance (COP) as a function of average water temperature. As well, COP and heating capacity increased as a function of the number of circuits in the U-tube style condensers, with the seven-circuit style maintaining a COP of 2.7 and a capacity of 12,500 Btu/h (3,662 W), with an ambient air temperature of 80°F (27°C) and an average water temperature of 130°F (54°C) as in the literature for enclosed parking garages.

INTRODUCTION

There are two primary types of residential potable water heaters that see widespread use in the American market: direct fuel fired and electric resistance. Direct-fired water heaters may be fueled from natural gas lines, stored fuel oil, liquefied petroleum gas (LPG), or liquefied propane. Nationwide, sales of fuel-fired water heaters hold a slight majority with ~54% of the market, with the remaining 46% being almost entirely electric resistance units. In the year ending in December of 2000, just over 9.2 million total residential water heaters were sold, approximately 2,000 of which were heat pump water heaters (AMO 2000; Nisson and Shepard 1994; EIA 1997).

Heat pump water heating finds greater use in tropical climates where limited seasonal temperature variations promote year-round energy savings. Hawaii has the largest U.S. market for residential HPWHs, in part because of its favorable weather, but also because of the high cost of energy owing to its heavy dependence on non-native fossil fuels. Hawaii is 90% dependent on petroleum for its energy needs, all of which is imported (HD 2000), which results in high elec-

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tricity costs and making all traditional methods of water heating expensive. The federal government, in particular the military, has in the past been a significant purchaser of HPWHs; they were commonly installed in military barracks, again particularly in Hawaii.

Heat pump COP, a measure of efficiency by dividing the amount of energy used in water heating with the total power consumption, is intimately tied to the absolute temperature lift between the evaporator and the condenser. In any domestic water heat pump application the minimum high side water temperature is between 130°F and 140°F (54°F and 60°C), necessitating an average condensing temperature on the order of 150°F to 160°F (66°C to 71°C). Using the U. S. Department of Energy standard rating air conditions for heat pump water heating—67°F (19°C)—there is a 63°F to 73°F (17°C to 23°C) temperature lift (Federal Register 1998). This is higher than that of a space-heating heat pump, which may see typical temperature lifts on the order of 45°F to 55°F (7°C to 13°C). The Carnot efficiency of a heat pump (highest theoretical efficiency) is given by this formula:

$$COP_{CARNOT} = T_C / (T_C - T_E) \quad (1)$$

where

T_C = heat sink temperature (K)

T_E = heat source temperature (K)

For a theoretical HPWH operating to heat water to 140°F (60°C) from air at 67°F (19°C), the COP_{CARNOT} equals 8.2, whereas the temperature constraints on a theoretical home heating heat pump, with a 55°F (13°C) temperature lift, yield a COP_{CARNOT} of ~10.1. Although these theoretical COPs are unattainable, they offer insight in that a machine can be built to operate at some percentage of Carnot COP, and thus the lower the Carnot COP, the lower the actual operating COP. Because the Carnot COP is a consequence of thermodynamics, the only recourse when trying to achieve a high operating COP is to build a machine that has as few losses as possible. There are limits to what can be done on this front, and generally, marginal improvements come with added cost.

Several past and current styles of HPWH use a pump to circulate water from the storage tank through the heat pump condenser. Present models either pump water from the storage tank through a water to refrigerant heat exchanger or wrap the condenser around the outside of the water tank (this style does not use a pump). The design currently under study seeks to eliminate the pump by directly immersing the condenser through a port in the top of the storage tank, and it will be able to be installed without major changes to tank manufacturing techniques. A report by Slone et al. (1979) provided information about the test of an integrated condenser heat pump water heater with a finned condenser coil in the middle of the tank. The performance data indicated that at the water tank temperature of 80°F, the heat pump COP was 2.4 at 75°F ambient. Our laboratory test of the current immersed condenser unit showed COPs of 4.0 and 4.5 at 80°F tank water temperature and at 67°F and 80°F ambient, respectively, with R-22 as the

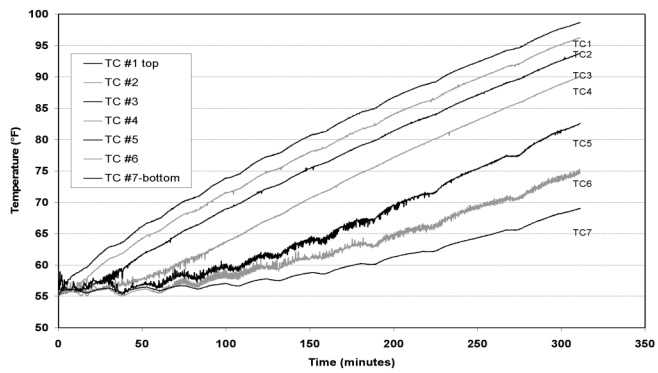

Figure 1 *Tank stratification with a vertical 7/8 in. ϕ tube-in-tube condenser.*

refrigerant (R-134a is currently used). It is clear that ORNL's current immersed condenser design performed better. However, the performance difference could be due to better compressor and heat exchanger design. After all, the other unit was built 23 years ago. The major difference between the current and previous direct immersion condenser designs is that previous design required taking off the tank top in order to install the immersion condenser. Current design just inserts the condenser coils through the opening on the top of the water tank, which is much simpler. An HPWH design that incorporates an immersed condenser could potentially be less expensive than present models because of the elimination of the pump and associated piping and because of ease of installation.

In initial testing, it was shown that a condenser style with a vertical component only would produce temperature stratification within the tank, regardless of heat flux, within the range of testing. In that setup the heat flux from the condenser had an approximate maximum of 20 Btu/h · in^2 (8,920W/m^2). Figure 1 is an example of the stratification caused by a vertical condenser. The tank starts at a uniform temperature of ~57°F (14°C) and shows continuous temperature divergence from the tank bottom to tank top to where a 30°F (17°C) difference exists by the time the highest water temperature—top of the tank—reaches 98°F (37°C).

The refrigerant condensing temperature naturally adjusts itself to an unnecessarily high temperature because of the condenser contact with the hot water at the top of the tank. When temperature stratification occurs, the heat pump is prematurely forced to operate in adverse conditions, dictated by the hottest water temperature. If the tank is evenly mixed, the total energy in the tank does not change, but the hottest temperature is lower, and the heat pump thus runs at a more efficient state. The need to eliminate the penalty of temperature stratification motivated the present work on condensers with non-vertical components.

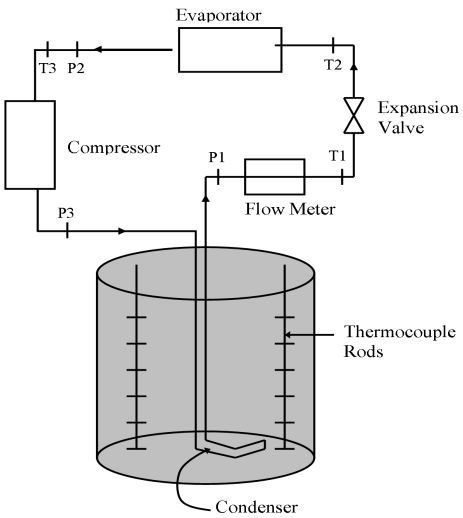

Figure 2 *Schematic of open tank test stand.*

TEST SETUP

An insulated stainless steel tank of nominal 55-gallon capacity was fitted with a test stand heat pump, whose condenser could be easily interchanged. The heat pump consisted of a nominal 11,000 Btu/h (3,223 W) reciprocating hermetic compressor, a 1.5 ton thermostatic expansion valve, and a 1.5 ton five-circuit finned tube evaporator. The water tank was instrumented with twin parallel columns of thermocouples at a radius of three inches and six inches, respectively. Each column had seven thermocouples spaced at four-inch intervals, spanning the height of water to within one inch of the top and bottom. Thermocouples were placed at the refrigerant entrance and exit of each component of the heat pump, and pressure transducers measured compressor suction and discharge pressure, liquid line pressure, and evaporator inlet pressure. Compressor and fan power was measured continuously with a watt transducer. All the condenser coils were connected in parallel.

The entire test stand was placed inside a controlled environmental chamber and tests were performed at both 67°F (19°C)/50% RH and 80°F (27°C)/50% RH ambient air conditions. With a particular condenser installed, the water tank was filled with 460 pounds of water at approximately 57°F (14°C). Data collection—at 15-second intervals—was started and the compressor and fans were switched on. Data were collected for the duration of the test, which was ended when all of the 14 water tank temperatures were above 130°F (54°C). Figure 2 shows a picture of the water heater heat pump test stand.

Bayonet condensers (a bayonet condenser is a tube-in-tube condenser) were constructed of ½ in. soft copper tubing surrounding an internal ¼ in. copper hot gas line. Hot gas flows from the compressor through the ¼ in. inner tube to the bottom of the condenser where the condensing refrigerant then flows back out of the condenser through the annular region formed between the two tubes. In the two- and three-circuit designs, an appropriate entrance head and exit manifold were used to distribute refrigerant to the various circuits.

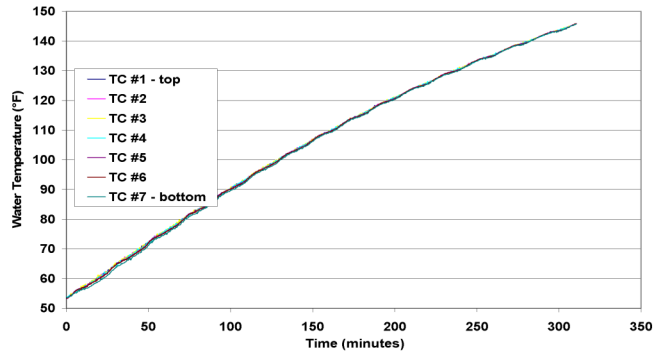

Figure 3 *Vertical water temperature profile with a non-vertical bayonet condenser.*

U-tube condensers were constructed of ¼ in. soft copper tubing, each circuit of which was approximately 12 feet in total length. Seven circuits in all were combined with refrigerant distributors to form the condenser. The package of circuits was bent into a half-turn of a helix with a hockey stick bend at the bottom. (This geometry was chosen because it is possible to insert it into a 2 in. opening on the top of a standard 60-gallon water heater.) Both non-vertical bayonet tube condenser and non-vertical U-tube condensers were tested.

Results of Testing

All condenser designs that had a non-vertical component, both bayonet and U-tube, showed no discernable temperature stratification; this is in contrast to the 30°F or greater top to bottom stratification noted with a purely vertical condenser as seen in Figure 1. Figure 3 shows water temperature profile versus time for the three-circuit bayonet condenser. The seven thermocouple readings are those of the outermost vertical dip-tube, located at a radius of six inches. At no time is the difference between any two of the temperatures greater than ~2°F (1.1°C). This is the case for all seven non-vertical condenser styles.

Heating capacity for each of the five U-tube tests and two bayonet tests is shown in Figure 4. In each case, evaporator inlet air conditions were held constant for the duration of testing at 67°F (19°C) DB and 50% RH. Additional tests at 80°F (27°C) ambient air conditions, for which results are described later in the paper, were also performed. Heating capacity, with all else held constant, is dependant on the average water temperature, since the water in this case is the high-temperature heat sink. For the U-tube cases, heating capacity is generally higher across the board for a higher number of condenser circuits. There is, however, a larger jump in capacity from three circuits to four than between any other successive jump. At 130°F (54 °C) water temperature, the seven-circuit condenser produces approximately 9,800 Btu/h (2.87 kW) and the four-circuit condenser produces 8,800 Btu/h (2.57 kW).

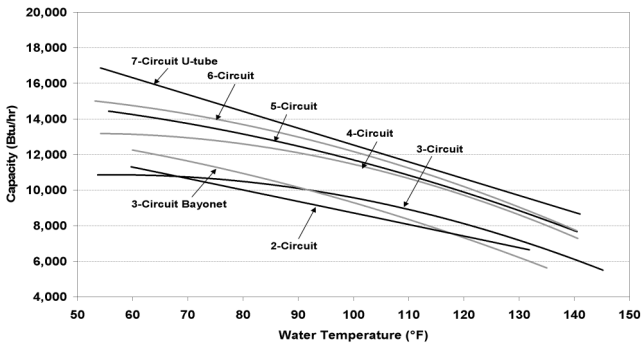

Figure 4 *Heating capacity vs. water temperature (67°F/ 50% RH ambient air conditions).*

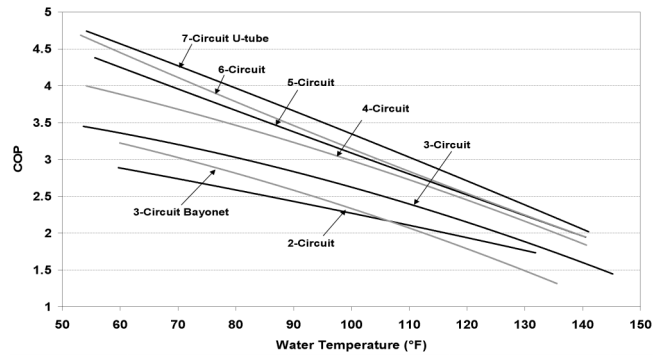

Figure 5 *Coefficient of performance vs. water temperature (67°F/50% RH ambient air conditions).*

The three-circuit bayonet condenser produces ~7,200 Btu/h (2.11 kW) and the two-circuit produces 6,200 Btu/h (1.82 kW) at 130°F (54°C) water temperature.

Heating COP follows much the same pattern as heating capacity in that larger numbers of condenser circuits for a respective condenser style give rise to higher COPs. Results of COP as functions of average water temperature are seen in Figure 5. Again, there is a larger step in COP between the three and four circuit U-tube tests than between any other successive step, indicating that use of more than four to five circuits may give rise to diminishing returns. COPs for both of the bayonet tests are at or below the corresponding levels for the three-circuit U-tube test and drop below 2.0 between 120°F and 130°F (49°C – 54°C).

Figures 6 and 7, respectively, show COP and heating capacity for the four-circuit U-tube condenser at two ambient air conditions—67°F and 80°F (19°C and 27°C)—both at 50% RH. At 80°F (27°C) ambient conditions, COP is approximately greater by 0.3, which is a 13% increase at 130°F (54°C) water temperature. As well, heating capacity increases by 2,000 to 3,500 Btu/h when ambient air is at 80°F (27°C) versus 67°F (19°C). At 130°F (54°C) water temperature the capacity increase is ~3,100 Btu/h (0.99kW), or 29%.

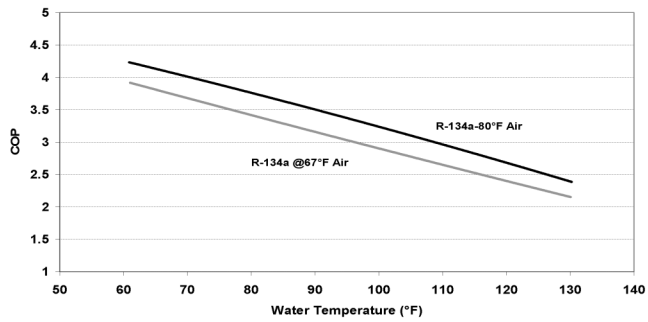

Figure 6 *COP vs. average water temperature for a four-circuit U-tube condenser.*

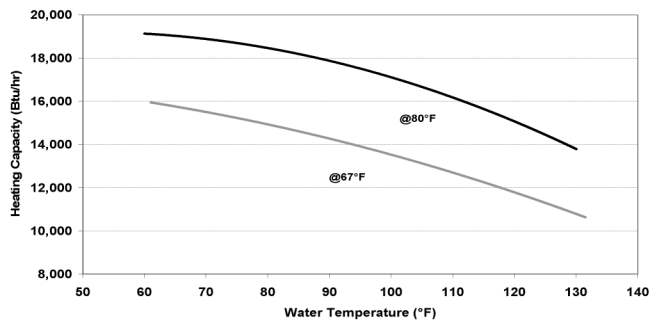

Figure 7 *Heating capacity vs. water temperature for a four-circuit U-tube condenser.*

DISCUSSION AND CONCLUSIONS

As mentioned in the introduction, achieving high operating COPs in a heat pump water heater is more difficult than in an equivalent home heating heat pump. This is primarily due to the higher temperature lift required for heating water to a usable temperature (130°F to 140°F or 54°C to 60°C). The required temperature lift puts constraints on the maximum theoretical efficiency, which in turn places limits on the operating efficiency. Figure 8 shows heat pump COP as a percent of theoretical COP, as a function of water temperature for air at 67°F and 80°F (19°C and 27°C). It shows the difficulty of approaching the theoretical values of efficiency. The reason for the percentage to go up at higher tank water temperature is because the values of the theoretical COP drop. At 80°F ambient and 80°F water temperature, for example, the theoretical COP is infinite, which makes the percentage 0.

The required temperature differences between the heat exchangers and their respective heat reservoirs—air for the evaporator and water for the condenser—are a primary source of efficiency loss. In any heat exchange process, there must be a temperature gradient to cause heat flow. In a typical home heat pump, the heat exchange coils operate with approximately 10°F to 15°F (6°C to 8°C) of separation—commonly called delta-T. The level of delta-T is a function of many parameters including the heat source/sink fluid (air or water), the geometry and structure of the coil, and the regime of heat transfer (natural or forced convection). For air-to-air heat pumps and water pump-assisted heat pump water heaters, the

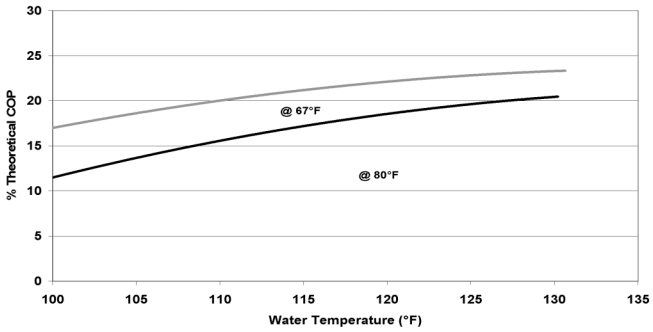

Figure 8 *Percent of theoretical COP at 67°F and 80°F ambient air conditions.*

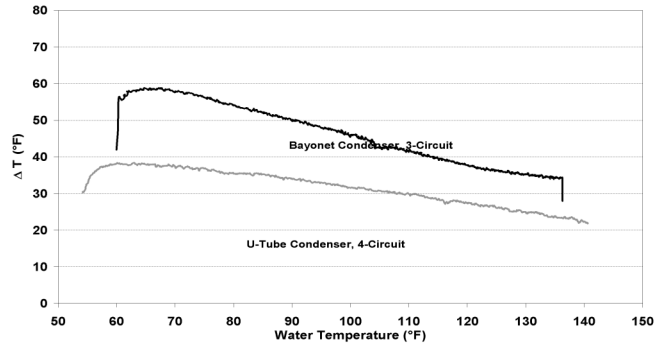

Figure 9 *Comparison of high side ΔT vs. water temperature (67°F/50% RH ambient air conditions).*

heat transfer regime is forced convection. The current system has a forced air evaporator and a natural convection condenser.

Values for heat transfer coefficients for a particular fluid are typically ten times higher for the forced convection regime as compared to the natural convection regime. However, values within a regime are on the order of ten times higher for liquids compared to gases. So while the current design loses ground by having a natural convection condenser, those losses are in large part mitigated because the heat sink is water.

Figure 9 shows approximate condenser-side delta-T for the four-circuit U-tube and three-circuit bayonet condensers. These two geometries have approximately the same immersed surface area. The delta-T is calculated by subtracting the instantaneous average water temperature from the refrigerant saturated temperature. The saturated temperature is calculated from the average high-side pressure as measured at the inlet and outlet of the condenser. In both cases the delta-Ts are higher than what is typical for a similar forced convection system, but the U-tube performance is within reason. The higher delta-T at lower water temperatures corresponds to higher heating capacities. The bayonet condenser shows a substantially higher delta-T at a corresponding water temperature, but it is difficult to pinpoint why. In both cases, the internal refrigerant dynamics are not known, nor are the lengths of the desuperheating, condensing, and subcooling regions. Because these regions are not identified it is difficult to gauge the local heat flux at particular points on the condenser. The bayonet condenser presents an additional twist in that heat is presumably exchanged internally, between the entering hot gas and the exiting subcooled liquid. This may cause an effect similar to stratification where the heat pump is tricked into operating at a higher than necessary condenser temperature.

The heat pumps employing U-tube style condensers generally outperformed those employing bayonet condensers in terms of heating capacity and heating COP. The bayonet heat exchanger, although it under-performed, showed promise by maintaining COPs above 1.5 for all but the highest water temperatures. To get full performance from the bayonet style, further work needs to be done to understand more fully the internal dynamics of the condensing refrigerant. Both condenser styles were made to fit through a two-inch opening on the top of a residential domestic water heater. It was shown that with a relatively simple and compact heat pump, efficiencies of 2.0 to 2.5 could be reached at 67°F (19°C) ambient, with heating capacities meeting or exceeding an equivalent of a 2.57 kW electric resistance heating element even at tank water temperature of 130°F (54°C). Laboratory test data (not shown) indicated that the tank water temperature recovered less than 45 minutes after a draw of more than 10 gallons, as specified by the federal test standard for the 24-hour draw test. This design is aimed to eliminate the application of electric resistant heating completely.

The described set of experiments demonstrated the viability of an immersed condenser, natural convection, heat pump water heater. Aside from the condenser, all parts are off-the-shelf and readily available, and the U-tube condenser is made from standard size copper tubing. Work is ongoing to develop several field test prototypes to prove the concept outside the laboratory.

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