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DEVELOPMENT OF A LOW COST HEAT PUMP WATER HEATER — SECOND PROTOTYPE

May 2007

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Engineering Science and Technology Division

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Abstract

Since the 1980s various attempts have been made to apply the efficiency of heat pumps to water heating. The products generated in the 80s and 90s were not successful, due in part to a lack of reliability and difficulties with installation and servicing. At the turn of the century, EnvironMaster International (EMI) produced a heat pump water heater (HPWH) based on a design developed by Arthur D. Little (ADL), with subsequent developmental assistance from Oak Ridge National Laboratory (ORNL) and ADL. This design was a “drop-in” replacement for conventional electric water heaters. In field and durability testing conducted by ORNL, it proved to be reliable and saved on average more than 50% of the energy used by the best conventional electric water heater. However, the retail price set by EMI was very high, and it failed in the market. ORNL was tasked to examine commercially available HPWH product technology and manufacturing processes for cost saving opportunities.

Several cost saving opportunities were found. To verify the feasibility of these cost saving measures, ORNL completed a conceptual design for an HPWH based on an immersed condenser coil that could be directly inserted into a standard water tank through a sleeve affixed to one of the standard penetrations at the top of the tank. After some experimentation, a prototype unit was built with a double-wall coil inserted into the tank. When tested it achieved an energy factor (EF) of 2.12 to 2.2 using DOE-specified test procedures.

A.O. Smith contacted ORNL in May 2006 expressing their interest in the ORNL design. The prototype unit was shipped to A.O. Smith to be tested in their laboratory. After they completed their test, ORNL analyzed the raw test data provided by A.O. Smith and calculated the EF to be approximately 1.92. The electric resistance heating elements of a conventional electric water heater are typically retained in a heat pump water heater to provide auxiliary heating capacity in periods of high demand. A.O. Smith informed us that when they applied electric resistance backup heating, using the criterion that resistance heat would be applied whenever the upper thermostat saw water temperatures below the heater’s nominal setpoint of 135^{o}F, they found that the EF dropped to approximately 1.5. This is an extremely conservative criterion for backup resistance heating. In a field test of the previously mentioned EMI heat pump water heater, residential consumers found satisfactory performance when the criterion for use of electric resistance backup heating was the upper temperature dropping below the set point minus 27 degrees. Applying this less conservative criterion to the raw data from the original A.O. Smith EF tests indicates that electric resistance heating would never have come on during the test, and thus the EF would have remained in the vicinity of 1.9.

A.O. Smith expressed concern about having an EF below 2, as that value triggers certain tax advantages and would assist in their marketing of the product. We believe that insertion of additional length of tubing plus a less conservative set point for electric resistance backup heating would remedy this concern. However, as of this writing, A.O. Smith has not decided to proceed with a commercial product.

A. Introduction

Since the 1980s various attempts have been made to apply the efficiency of heat pumps to water heating. The products generated in the 80s and 90s were not successful, due in part to a lack of reliability and difficulties with installation and servicing. At the turn of the century, Environmaster International (EMI) produced a heat pump water heater (HPWH) based on a design developed by Arthur D. Little (ADL), with subsequent developmental assistance from Oak Ridge National Laboratory (ORNL) and ADL. This design was a “drop-in” replacement for conventional electric water heaters. In field and durability testing conducted by ORNL, it proved to be reliable and saved on average more than 50% of the energy used by the best conventional electric water heater. However, the retail price set by EMI was very high, and it failed in the market. ORNL was tasked to examine commercially available HPWH product technology and manufacturing processes for cost saving opportunities. In addition, ORNL was tasked to verify the technical feasibility of the cost saving opportunities where necessary and appropriate. The objective was to retain most of the HPWH’s energy saving performance while reducing cost and simple payback period to approximately three years in a residential application.

B. Design Changes

Several cost saving opportunities were found. Immersing the HPWH condenser directly into the tank allowed the water circulating pump to be eliminated and a standard electric resistance storage water heater tank to be used. In addition, designs could be based on refrigerator compressors. Standard water heater tanks and refrigerator compressors are reliable, mass produced, and low cost.

To verify the feasibility of these cost saving measures, ORNL completed a conceptual design for an HPWH based on an immersed condenser coil that could be directly inserted into a standard water tank through a sleeve affixed to one of the standard penetrations at the top of the tank. The sleeve contour causes the bayonet-style condenser to curve into a helix while being pushed into the tank, enabling a condenser of sufficient heat transfer surface area to be inserted.

In a previous report[1], we discussed the first immersed direct heat exchanger (IDX) prototype HPWH, which had a 70-ft, single-wall tube inserted into a 60-gal tank. The report reviewed laboratory tests, which indicated that this HPWH had an EF of 2.02. In this study, a second prototype was built having a condenser coil composed of a 70-ft, double-wall, copper-tube, ½-in.-OD outer tube and 7/16-in. inner tube, inserted into a 66-gal tank. The laboratory test results indicated that it had an EF of around 2.12.

[1] *Development of a Low Cost Heat Pump Water Heater – First Prototype*, ORNL/TM-2007/154, V. C. Mei and J. J. Tomlinson, Sept. 2005.

The new design requires not only that a double-wall coil be inserted into the tank, it also requires that a ¼-in. Teflon tube be inserted into the double-wall coil. Thus it becomes a tube-in-tube heat exchanger, with the Teflon tube serving as the liquid return line. The vapor from the compressor will flow through the annulus region between the copper tube and the Teflon tube. Figure 1 shows the design of the coil inside the tank.

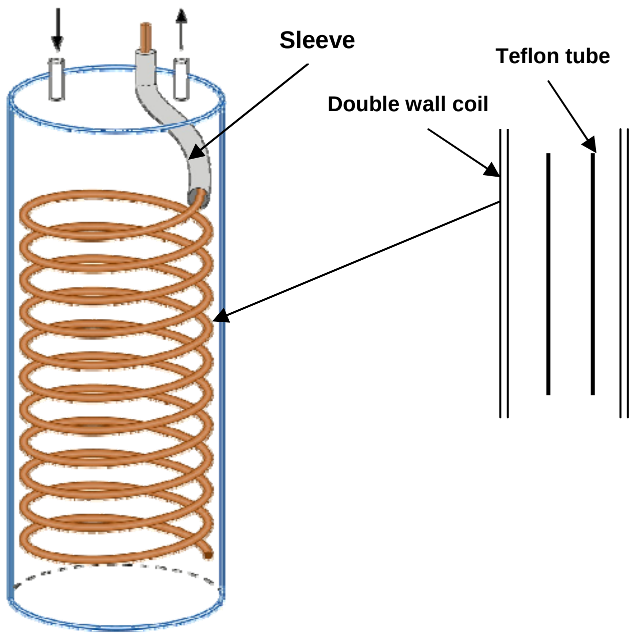

Fig. 1. IDX coil design.

Using soft copper coils provided by Wolverine Tube Inc., a prototype unit with the double-wall coil was built. A total of 70 ft of double-wall coil was inserted into the tank. The heat pump to be mounted on top of the unit was taken from one of the EMI HPWH laboratory test units.

C. ORNL Laboratory Test Results

The initial laboratory testing was funded by the Tennessee Valley Authority (TVA). As mentioned above, one test was conducted with a single-walled tube in a 60-gal tank, and a second test was conducted with a double-walled tube in a 66-gal tank. The tests were performed according to the federal HPWH test standard. The two tests resulted in EFs of 2.10 and 2.20. These results could be further improved by inserting more coil footage into the tank. Figure 2 shows the laboratory test arrangement in a single room environmental chamber.

Fig. 2. HPWH test setup.

Figures 3 and 4 show the water temperature distribution for the first (60-gal) and second (66-gal) tests, respectively, during the 24-hour tests. It is clear that use of a 66-gal tank with an HPWH is preferable. The figures show why: For a 66-gal tank, after 6 draws, the top water temperature was still at 116°F, which would be high enough to take a shower, while the 60-gal tank had dropped to 107°F. With a 55-gal tank, the temperature at the top of the tank would have dropped further. Figures 5 and 6 show the water temperature recovery after 6 draws for both tanks. After 3 hours of heat pump operation (at the 8 hour mark on the figure), the tank water temperature has increased to over 115°F at the top for the 60-gal tank, and to 121°F for the 66-gal tank. After 5 hours of heat pump operation after the end of 6 draws (at the 10 hour mark on the figure), the tank water temperature has completely recovered. For the rest of the test period, the heat pump idled, while the tank slowly lost heat to its surroundings. In an actual home, this heat loss would eventually have been made up by the heat pump.

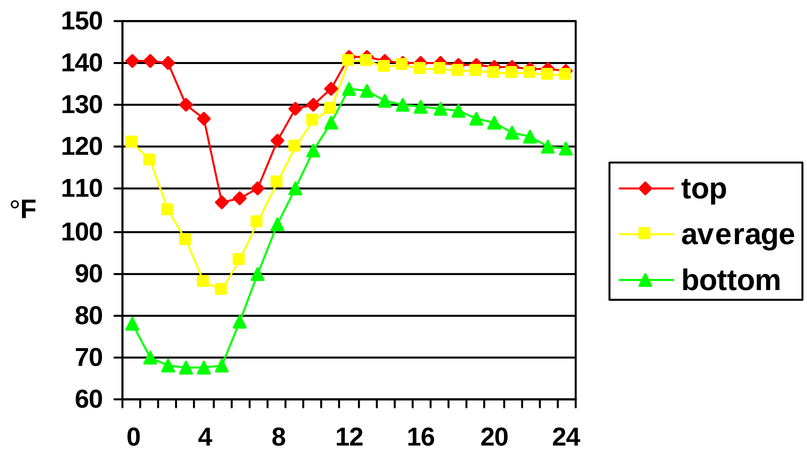

Fig. 3. Water temperature distribution for the 60-gal tank during the 24-hour test.

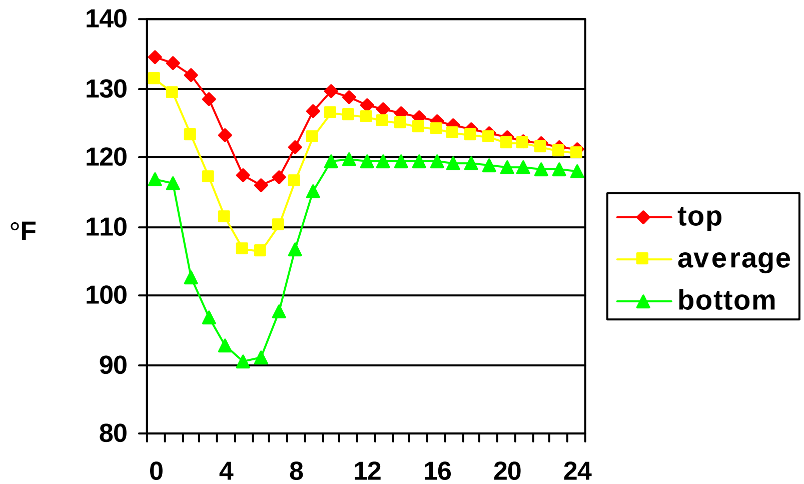

Fig. 4. Water temperature distribution for the 66-gal tank during the 24-hour test

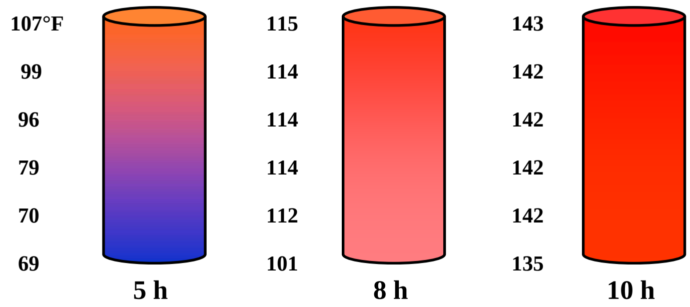

Fig. 5. 60-gal tank water recovery after 6 draws.

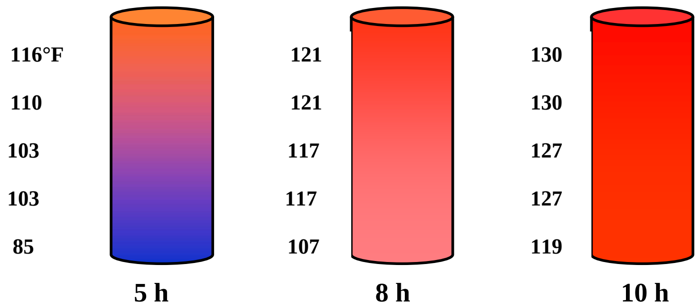

Fig. 6. 66-gal tank water recovery after 6 draws.

D. A.O. Smith Test Results

In May 2006, A.O. Smith contacted ORNL after reading a paper about the IDX HPWH from the 2006 Purdue International Refrigeration and Air Conditioning Conference. A meeting was set for June 26, 2006, with TVA as one participating party. At this meeting, A.O. Smith expressed serious interest in exploring a commercial product based on the low-cost HPWH design. A second meeting was requested by A.O. Smith and held on Sept. 28, 2006. In addition to TVA, Wolverine Tube Inc. was represented at the meeting. A.O. Smith continued to voice serious interest in producing a product. As a first step, they wanted to test the prototype unit at their laboratory. On Sept. 22, 2006, the prototype HPWH was shipped to A.O. Smith for their laboratory testing. On Jan. 19, 2007, their test data was sent to ORNL. ORNL's evaluation of A.O. Smith's raw data yielded EFs of approximately 1.92. ORNL's evaluation was sent to A.O. Smith.

A heat pump is much more energy efficient than electric resistance for heating water, but it is not faster. The electric resistance heating elements of a conventional electric water heater are typically retained in a HPWH to provide auxiliary heating capacity in periods of high demand. A.O. Smith informed us that when they applied electric resistance backup heating, using the criterion that resistance heat would be applied whenever the upper thermostat saw water temperatures below the heater's nominal setpoint of 135 ^{o}F, they found that the EF dropped to approximately 1.5. This is an extremely conservative criterion for backup resistance heating. In a field test of an earlier HPWH, residential consumers found satisfactory performance when the criterion for use of electric resistance backup heating was the upper temperature dropping below the setpoint minus 27 degrees.[2] Applying this less conservative criterion to the raw data from the original A.O. Smith EF tests indicates that electric resistance heating would never have come on during the test, and thus the EF would have remained in the vicinity of 1.9. Figure 7 shows the tank water temperature distribution from the A.O. Smith test performed without resistance heating.

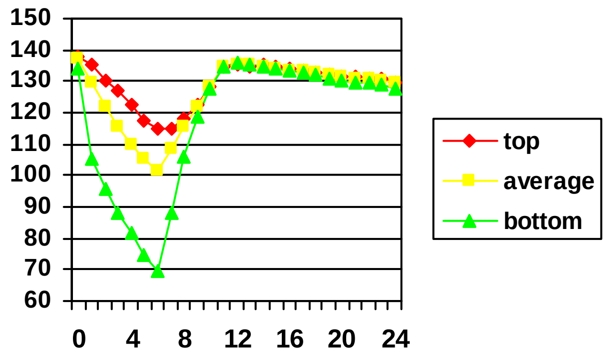

Fig. 7. Water temperature distribution for the 66-gal tank during the 24-hour test (A.O. Smith test data).

According to A.O. Smith, the resistance heating engaged during the fifth water draw. A check of their raw data indicated that the first 4 thermocouples read 122.34, 123.57, 119.05, and 113.68°F, respectively, all of which are higher than 108°F (135 minus 27). The resistance heating element would not have been triggered if the less conservative criterion had been used. Further, the water temperatures just after the sixth draw were 117.71, 118.74, 114.41, and 109.85°F, respectively. Again, the heating element would not be energized with the less conservative criterion. Figure 8 shows the tank water temperature recovery after the sixth draw. The water temperature actually recovered very quickly.

[2] *Field Test of a "Drop In" Residential Heat Pump Water Heater*, Murphy, et al., ORNL/TM-2002/207

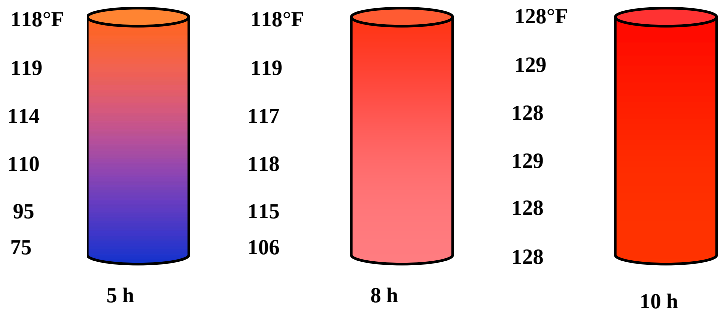

Fig. 8. The 66-gal tank's water recovery after 6 draws (A.O. Smith test data).

E. Conclusions

A design for a low-cost HPWH was devised and a prototype built and tested. A paper was presented at the 2006 Purdue Refrigeration Conference. An A.O. Smith engineer read the paper, after which A.O. Smith contacted ORNL. A.O. Smith expressed interest in exploring the possibilities for a commercial product based on this design. The prototype was shipped to A.O. Smith and they conducted their own tests. These tests indicated energy factors below 2, which is considered by A.O. Smith to be a significant threshold from a marketing perspective (e.g., tax incentives are triggered for EFs at 2 or above). We believe that adding some length to the immersed coil and using a less conservative setpoint for the use of electric resistance backup heating would allow a unit of this design to have an EF equal to or greater than 2. A.O. Smith informed ORNL that they have not decided to proceed to a commercial product, but would probably not make a final decision until later this summer.