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PERFORMANCE ANALYSIS OF DEDICATED HEAT-PUMP WATER HEATERS IN AN OFFICE BUILDING

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NOTICE

PERFORMANCE ANALYSIS OF DEDICATED HEAT-PUMP WATER HEATERS IN AN OFFICE BUILDING

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ABSTRACT

Implementing energy conservation measures in office and light commercial buildings has great potential. This paper evaluates the performance of two generic dedicated heat pump water heaters (HPWHs) in supplying the domestic hot water (DHW) needs of a medium-sized office building in Colorado. The HPWHs are sized for residential use, since no industrial-grade HPWHs were manufactured at the start of the experiment. Results are based on preliminary data measurements, and assumptions are made to compensate for a faulty flow meter. A stand-alone heat pump plumbed to a conventional tank obtains a coefficient of performance (COP) of 2.4 but only delivers load water temperatures of about 41°C (105°F) because of the 15,142 L/day (4000 gal/day) recirculating loop flow. An industrial-grade stand-alone HPWH will replace this unit, and results will be forthcoming. An integral heat pump/tank unit is being tested, but results are not available because of compressor starting problems. Recirculating loop losses account for 75% of the energy delivered by the HPWHs. These losses could be reduced by 75% if the recirculating loop were insulated, thus reducing the DHW fuel costs by 50%. The insulation expense could be paid in less than 3 years by savings in DHW fuel costs.

1. BUILDING AND HVAC EQUIPMENT DESCRIPTION

Two generic dedicated HPWHs are operated singly, for individual performance evaluation, in supplying water to the recirculating DHW system of a 4-story office building. The building houses about 200 office workers of the Solar Energy Research Institute (SERI) in Golden, Colo. The HPWHs use waste heat from a gas boiler and a compressor in an unconditioned top-floor room [58 m x 52 m (19 ft x 17 ft)], which is vented through the roof (see Fig. 1). The boiler* heats water for a closed 4-pipe space heating and cooling system that supplies the building's fan coil distribution units. The compressor operates the pneumatic thermostats. During the cooling season, the HPWHs use warm air that infiltrates from the conditioned space and the outdoors.

One HPWH is an integral unit with a heat pump housed on top a 310-L (82-gal) tank (see Fig. 2). The heat exchanger/condenser is installed in the tank bottom and is connected to the heat pump through the tank top. The other HPWH is a stand-alone heat pump hard-plumbed with flexible copper tubing to a well-insulated 159-L (42-gal) tank (see Fig. 3). Water is pumped from the tank bottom to the heat exchanger/condenser in the heat pump and back to the tank top. In each system, a heat pump extracts heat from the room air and rejects it to the tank water. R-12 is the working fluid in the refrigerant

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*Rated at 2.1 million kJ/hr (2 million Btu/hr) input and 1.7 million kJ/hr (1.6 million Btu/hr) output (adjusted for altitude).

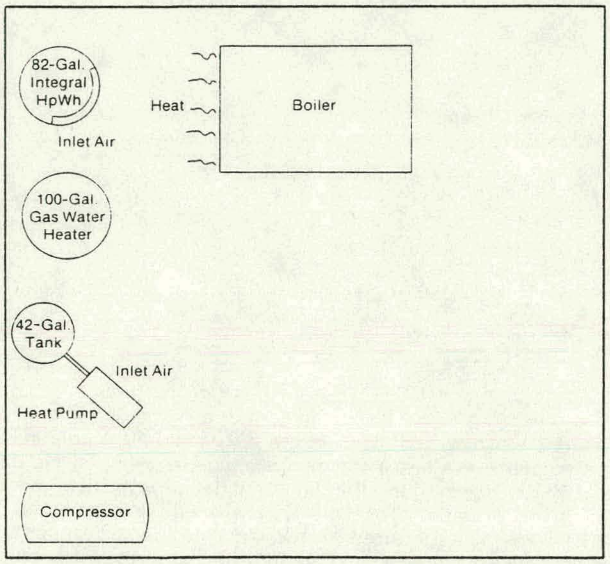

Figure 1. Boiler Room Equipment

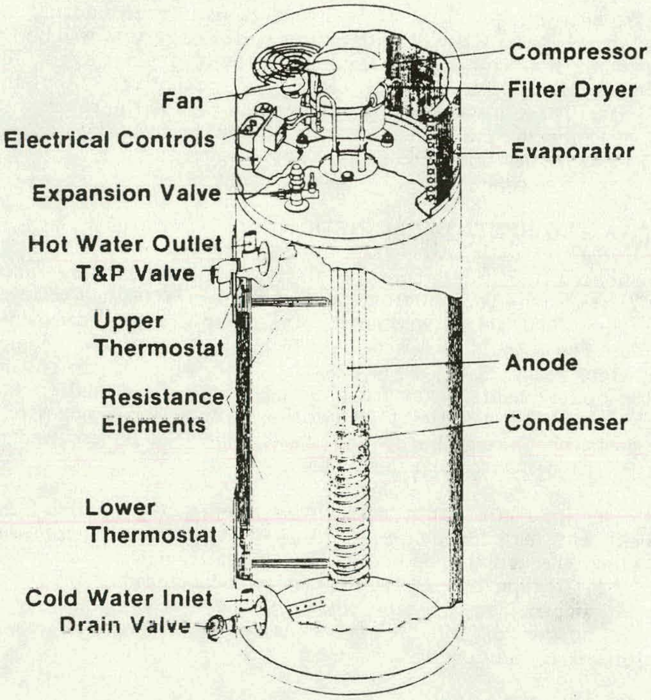

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Figure 2. Integral HPWH

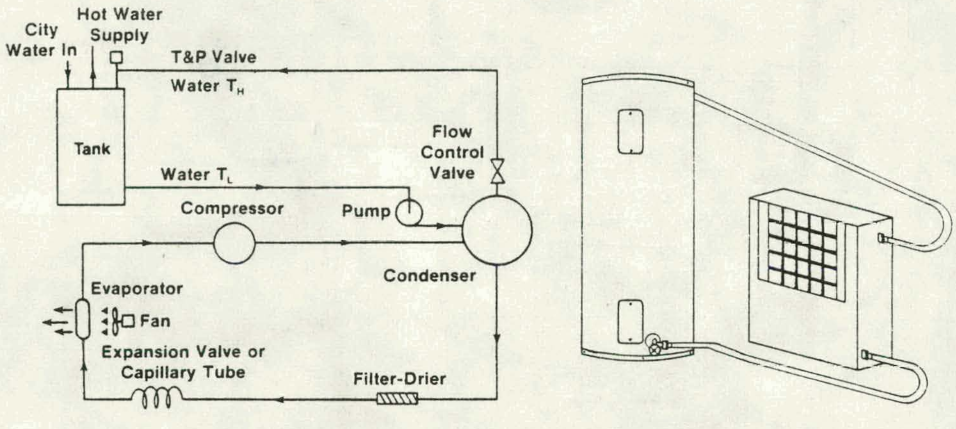

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Figure 3. Stand-Alone HPWH

loop of the integral unit, and R-22 is used in the stand-alone unit. A 208-volt power supply is used with 220-230-volt equipment. The HPWHs are sized for residential applications because no industrial-grade HPWHs were being manufactured at the start of the experiment. The equipment replaces the 379-L (100-gal) gas water heater (see Fig. 4) in supplying the building's hot water needs, which consist primarily of warm water for washing hands. Hot water is also used in small employee convenience kitchens on each floor and after working hours to clean the building. The delivery temperature of the water has been about 71°C (160°F) with gas water heating, but a temperature of 49°C (120°F) would be adequate for most of the building's hot water uses and would reduce the losses of the recirculating loop, tanks, and pipes. Instantaneous electric water heating units provide hot water in some kitchen areas.

This application is of special interest because the building has a large space heating load that creates substantial waste heat and a minimal water heating load. The COP of the HPWH increases as inlet air temperature increases and decreases as inlet and outlet water temperatures increase. In this application the COP is enhanced by the high room air temperature and the low outlet water temperature (relative to residential applications).

An experiment is being conducted to measure the thermal performance of each HPWH in the office building application and to analyze the thermal performance of the recirculating loop. Each can be operated in either heat pump or resistance mode. In resistance mode, the water of the integral HPWH unit is heated by two 2500-W (8532 Btu/hr) resistance elements not interlocked. In heat pump mode, heat pump operation is controlled by a thermostat near the bottom resistance element, and the top resistance element is used to assist fast recovery. The electrical usage of the heat pump alone is about 975 W (3328 Btu/hr). The thermostats are set at 49°C (120°F). In resistance mode, the water of the stand-alone HPWH system is heated by two 4500-W (15,358 Btu/hr) interlocked resistance elements. In heat pump mode, heat pump operation is controlled by a special thermostat near its bottom resistance element. No auxiliary backup is used. About 1260 W (4300 Btu/hr) of electricity are used by the heat pump. When the water drops below 49°C (120°F), water is pumped from the tank bottom, through the heat pump unit, and back to the tank top. This continues until the thermostat registers about 56°C (133°F). A variable flow control valve reduces the water flow, as necessary, to

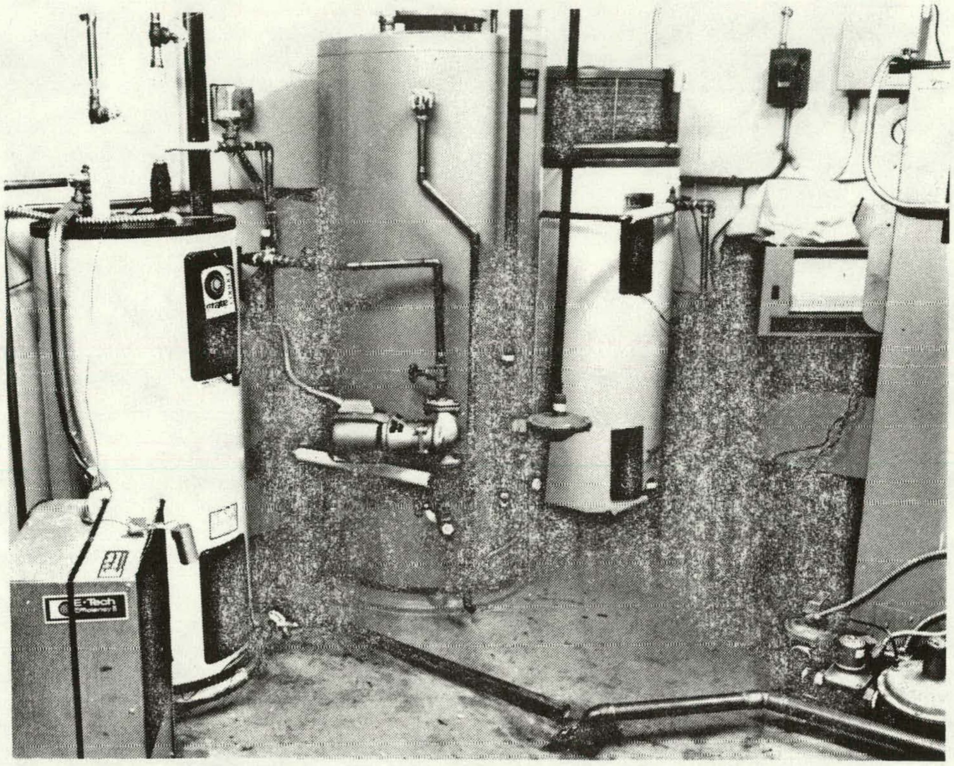


Figure 4. HPWHs, Gas Water Heater, and Boiler

return water to the tank at a minimum of 41° C (115° F). A 62-W (1/12-hp) pump circulates water through the building to supply the DHW load. The pump is installed immediately before the tank and draws water from the loop by suction. A thermostat activates the pump when the water temperature drops below 46° C (115° F).

2. INSTRUMENTATION

Thermocouples are used to measure the cold water supply temperature, the outlet water temperature of each tank, the return water temperature of the recirculating loop, the inlet and outlet water temperatures of the stand-alone heat pump unit, and the inlet air temperature of each heat pump. The cold water supply sensor is installed on the line before it enters the boiler room to prevent radiative and convective heat gain from the boiler room equipment. Check valves and nonconductive plastic pipe are installed in the cold water supply line to the tanks and boiler to minimize nocturnal and weekend conductive heat loss back up the line. Nightly and weekend increases in cold water supply temperature readings occur, nevertheless, because the lack of water draw allows heat conduction in the stagnant pipe water. The air temperature thermocouples are installed with radiation shields to protect them from thermal radiation of the water tanks and boiler and from air currents of the HPWH evaporator fans.

Heat flux transducers are used to measure the heat flow through the tank walls. A transducer is attached on the front of each tank between the insulation and tank skin.

Another, protected by a radiation shield, is attached to the rear tank surface. Front heat loss measurements vary widely in response to boiler cycling and flue drafts. A watt-hour meter measures the quantity of electrical energy used by each system in each mode. In heat pump mode, the integral unit requires electricity for its fan and compressor; the stand-alone unit requires electricity for its fan, compressor, and water pump. Turbine flow meters, with pulse rate/voltage converters, are used to measure the flow rates of the cold water supply line and the recirculating DHW loop. An elapsed time indicator records recirculating loop pump operation. A thermocouple-activated strip chart recorder profiles boiler operation. A 16-channel data logger scans data measurements at an 8 channels/sec rate. Instantaneous and average data measurements are recorded every 5 min.

3. ANALYSIS METHODS

I calculated 24-hour COPs for weekdays (Mon-Fri), as well as separate COPs for the workday period (6:30 a.m.-8:00 p.m.) and for the nighttime period (midnight-6:30 a.m. and 8:00 p.m.-midnight). I also calculated 24-hour COPs for weekend days, but weekly COPs are estimated. HPWH performance differs for these periods primarily because of the minimal hot water usage at night and on weekends. (The circulating loss load is substantial at all times.) The COP of each HPWH is calculated as follows. The quantity of energy delivered to the recirculating loop is

$$Q_{DEL} = M_{SUPPLY} \cdot C_p(T_{OUT} - T_{SUPPLY}) + M_{CIRC} \cdot C_p(T_{OUT} - T_{RETURN}) \quad (1)$$

where M_{SUPPLY} is the mass of water delivered to the load; M_{CIRC} is the mass of water returning to the tank from the recirculating loop; T_{OUT}, T_{SUPPLY}, and T_{RETURN} are the average tank outlet, cold water supply, and recirculating return water temperatures, respectively; and C_p is the specific heat of water. The quantity of energy lost through the tank surface during a period of time t is

$$Q_{LOSS} = h \cdot t \cdot A_s \quad (2)$$

where h is the average of the heat loss rates measured at the front and rear of the tank and A_s is the tank surface area. E_{AUX}, the quantity of electrical energy supplied to the HPWHs' fan, compressor, and pump or resistance element, is calculated from the watt-hour measurements. The COP is

$$COP = \frac{Q_{DEL} + Q_{LOSS}}{E_{AUX}} . \quad (3)$$

Since the average tank water temperature is nearly the same at the beginning and end of each period of data analysis, there is no calculation of the change in internal tank energy.

An estimate of the average temperature of the water supplied to the building taps is

$$T_{LOAD} = \frac{T_{OUT} + T_{RETURN}}{2} . \quad (4)$$

T_{OUT} and T_{RETURN} are averaged during the period 6:30 a.m.-8:00 p.m. (Mon-Fri only), since virtually all of the DHW load occurs during this time. T_{LOAD} is estimated rather than measured because of the many taps in the building. (The water temperature at a tap decreases as its distance from the tank's outlet increases). An estimate of the daily quantity of energy delivered to the load is

$$Q_{LOAD} = M_{SUPPLY} \cdot C_p(T_{LOAD} - T_{SUPPLY}) \quad (5)$$

An estimate of the losses of the recirculating loop is

$$Q_{CIRC} = M_{SUPPLY} \cdot C_p(T_{OUT} - T_{LOAD}) + M_{CIRC} \cdot C_p(T_{OUT} - T_{RETURN}) \quad (6)$$

where the first term is an estimate of the energy lost between the tank outlet and the tap by the water delivered to the load. The second term is an estimate of the energy lost by the water returning to the tank as it passes through the entire recirculating loop.

4. PERFORMANCE RESULTS

Preliminary results are presented for measurements taken in April 1981 immediately following completion of instrumentation. Performance analysis is only given for the stand-alone HPWH because the integral HPWH is experiencing compressor starting problems. Typical weekday and weekend results for the stand-alone HPWH, operating in heat pump mode, are presented in Tables 1-3. Because there is a transition in HPWH performance at the beginning and end of the weekend, weekday results are given for a Tuesday and weekend results are given for Saturday noon to Sunday noon.

Daytime ambient high temperatures are about 23°C (73°F) and nighttime lows are about 7°C (44°F) during the period of data collection. The frequency and duration of boiler operation, and thus waste heat availability, are inverse functions of ambient temperature. The boiler is sized to maintain 20°C (68°F) indoor building temperature at -23°C (-10°F) outdoor temperature with continuous operation. During the period of data collection, the boiler cycling varied from 2.5-min duration every 5 min on colder nights to 1-min duration every 30-45 min on warmer afternoons.

The stand-alone HPWH obtains a COP of about 2.3 at night and on the weekend during periods of time when there is little or no draw. This validates the performance predicted by the manufacturer's literature (see Fig. 5) for the average heat pump inlet air and water temperature of 23°C (73°F) and inlet water temperature of 40°C (104°F). Because of a faulty supply water flow meter, the quantity of water drawn at the taps is unknown. Based on the validation of the manufacturer's performance curves (see Fig. 6) at night and on the weedends, it is assumed that an average of 11,600 KJ (11,000 Btu/hr) of energy are transferred by the heat pump to the water during the Tuesday workday when heat pump inlet air and water temperatures average 23°C (74°F) and 35°C (95°F), respectively. From an energy balance on the tank, it is estimated that approximately 871 L (230 gal) of water were drawn at the taps that day. The resultant calculated workday COP of 2.6 is subject to considerable uncertainty.

On weekdays the stand-alone heat pump operates continuously because the HPWH is sized for residential installation and cannot maintain sufficiently high tank outlet water temperatures. A larger capacity industrial-grade heat pump would facilitate heating the 7570-15,140 L/day (2000-4000 gal/day) recirculating return flow. The 19-mm (3/4-in.) copper tubing of the HPWH restricts the flow of the 25-mm (1-in.) pipe of the recirculating loop. In addition, a valve restricts flow through the stand-alone heat pump unit to 5.7-7.6 L/min (1.5-2.0 gal/min). Since the recirculating flow is about 10.6 L/min (2.8 gal/min), a large amount of water bypasses the heat pump and goes directly to the tank outlet. This water is warmed only by mixing with hot water at the tank top. The average tank outlet water temperature of 39°C (102°F) weekdays is lower than optimum and is lower than the heat pump outlet water temperature of 46°C (114°F) because of the water which bypasses the heat pump. The average tap water temperature near the end of the recirculating loop of 37°C (99°F) on weekdays is even lower. The average outlet water temperature of the heat pump, 46°C (114°F), is approximately the expected design value from its average inlet water temperature of 35°C (95°F). The tank heat loss rate for the stand-alone HPWH is about 23 kJ/hr-°C (12 Btu/hr-°F). Air temperature readings near the tank are 21°-24°C (70°-75°F), and average tank outlet temperatures are 39°-48°C (102°-118°F).

Table 1. STAND-ALONE HPWH OPERATION

Tuesday, April 15

	6:30 am–8:00 pm	Midnight–6:30 am 8:00 pm–Midnight	Daily
Quantity of Water to Load	871 L (230 gal)	0	871 L (230 gal)
Quantity of Water Returning from Recirculating Loop	8483 L (2241 gal)	6677 L (1764 gal)	15,161 L (4005 gal)
Cold Water Supply Temperature	13° C (56° F)	—	13° C (56° F)
Tank Outlet Water Temperature	39° C (102° F)	44° C (111° F)	41° C (106° F)
Recirculating Return Water Temperature	37° C (99° F)	40° C (104° F)	38° C (101° F)
Heat Pump Inlet Air Temperature	23° C (74° F)	21° C (70° F)	22° C (72° F)
Heat Pump Inlet Water Temperature	35° C (95° F)	38° C (101° F)	37° C (98° F)
Heat Pump Outlet Water Temperature	46° C (114° F)	46° C (115° F)	46° C (114° F)
Energy Delivered to Taps	9.0×10^4 kJ (8.5×10^4 Btu)	0	9.0×10^4 kJ (8.5×10^4 Btu)
Energy Delivered to Recirculating Loop	1.5×10^5 kJ (1.4×10^5 Btu)	1.1×10^5 kJ (1.0×10^5 Btu)	2.6×10^5 kJ (2.4×10^5 Btu)
Energy Lost in Recirculating Loop	6.0×10^4 kJ (5.9×10^4 Btu)	1.1×10^5 kJ (1.0×10^5 Btu)	1.7×10^5 kJ (1.6×10^5 Btu)
% of Energy Delivered to Loop that is Lost	42%	100%	65%
Tank Heat Loss Rate	21 kJ/hr-° C (11 Btu/hr-° F)	25 kJ/hr-° C (13 Btu/hr-° F)	23 kJ/hr-° C (12 Btu/hr-° F)
Energy Lost Through Tank Surface	3987 kJ (3784 Btu)	5443 kJ (5163 Btu)	9430 kJ (8947 Btu)
HPWH Electrical Usage Rate	1257 W (4290 Btu/hr)	1260 W (4300 Btu/hr)	1258 W (4293 Btu/hr)
Electrical Energy Supplied to HPWH	6.1×10^4 kJ (5.8×10^4 Btu)	4.7×10^4 kJ (4.5×10^4 Btu)	1.1×10^4 kJ (1.0×10^4 Btu)
HPWH COP	2.6	2.4	2.5

Table 2. STAND-ALONE HPWH PERFORMANCE

Saturday-Sunday, April 11, 12
12:00 Noon - 12:00 Noon

Quantity of Water to Load	0
Quantity of Water Returning from Recirculating Loop	7192 L (1900 gal)
Tank Outlet Water Temperature	48° C (118° F)
Recirculating Return Water Temperature	40° C (104° F)
Heat Pump Inlet Air Temperature	24° C (75° F)
Heat Pump Inlet Water Temperature	44° C (111° F)
Heat Pump Outlet Water Temperature	48° C (118° F)
Energy Delivered to Taps	0
Energy Delivered to Recirculating Loop	2.3 x 10^5 kJ (2.2 x 10^5 Btu)
Energy Lost in Recirculating Loop	2.3 x 10^5 kJ (2.2 x 10^5 Btu)
% of Energy Delivered to Loop that is Lost	100%
Tank Heat Loss Rate	27 kJ/hr- °C (14 Btu/hr- °F)
Energy Lost Through Tank Surface	13,000 kJ (12,000 Btu)
HPWH Electrical Usage Rate	1252 W (4273 Btu/hr)
Electrical Energy Supplied to HPWH	1.1 x 10^5 kJ (1.0 x 10^5 Btu)
HPWH COP	2.3

Table 3. STAND-ALONE HPWH PERFORMANCE

Weekly Performance Results (Estimated)

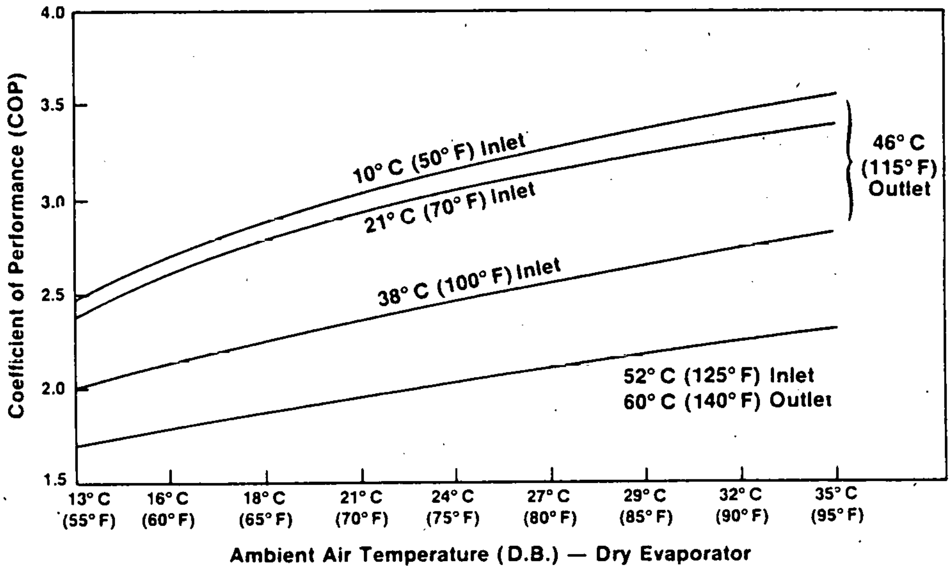
COP	2.4
% of Energy Supplied to Recirculating Loop that is Lost	76%
% of Energy Supplied to Water by Heat Pump and Lost Through Tank Surface	5%

The recirculating loop pump operates almost continuously on weekdays during HPWH operation because the recirculating return water temperatures are below its thermostat set point temperature of 46° C (115° F). The reduction in recirculating flow on the weekend is because of decreased pump operation. Parasitic power consumption would be included in system efficiency calculations if performance comparisons were being made between HPWH and conventional DHW systems.

To comply with building codes, the stand-alone heat pump was hard plumbed to its tank instead of being attached with the supplied nylon hoses. Because of the quantity of dust in the boiler room, it is necessary to periodically clean the heat pump evaporator grills. Both HPWHs are equipped to handle condensate resulting from the dehumidification effects of operation. Because the office building is located in the dry climate of Colorado, condensate is not noticeable.

5. ECONOMIC ANALYSIS

The present nonsubsidized cost of each of the HPWH systems used in the experiment is about $1100-$1200 including tank and installation. HPWH purchases can cost less in demonstration programs and are eligible for tax credits and utility subsidies in some states. An industrial-grade stand-alone HPWH unit with 4 times the capacity of the experimental equipment is now being marketed at a wholesale cost of $2000 without tank or installation.



Source: [2]

Figure 5. COP vs. Ambient Temperature for Stand-Alone HPWH

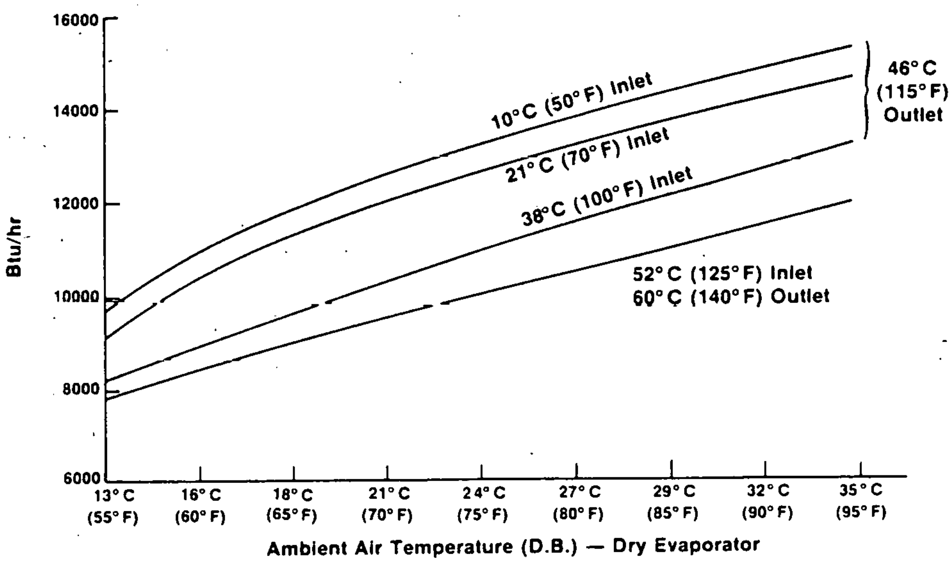


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Figure 6. Heating Rate vs. Ambient Temperature for Stand-Alone HPWH

The gas water heater had been operated with a set point temperature of 71°C (160°F). Recirculating loop losses are greatly decreased by the lowered tank outlet temperatures to the loop. Even so, about 75% of the energy delivered to the loop by the HPWHs is lost; 25% is delivered to the taps. The energy delivered by the HPWHs to the water also includes tank losses, which are about 5% of the total.

When the stand-alone HPWH is operating, the average daily and weekend recirculating water temperatures are 40°C (104°F) and 44°C (111°F), respectively. If an average building air temperature of 32°C (72°F) is assumed, the rates of heat loss of an insulated recirculating loop would be 1839 kJ/hr (1743 Btu/hr) and 2240 kJ/hr (2124 Btu/hr), respectively [3] instead of the measured values of 7032 kJ/hr (6667 Btu/hr) and 9668 kJ/hr (9166 Btu/hr). This represents an approximate by 75% reduction in recirculating loop losses and more than a 50% reduction in the energy required for domestic water heating. The recirculating loop losses benefit the space heating load but penalize the space cooling load. To maintain a constant building temperature, space heating and cooling occur simultaneously in various parts of the building during most months of the year. Thus, it is difficult to determine the space conditioning impacts of the losses.

The installed cost of fiberglass pipe insulation for commercial buildings is about \$7.38-\$8.20/m (\$2.25-\$2.50/ft). The recirculating loop is 244-m (800-ft) long, it could be insulated in new construction for a total of \$1,800-\$2,000. At present electricity costs in Golden, Colo., the monthly DHW electricity bill for the stand-alone HPWH is \$122. If this cost were reduced to \$60 with recirculating loop insulation, the pay-back of the insulation would be less than 3 years. The reduced heat loss of insulated pipe with water at temperatures of 49°C (120°F) or higher would represent even larger monthly dollar savings.

6. CONCLUSIONS

The stand-alone HPWH obtains a weekly COP of 2.4 in heating the 871 L/day (230 gal/day) draw and the 7570-15,140 L/day (2000-4000 gal/day) recirculating loop flow. However, because it is sized for residential applications, the HPWH is only able to maintain workday tank outlet water temperatures of about 41°C (106°F). This is less than the desirable temperature level of 49°C (120°F). SERI will replace the present HPWH with a newly marketed, high-capacity industrial-grade stand-alone HPWH and will test its performance in supplying the office building's DHW needs. Industrial-grade stand-alone HPWHs should prove to be high performing and more cost-effective than resistance water heaters. Performance analysis of the integral HPWH will be forthcoming after equipment repairs are made.

Approximately 75% of the energy delivered to the recirculating loop is lost from the uninsulated pipes. If the loop were insulated, the losses would be reduced by 75% thus reducing the monthly fuel bills for DHW by 50%. The cost of insulation could be paid in less than 3 years with savings in DHW fuel costs.

ACKNOWLEDGMENTS

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