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RESEARCH ARTICLES

RESIDENTIAL DRAIN WATER HEAT RECOVERY SYSTEMS: MODELING, ANALYSIS, AND IMPLEMENTATION

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ABSTRACT

This paper describes the design and environmental improvements that can be achieved using drain water heat recovery systems (DWHR) to reduce the energy consumption associated with residential showering. DWHR systems transfer heat from hot drain water to the shower's incoming cold water stream, thus reducing the demand on the hot water heater. There are various DWHR systems available that differ in heat exchanger type, cost, and performance. This article focuses on designing a flat plate and gravity fed heat exchangers for a range of residential showering conditions. This is useful since there currently is no peer-reviewed published data on the effectiveness of DWHR, nor is there published research considering the emissions reductions that can be achieved with realistic DWHR systems. The governing equations for heat exchangers are used to model empirical data and to derive implementation recommendations for DWHR design. The model is validated using a prototype flat plate heat exchanger and test stand under varying flow rates and temperatures. A Monte Carlo simulation of the results showed that DWHR could save an average \$74 a year for homes with natural gas water heaters and \$160 a year for homes with electric water heaters. This corresponds to 0.3 metric tons and 1.5 metric tons of CO_2 offset per home per year for natural gas and electric water heaters, respectively. The results are compiled and organized into a software program that allows consumers to input their household showering habits and location to get an estimate of their CO_2, energy, and cost savings to determine if they should install a DWHR system.

INTRODUCTION

Rising energy costs as well as increasing environmental awareness are leading consumers to demand energy saving products. One potential area for energy savings exists in the heating of residential water, specifically the heating of shower water. According to the US Department of Energy, the average household in the United States spends \$170 a month on energy costs: 60% goes to space heating, 25% goes to water heating and the rest goes to other uses such as cooking and lighting [1]. Wasted heat energy can be reclaimed to reduce a household's carbon footprint through a process called Drain Water Heat Recovery (DWHR).

DWHR systems have been around for decades but have only seen limited implementation due to high initial costs. However, recent incentives, like Minnesota Power's \$400 rebate on DWHR systems, make DWHR more economically feasible. The devices themselves are simple, consisting of a fluid-to-fluid heat exchanger, a filter and the required plumbing (Fig. 1). A single DWHR system is capable of servicing multiple showers. Often the impact of hot water heating is ignored, with consumers seeking more complex or expensive methods, such as solar power, to reduce their energy dependence. The shower is well suited for DWHR because of its high energy demand, continuous hot water usage and drainage, and general steady state operating conditions. This stands in contrast to other residential water usage devices such as dishwashers and laundry machines, which consume hot water and dump waste water intermittently. The majority of homeowners could install a DWHR system with very little effort or renovation, and most systems are designed to be completely passive—requiring almost no maintenance.

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The DWHR systems available are constructed using shell-and-tube and flat plate style heat exchangers. Each has its own advantages and disadvantages. Ultimately, the Authors chose to research the flat Plate Heat Exchanger (PHE), which, according to the Heat Exchanger Design Handbook, is the most effective for fluid-to-fluid type applications [2]. Parameters such as material selection, surface area, plate quantity, and corrugation angle determine a PHE's performance. The governing equations for heat transfer are well known and it is clear that the exchangers with the greatest surface area and most thermally conductive materials yield the greatest effectiveness. However, the economic and environmental costs associated with heat exchangers also need to be considered. The system must be low cost to be implemented on a large scale, and it should eventually pay for itself in reduced energy bills. The Authors' goal was to model the energy savings of a PHE in order to calculate the cost-benefit of DWHR systems and determine its feasibility for consumers.

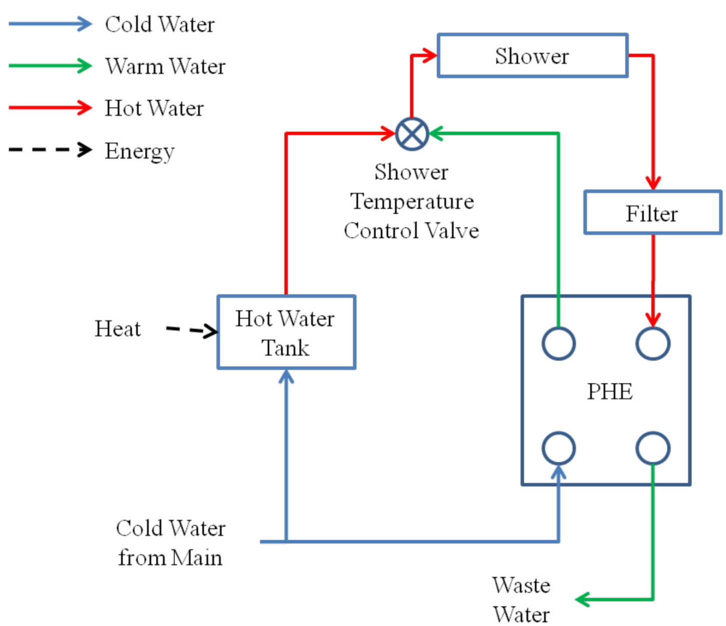
PREVIOUS LITERATURE

There is a great deal of research available for fluid-to-fluid heat exchangers [6,7], but the information is generally for large scale plant operations and not for residential water usage [2]. As such, convection coefficient and effectiveness data are unavailable for the relatively low temperature and pressure conditions present in shower DWHR systems. From the literature review and product benchmarking conducted during this research it was determined that DWHR products could benefit from a more thorough analysis considering design, cost, and environmental impact [3, 4].

Shell and Tube DWHR Products

The most common type of DWHR, the shell and tube, consists of copper lines wrapped around a main drain pipe. This type of system is currently being used in the consumer products made by GFX Technology (Patchoque, NY), RenewABILITY (Waterloo, ON), and ReTherm (Summerside, PEI). Some of these products return heat to the hot water tank, which could pose a problem to new homes that often use on-demand tank-less water heaters. Copper coil heat exchangers are large (models range from 30 inches to 60 inches) which can make installation difficult if space is constrained. One of the advantages of this type of DWHR is that it replaces a section of a home's main drain pipe and

FIGURE 1. Drain Water Heat Recovery (DWHR) system schematic.



requires no more additional maintenance than the original section of pipe. As of February 2009, these products retail cost ranged from $445 to $734 [5]. The effectiveness of each of these three products was determined in a series of tests run by the Canadian Centre for Housing Technology [3].

Horizontal Plate Heat Exchangers

Currently there is only one DWHR product on the market which falls into the PHE category: the EcoDrain produced by EcoDrain of Montreal, Canada. As of February 2009, EcoDrain representatives quoted $500 per unit for a horizontally orientated model in the US market. The compact design of this model allows for installation directly below the shower, and it is connected directly to the drain. EcoDrain claims to reduce water heater demand for showers by 25%–70% although there are no independent studies available to confirm this assertion [4]. EcoDrain uses a proprietary coating and larger plate spacing than conventional PHEs to avoid fouling. At the time of this article, the EcoDrain was not available for purchase in the US, nor were additional details available.

Vertical Plate Heat Exchanger

There are currently no vertically mounted PHE DWHR systems on the market. Water flows by gravity, achieving high flow rates, and energy exchange, than an unforced horizontal PHE. This system would require a PHE, filter and the necessary plumbing for installation. The system prototype shown in Fig. 1 costs approximately $500 to build, considering parts but excluding labor. A licensed plumber could be contracted to install the device, though in many homes the required plumbing is easily accessible. Brazed PHEs are typically more compact and less expensive than frame and plate (gasket) PHEs. PHEs come in a variety of corrugation types, the two most common are shown below in Fig. 2 where (a) is a washboard corrugation and (b) is a chevron, or herringbone, corrugation. Washboard PHE's are less prone to fouling and are effective at lower temperatures. Chevron PHE's are typically more effective but contribute to larger head loss [2]. The plates also come in a variety of materials; some common materials include AISI 304 and AISI 316 stainless steel [2].

MATERIALS

The vertical PHE configuration was selected for evaluation because of its perceived advantages. A variety of PHEs were identified for the prototype DWHR system. However, the proposed testing only allowed for the construction of one DWHR prototype. A PHE was selected considering cost, net heat transfer area and head loss. The PHE selected was the LB31-40 model from Advanced Industrial Components (AIC) of Ontario, Canada

PHE Selection

PHE performance is related to the total energy transferred, which is dictated by net transfer area and plate material. Since plate material was similar across all the PHEs investigated (AISI 316 and AISI 304), the desired PHE was selected based on transfer area The net heat transfer area for PHEs varies depending upon the number of plates and plate geometry, and cost tends to increase with transfer area. Cost and transfer area data were gathered for 58 PHEs from the suppliers McMaster-Carr, Grainger and AIC. Several PHEs were identified as candidate models because of their low cost-to-area ratios and low total cost (less than $500, an arbitrary amount based on current DWHR systems). The model selected was the LB31-40, which is a single pass brazed plate heat exchanger with forty AISI 316 plates (13.60 sq.ft at $34.41/sq.ft).

FIGURE 2. Corrugation types for PHE.

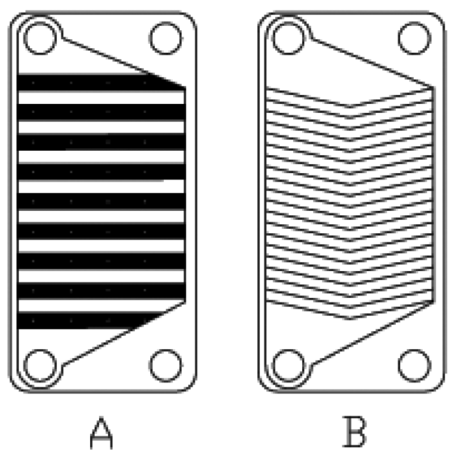


Plate Selection

Chevron configuration plates (Fig. 2.B) were selected for the prototype to induce turbulent flow, which increases heat transfer. The resulting gain in heat transfer was balanced against shower head loss. The following calculations show that a 30° inclination angle is the maximum allowable angle considering for the specified 5 psi head loss. Thus 30°/30° chevron corrugated plates were chosen for the prototype.

According to Martin, who modeled heat transfer across chevron PHE plates, the inclination angle is the most important parameter in determining pressure loss and heat transfer [7]. Martin showed that the friction factor can be approximated within ±10% for single phase counter flow using Eq. 1 shown below, where ϕ is the inclination angle and f is the friction factor [6,7]:

$$\frac{1}{\sqrt{f}} = \frac{\cos\varphi}{\sqrt{b\tan\varphi + c\sin\varphi + \frac{f_0}{\cos\varphi}}} + \frac{1-\cos\varphi}{\sqrt{af_1}} \qquad \text{(Eq. 1)}$$

Constants f_0 and f_1 depend on Reynolds number and were calculated according to Martin to be 7.75 and 2.27 respectively for the selected PHE (AIC LB31). For this case, Reynolds number (Re) was determined to be 1,100 based on the density (ρ) and viscosity of residential water (80 psi and 60°F or 552 kPa and 15.6°C), the volume flow rate (2.5 gpm or 0.16 L/s) and a hydraulic diameter (D_h, 180mm) as defined by Martin according to PHE parameters [7]. Constants a, b and c in Eq. 1 were determined by Wang to be 3.8, 0.045 and 0.09 respectively [6]. Martin also showed that head loss is related to the friction factor by Eq. 2 where ΔP is the pressure drop across the heat exchanger, u is the velocity across the plate channel (0.16 m/s) and L_p is vertical length between PHE ports (444 mm) [7]:

$$f = \frac{2\Delta P D_h}{\rho u^2 L_p} \qquad \text{(Eq. 2)}$$

Martin also determined a relation for the average Nusselt Number (Nu), a measure of convective heat transfer across a surface, inclination angle and other dimensionless variables as given in Eq. 3 [7]. The Prandlt Number (Pr) for water is approximately 7 and the ratio (d/L) is defined as the hydraulic diameter (D_h) divided by sin(2ϕ).

$$Nu = 0.40377\, fRe^2 \left(Pr\frac{d}{L}\right)^{1/2} \qquad \text{(Eq. 3)}$$

The Nusselt Number and pressure drop were calculated for inclination angles ranging from 10° to 80°, the valid range for the equations. The resulting values are plotted in Fig. 3. In keeping with the DWHR benchmark systems on the market today, it is required that the pressure drop across the heat exchanger not exceed 5 psi (34.5 kPa). At head losses greater than 5 psi (34.5 kPa), users may notice the loss of pressure at the shower head. This specification ensures that shower performance is not significantly affected by the presence of a DWHR system. From Fig. 3, a 5 psi (34.5 kPa) pressure drop corre-

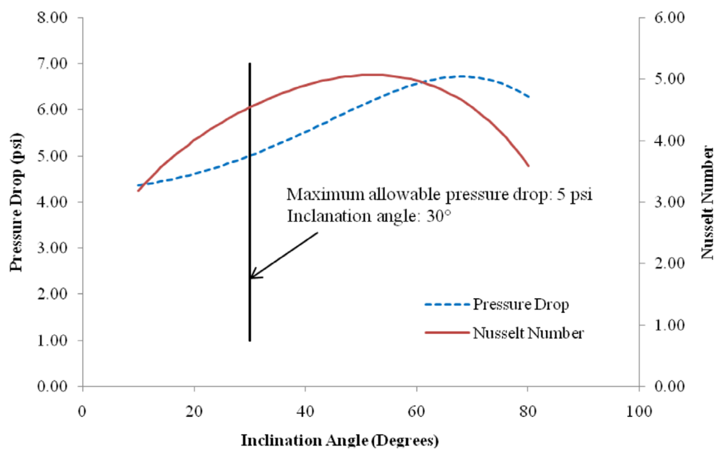


FIGURE 3. The maximum allowable pressure drop occurs at ϕ = 32°.

sponds to 30° inclination. Heat exchanger effectiveness is maximized at the largest value of Nu (5.07 at 52° inclination); however, this inclination corresponds to a pressure exceeding the target specifications (6.7 psi at 52° inclination). There appears to be a trade-off between heat exchanger performance, as characterized by Nu, and pressure loss. Therefore, a reasonable inclination angle to test is 30°. This analysis can be repeated as needed to determine inclination angles for a variety of shower conditions and PHE geometries.

METHODS

To evaluate heat exchanger effectiveness for residential showering conditions, a test stand was constructed and several tests were performed. The methods used for this testing are described in the following paragraphs.

PHE Performance Test Setup

The setup for the heat exchanger performance testing is shown below in Figs. 4 and 5. Temperatures for cold inlet, cold outlet, hot inlet and hot outlet are referred to as T_{ci}, T_{co}, T_{hi}, T_{ho} respectively in the figure. Cold water was supplied by an Ann Arbor, Michigan residential water main at approximately 45°F (7.2°C) during March 2009. Hot water was generated by a 77 gallon (291 L), natural gas hot water tank maintained at 120°F (48.9°C). These parameters are not controllable and thus represent the upper and lower limits for temperature. The PHE tested was the AIC LB31-40 with temperature and flow rate manually adjusted by two control valves. Note that T_{ci}, T_{co}, T_{hi}, T_{ho}, cold flow and hot flow all depend on the same sources and must all be monitored when adjusting any variable. Temperature data was acquired with a National Instruments USB DAQ 6009 at a sampling rate of 1 Hz. Each test lasted between five and ten minutes, with fifteen minutes between testing to allow the water tank to recharge. External water use was avoided during testing to mitigate the effect of pressure disturbances on temperature and flow rate.

PHE Performance Test Procedure

In order to measure PHE effectiveness, thirty-one separate tests were conducted. For each test, the hot and cold flow rates were set using control valves. Water from the hot water tank mixed with the cold water from the main line to achieve the desired temperatures. Flow rates were measured with analog flow meters (± 0.125 gpm or 7.9 mL/s) at T_{ci} and T_{ho}. Cold water flow rates were varied from 0.50–3.00 gpm (31.5–189.3 mL/s) and hot water flow rates ranged from 1.00–3.00 gpm (63.0–189.3 mL/s) for T_{ci} and T_{hi} respectively as shown in Fig. 4. To simulate real-world conditions, the cold flow rate never exceeded the hot flow rate. Conventionally, showers mix hot and cold water to achieve a desired temperature. Thus the hot flow, which simulates the drain flow, must be greater than the cold flow assuming mass conservation and negligible accumulating. Once the control valves had been set, the resulting pressure drop across the cold side of the PHE and the temperatures at all of the PHE inlets and outlets were recorded. The temperature of T_{ci} was varied from 45°F (7.2°C) to 70°F (21.1°C) and T_{hi} from 95°F (35.0°C) to 120°F (48.9°C). Once the

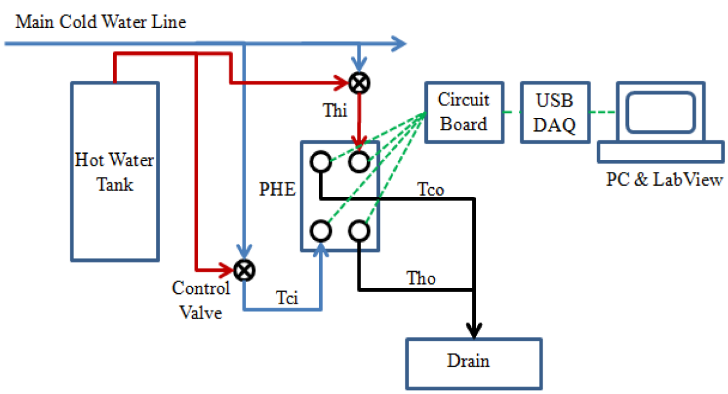


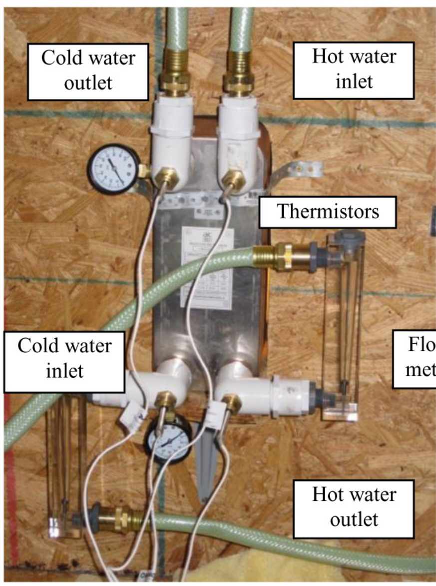
FIGURE 4. PHE performance test setup.

flows had been established, temperature data was continuously recorded for each port in LabView 8.6 (sampling rate 1 Hz). Temperature was measured as shown in Fig. 4 with four 1000 Ω thermistors, four 1000 Ω precision resistors and a 5 V power supply. Each parameter was verified with a digital multimeter prior to testing. Note that data was only taken once the system had reached a steady state for one minute, meaning all temperatures remained constant and deviated by no more than 2%. This generally took no more than two minutes after the control valves had been set. The pressure at each cold port (T_{ci} and T_{co}) was measured with an analog pressure gauge (± 3 psi or 20.7 kPa) once the system had reached steady state.

MODELING

Effectiveness (ε) is a measure of the actual heat transfer (q) with respect to the maximum possible heat transfer (q_{max}). This parameter varies with flow and temperature and is instrumental in determining a DWHR system's feasibility. Effectiveness is not to be confused with efficiency, which is defined as the ratio of heat output and input. Heat exchangers are typically designed to have very high efficiencies (80%-90%). It is possible to determine PHE effectiveness for our tests from the equations in Dr. Frank P. Incorpera's textbook *Fundamentals of Heat and Mass Transfer*. Effectiveness is shown to depend on the cold inlet temperature (T_{ci}), the cold outlet temperature (T_{co}), the hot inlet temperature (T_{hi}) and heat capacity rates C_c and C_{min} as shown in Eq. 4 [8]. The heat capacity rates are defined as the product of density, heat capacity and volume flow rate where subscript c represents the cold side and subscript min represents the minimum heat capacity rate of the hot and cold sides. Fluid density and specific heat vary with temperature; exact values were interpolated based on the reference values found in *Fundamentals of Heat and Mass Transfer* [8].

FIGURE 5. Test stand subassemblies.



$$\varepsilon = \frac{q}{q_{\max}} = \frac{C_c(T_{co} - T_{ci})}{C_{\min}(T_{hi} - T_{ci})} \qquad \text{(Eq. 4)}$$

The overall convective coefficient (UA) can be determined experimentally from the cold heat capacity rate and fluid temperatures as shown in Eq. 5, which is defined in *Fundamentals of Heat and Mass Transfer* [8]. The computed UA values are needed for calculating the number of thermal transfer units (NTU).

$$UA = \frac{C_c(T_{co} - T_{ci})}{\Delta T_{lm}} \qquad \text{(Eq. 5)}$$

$$\text{where} \quad \Delta T_{lm} = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\dfrac{\ln(T_{hi} - T_{co})}{T_{ho} - T_{ci}}}$$

According to Dr. Incropera, NTU is defined by the overall convective coefficient (UA) and the minimum heat capacity rate (C_{min}) as shown in Eq. 6. Larger values for NTU correspond to greater PHE effectiveness values [8]. Heat exchangers with larger areas and lower thermal resistance will have larger overall convective coefficients and thus larger values of NTU.

$$NTU = \frac{UA}{C_{\min}} \qquad \text{(Eq. 6)}$$

Finally, heat capacity gain ratio (C_r), also derived in *Fundamentals of Heat and Mass Transfer*, is defined as the ratio of heat capacity rates C_{min} and C_{max} as shown below in Eq. 7, where heat capacity rates depend on fluid density (ρ), volume flow rate (V) and heat capacity (c_p) [8].

$$C_r = \frac{C_{\min}}{C_{\max}} = \frac{\rho_c V_c c_{pc}}{\rho_h V_h c_{ph}} \qquad \text{(Eq. 7)}$$

RESULTS AND DISCUSSION

Over the range of tested showering conditions, the observed head loss never exceeded 4 psi, less than the anticipated 5 psi head loss. Head loss was higher for larger flow rates. A 30 chevron configuration does not have a significant effect on perceived shower performance.

It was expected that effectiveness would be constant across the range of showering conditions. However, PHE effectiveness was found to vary from 10% to 80% as shown in Fig. 6. The results are subject to the control variables: hot flow, cold flow, T_{ci} and T_{hi}. The majority of showering conditions had effectiveness values of 50% or lower (19 of 31 tests). Effectiveness values near 70% and 80% were only observed in cases with large inlet temperature differences (eg. T_{ci} = 45°F, T_{hi} = 120°F) and large flow rate differences (cold flow = 0.5 gpm, hot flow = 3.0 gpm). However, this does not imply that the selected PHE is not effective with respect to cost savings and CO_2 offset. Also, PHEs with a transfer area greater than the 13.60 sq.ft of the tested model would produce larger effectiveness values (though they would also cost more).

Since density (ρ) and heat capacity (c_p) only vary slightly over the range of showering conditions (density ranges by 1.3% from 1000 kg/m^3 to 987 kg/m^3 and specific heat ranges by less than 1% from 4211 J/kg-K to 4182 J/kg-K), the most significant variables in C_r are cold volume flow rate (V_c) and hot water flow rate (V_h). Cold flow rate is always less than the hot flow rate; thus, C_{min} is equal to cold water heat capacity rate (C_c). This is significant because large effectiveness values are expected for smaller values of C_r when in fact a maximum upper bound on effectiveness exists at C_r equal to zero as shown in Fig. 6. Thus, a PHE is expected to be most effective when V_c is sufficiently smaller than V_h. However, the ratio of V_c to V_h is dictated by the user as he or she sets the desired shower temperature.

Based on this development, a regional savings calculator was created as described below. The savings calculator was developed based off of the measured effectiveness data, information on water temperatures throughout the country, and energy costs by census region from the 2009 Energy Cost Projections of the Department of Energy [9]. This calculator informs potential DWHR users of their annual savings and their carbon offset. The ability to easily make reasonable predictions on these two aspects of the DWHR performance could prove helpful in spreading DWHR technology and creating greener homes and buildings.

The savings and carbon offset per year from use of the DWHR are dependent on many parameters including the cold water inlet temperature, hot water inlet temperature, effectiveness, local energy costs, and carbon emissions due to either gas or electrical energy production. To calculate the savings and carbon offset for a particular consumer a graphical user interface (GUI) was created in which information could be entered by the user. The GUI for the sav-

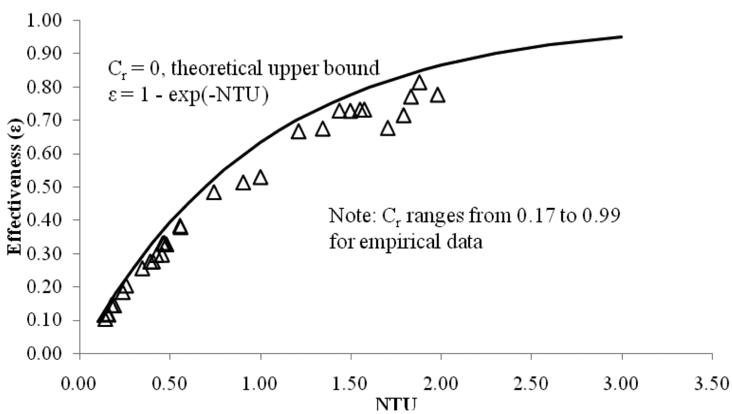


FIGURE 6. AIC LB31-40 effectiveness ranges from 10% to 80% across the tested showering conditions.

ings calculator as well as the background calculation program was created using Visual BASIC 2005 and is shown below in Fig. 7.

Data for the calculations is specified by the user based on showering habits in the user's residence as well as by the specific showering facilities. The average cold water inlet temperature, energy costs and carbon emissions for both natural gas and electricity are determined from the region entered. The energy costs and carbon emissions for each region are based off of projected 2009 data from the U.S. Energy Information Administration (EIA) energy outlook [10]. Depending on whether a user has a natural gas or electric water heater the corresponding values of cost and CO_2 emission values are used. The hot water flow rate is determined by the type of shower head selected, which along with the number of people in the household and average shower length, gives the mass of water used in a typical year. With the hot water inlet temperature submitted, the reduction in BTUs needed to heat the total mass of water used in a year can be found. The program then converts the BTUs saved in a year to dollars and carbon in metric tons using conversions based on the EIA projected information for 2009 [10].

In order to evaluate the feasibility of DWHR, several different example households were examined. For instance, the information was determined for a family of four living in Michigan who takes 10-minute showers on average at the average temperature of 105°F with a standard shower head (2.5 gpm) and a natural gas water heater. These values represent typical shower conditions according to the REUW [1]. In this instance, the household's annual savings would be $101.87 and nearly half a metric ton of CO_2. On one end of the spectrum a large house for seven roommates attending the University of Michigan with an electric water heater and an old shower head could save $1143.80 and offset 9.45 metric tons of CO_2 per year. On the other end of the spectrum is a single person in a apartment located in Florida. He or she has a natural gas water heater, an ultra low flow shower head and takes short, cold showers. This individual would only save $6.03 per year and would offset just 0.02 metric tons of CO_2. The rest of the results along with the examples described above are summarized in Table 1 below. The Authors determined that these results were comparable to the claims of other DWHR systems and in many cases exceeded them.

A Monte Carlo simulation, Fig. 8, was performed to characterize the variation in annual savings of typical households across the United States. The data included averages and standard deviations provided by the US Census and REUW [1]. The Monte Carlo simulation found that families with electric water

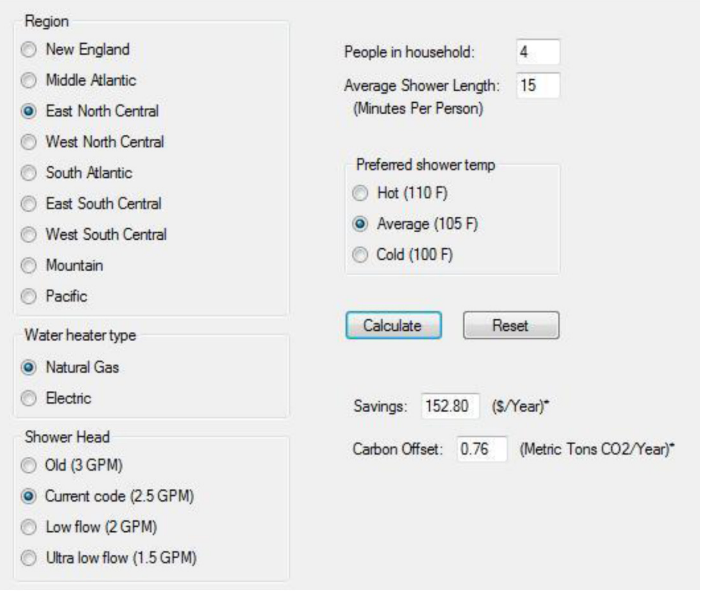


FIGURE 7. Data entry portion of savings calculator GUI.

TABLE 1. User input for example families and corresponding output from savings calculator.

People in Household	Region	Water Heater Type	Shower Head	Average Shower Length	Preferred Shower	Savings ($/Year)	Carbon Offset (Metric Tons CO_2/Year
4	East North Central	Natural Gas	Standard (2.5 GPM)	10	Average (105°F)	101.87	0.51
2	Middle Atlantic	Natural Gas	Standard (2.5 GPM)	15	Average (105°F)	92.65	0.38
5	Mountain	Electric	Low Flow (2.0 GPM)	10	Average (105°F)	150.54	1.47
3	Pacific	Electric	Old (3.0 GPM)	12	Hot (110°F)	449.68	0.69
1	South Atlantic	Natural Gas	Ultra Low Flow (1.5 GPM)	8	Cold (100°F)	6.03	0.02
7	East North Central	Electric	Old (3.0 GPM)	15	Hot (110 F)	1143.80	9.45

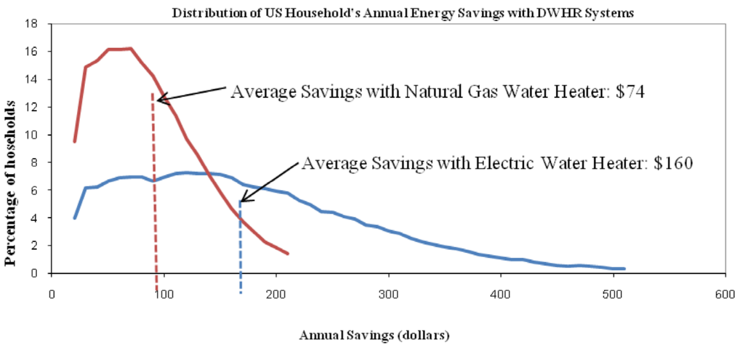


FIGURE 8. Monte Carlo simulation provides average annual energy savings based on US families' showering habits.

heating saved on average $160 per year and families with natural gas saved $74 per year. Although potential consumers may not know their specific flow rates or temperatures, the Savings Calculator results are representative of potential savings and are adequate for determining whether this DWHR system would be cost effective for a particular consumer.

CONCLUSIONS

From the modeling, analysis and validating tests, it was found that DWHR effectiveness varies substantially considering household showering conditions. Despite this variation, it was observed that significant savings for cost and carbon emissions were possible under most circumstances. A Monte Carlo analysis showed that the average American household can expect to save $74/year or $160/year and offset 0.3 to 1.5 metric tons of carbon a year depending to the type of water heating. The results were compiled into software to estimate individual household cost and energy savings, in the hopes that tangible calculations might make DWHR technology more commonplace. This exercise also showed that DWHR is the most feasible for households with frequent shower usage in cold climates. While PHE was studied here due to its excellent heat transfer characteristics relative to other heat exchangers, alternative heat exchangers and PHE geometries should be evaluated in order to provide a more comprehensive set of potential cost and energy savings. Nevertheless PHE is a viable DWHR solution with notable benefits both for individual consumers, especially in new homes but also in most existing homes, and the nation at large.

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