WATER AND ENERGY SAVINGS FROM ON-DEMAND AND HOT WATER RECIRCULATING SYSTEMS

Randi H. Brazeau[a] and Marc A. Edwards[b]

ABSTRACT

Electric hot water recirculation and on-demand instant hot water systems have been identified as "green" water systems due to purported energy and water savings, and some municipalities and districts even require green systems in residences. The performance of these devices have never been rigorously tested and evaluated. This work aims to address that gap by conducting a comparative, head-to-head study evaluating energy efficiency, temperature profiles and consumer issues such as cost and quality of system for two "green" water heating systems as compared to a standard water heater. Not only did the standard system outperform the hot water recirculation system with respect to temperature profile during flushing, but the standard system also operated with 32–36% more energy efficiency. Although the recirculation system did in fact save some water at the tap, when factoring in the energy efficiency reductions and associated water demand, recirculation systems actually consumed up to 7 gallons more water per day and cost consumers more money. On-demand systems operate with virtually 100% energy efficiency, but cannot be used in many circumstances dependent on scaling and incoming water temperature, and may require expensive upgrades to home electrical systems and use of low/ultra low flow showerheads. Although additional research is necessary to better understand nuances of electric water heating in the context of the water-energy nexus, this research provides a first step for rational decision making by regulators, public health officials, manufacturers and consumers.

KEYWORDS

water heaters, energy efficiency, water-energy nexus, green energy, premise plumbing, temperature profile

1. BACKGROUND

1.1 Residential Water Heating as Part of the Water-Energy Nexus

Water heating is the second largest source of energy consumption in buildings and has a total energy demand exceeding the entire water and wastewater sector [1-3]. Obtaining improved performance of water heating systems in buildings (> 100 million residential households and > 14.8 million commercial structures) can yield significant benefits in terms of public health,

[a]Corresponding Author: Metropolitan State University of Denver, Denver, CO, USA 80217, rbrazeau@msudenver.edu, 00-1-303-556-2699 (p); 00-1-303-556-4436 (f).
[b]Virginia Tech, 418 Durham Hall, Blacksburg, VA, USA 24060, edwardsm@vt.edu.

water conservation, energy efficiency and consumer comfort [4]. Some initiatives for more sustainable building are being addressed via standards promulgated by the United States Green Building Council (USGBC), LEED and Energy Star programs, which collectively attempt to achieve certain goals of "green" design for new construction, remodeling and retrofitting, but there seems to a gap in the research and guidelines when it comes to hot water infrastructure and consumer use. With over 100 million households in the United States using water heating systems and nearly 40% of those homes using electric water heaters, fundamental research is needed to better understand and optimize all dimensions of water heater system performance, and to inform development of sound guidance and standards for consumers [3].

1.2 Energy Efficiency and Conservation Programs

Energy Star, the lead rating system for appliance water/energy efficiency and sustainability, helps consumers identify products that reduce green-house gas emissions, are more energy efficient, and saves consumers money on energy use while still maintaining quality. According to Energy Star estimates, Americans reduced an equivalent of 33 million cars worth of greenhouse gas emissions and saved close to $18 billion dollars on utility bills by using Energy Star products in 2010 [5-7]. The Energy Star program is also a basis for certain tax incentives associated with water heating systems to encourage energy efficiency [8]. In addition to federal government initiatives, some cities where water conservation is a high priority due to environmental concerns, drought, cost, and other considerations, have adopted local ordinances which mandate new construction to have new, water saving, "green" plumbing designs. For example, one municipality in California has mandated that if a hot water tap is more than 10 feet from a water heater, that hot water recirculation or on-demand systems be used to reduce wasted water [9].

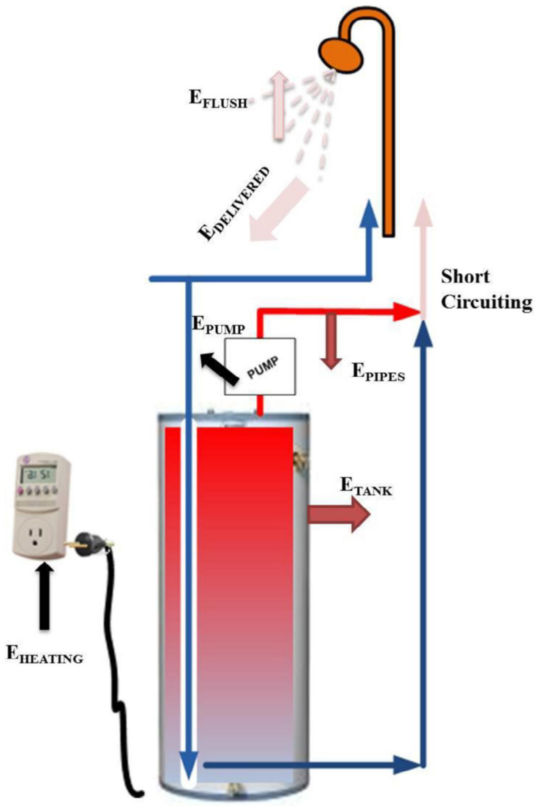
1.3 Water Heaters and Sustainability Efforts

Certain hot water systems have been marketed as "green" based on federal tax credit eligibility or municipal mandates [3]. Although these initiatives and mandates are assumed to provide net environmental benefits, there is surprisingly little scientific evidence documenting and quantifying the potential advantages. It is even possible that in many instances, there is a net energy and water loss associated with installation of certain "green" features, which can be counterproductive. For example, the hot water recirculation systems that have been mandated or otherwise encouraged in certain municipalities due to assumed reductions in energy and water use can actually be installed in a manner that has a potential to increase energy losses (Figure 1, Table 1). The few attempts that have been made to quantify the performance of these systems have not been completely successful.

For example, in 2002, the Oak Ridge National Laboratory (ORNL) and the City of Palo Alto conducted a study examining the use of hot water recirculation. They estimated that nearly 1–3 gallons of potable water are wasted down the drain, as a consumer waits for water to reach a comfortable level for showering. While they assert that this water wastage can be virtually eliminated by installing hot water recirculation systems, the authors correctly note numerous times that this only occurs in an "ideal" situation where residents push a button at tap starting the pump system and conveying hot water to the end use [10]. Such push button type systems are not always installed in recirculation systems and there are several other systems that dominate the market (i.e., continuous circulation, thermostat systems, timer-controlled systems, etc.) which may actually be counterproductive in terms of energy efficiency [11].

FIGURE 1. Hot water recirculation system (RECIRC). A hot water recirculation system showing energy consumption and heat losses throughout the system. If the recirculating pump is not in use, the tank may stratify (as shown) with hotter temperatures at the top of the tank and lower temperatures at the bottom. When the pump is in use, the temperature will be nearly the same (hot) everywhere (not shown). With the installation of a check valve, short circuiting should be eliminated (not shown).

Energy Efficiency = $E_{DELIVERED}/E_{TOTAL}$



LEGEND:

$E_{HEATING}$ = Total energy consumed from general power grid (as measured by energy meter) to heat water

E_{PUMP} = Total energy consumed by pump from general power grid (as measured by energy meter)

E_{TOTAL} = Sum of all energy inputs ($E_{HEATING}$ + E_{PUMP})

E_{TANK} = Heat loss from tank to ambient during stagnation (dependent on internal tank temperature and ambient temperature)

E_{PIPES} = Energy loss per volume of hot water produced during flushing (dependent on water temperature and ambient temperature)

E_{FLUSH} = Heat loss to the environment per volume of water produced after leaving pipe and before delivery to the consumer (dependent on water temperature, air temperature, drop size and other factors)

Short Circuiting = Phenomenon where cold water can backflow out the return line at the bottom of the tank "short circuiting" the storage tank when no check valve is installed (Short Circuiting can dramatically reduce $E_{PRODUCED}$ by lowering the delivered hot water)

$E_{DELIVERED}$ = Energy actually delivered to consumer in the form of heated water

The ORNL study was a first attempt at handling the complex issues of domestic water heating and hot water recirculation, but had typical field-study limitations including small sample size, inconsistent study parameters, inconclusive results, and a narrow range of home age not comparable to current age distribution of homes in the U.S. Furthermore, the study had some fundamental problems in its variables that may cast doubt on the conclusions drawn. These problems include a failure to consider the energy use of the pump and temperature setting of the system, not considering pipe networks, materials, and configuration, and not standardizing hot water use [10].

Other possible problems for certain "green" hot water heaters are associated with consumer satisfaction. For example, on-demand instantaneous water heaters are gaining popularity in the residential sector. These types of heaters are marketed as "green" since the electric systems are virtually 100% energy efficient as there are no standby heat losses. However, these systems may require low flow fixtures, provide water with inconsistent temperature, and impose other limitations [3].

TABLE 1. Expected Energy Consumption and Loss.[a]

System	Condition	E_{TANK}	E_{PIPES}	E_{FLUSH}	$E_{SHORT\ CIRCUITING}$	Total Energy Loss	Expected $E_{PRODUCED}$	E_{PUMP}[d]	$E_{HEATING}$	E_{TOTAL}	Expected Energy Efficiency[e]
Standard Tank with No Recirculation	49°C High Use[b]	Low	Low	Low	N/A	Low	Medium-High	N/A	Low-Medium	Low-Medium	High
	49°C Low Use[c]	Low-Medium	Low-Medium	Low-Medium	N/A	Low-Medium	Medium	N/A	Low	Low	High
	60°C High Use	Medium	Medium	Medium	N/A	Medium	High	N/A	Medium-High	Medium-High	Medium-High
	60°C Low Use	Medium-High	Medium-High	Medium-High	N/A	Medium-High	Medium-High	N/A	Medium	Medium	Medium-High
Tank with Recirculation and No Check Valve	49°C High Use	Low-Medium	Low-Medium	Low-Medium	Medium	Low-Medium	Low-Medium	Medium	Medium	Medium-High	Medium-High
	49°C Low Use	Medium	Medium	Medium	Medium	Medium	Low	Medium	Low-Medium	Medium	Medium-High
	60°C High Use	Medium-High	Medium-High	Medium-High	High	Medium-High	Low-Medium	Medium	High	High	Medium
	60°C Low Use	High	High	High	High	High	Low	Medium	Medium-High	High	Medium
Demand	Low Setting	N/A	Low	Low	N/A	Low	Medium-High	N/A	Low	Low	Very High
	High Setting	N/A	Low-Medium	Low-Medium	N/A	Low-Medium	High	N/A	Low-Medium	Low-Medium	Very High

[a]Expected energy performance (i.e., high, medium, low, etc.) are defined qualitatively based on the expected relative performance of each system/condition.
[b]During high use, the temperature of water produced fluctuates from hot-cold as the tank empties (i.e., as the tank flushes, the ΔT between water temperature and ambient lessens)
[c]During low use, the temperature of water produced is a small volume at maximum temperature (i.e., ΔT between water temperature and ambient is maximized)
[d]In recirculation systems, the pump is assumed to run constantly (24/7)
[e]Energy Efficiency = $E_{DELIVERED}$ /E_{TOTAL} (Figure 1)

1.4 Expected Energy Efficiency

It would be expected that the 49°C condition, which is recommended by the United States Environmental Protection Agency (US EPA) for energy savings, would have less standby energy loss than the 60°C condition, which is recommended by the World Health Organization (WHO) to reduce pathogen growth, due to lower temperature differentials between the tank and ambient room temperature [12, 13]. Based on a fundamental understanding of how these systems function (Figure 1, Table 1), it is instructive to consider the likely relative performance of each system (Table 1). To determine the overall efficiency of the systems, all the possible sources of energy loss must be quantified (Figure 1). While the temperature data can give insight to energy efficiency questions, the degree to which the efficiency is affected can only be determined through direct measurement.

2. RESEARCH GOAL AND OBJECTIVES

This work will provide the first head to head evaluation of electric hot water recirculation system performance compared to traditional electrical central storage system, which holistically considers: 1) relative energy efficiency data under various operating conditions, 2) overall impacts on water demand, and 3) consumer comfort and quality of energy delivery as measured by temperature profiles of delivered water.

3. EXPERIMENTAL DESIGN

3.1 Overview of Experimental Design

Three common electric water heater configurations (Figure 2) will be evaluated in the laboratory including one conventional (system 1) and two systems reported to be "green" by specific ordinance requirements, federal tax credit eligibility and/or Energy Star rated (systems 2–3) [8, 9, 14]:

1. Storage tank with no hot water recirculation **(STAND)**;
2. Storage tank with hot water recirculation **(RECIRC)**; and
3. Point-of-use on-demand with no storage and no hot water recirculation **(DEMAND)**

Each system was operated with an identical water supply, delivered water volume and flow rate, target temperature setting, and usage pattern (controlled with a timer). All electrical inputs were quantified [15-17]. The STAND and RECIRC systems were identical 20 gallon electric tanks with manufacturer equipped anode rods. The RECIRC system was equipped with a Watts 500800 Premier hot water recirculation pump and return line. All systems were fitted with 30 feet of 3/4" copper pipe coils to the laboratory tap, and the RECIRC system with an additional 30 feet of 3/4" copper coil as the return line. All taps, valves, connections, and adapters were copper or brass. Upstream of the water heating systems, a waste line was installed so municipal tap water could be flushed for at least 10 minutes prior to demand from the experimental apparatus, which was revealed to ensure delivery of water with constant temperature and chemistry.

The tap water is relatively soft, chloraminated water from the Town of Blacksburg. Prior to installation, both tanks were rinsed and spiked with 20 mg/L hypochlorite and total chlorine decay was measured over a 3-day period to quantify any differences in decay rates from the equipment (i.e., tank) alone. Moreover, at the start of the experiment, both tank systems were operated under a similar set of conditions (i.e., return line closed via a valve and the pump shut off in RECIRC system), and energy consumption of the tanks was identical.

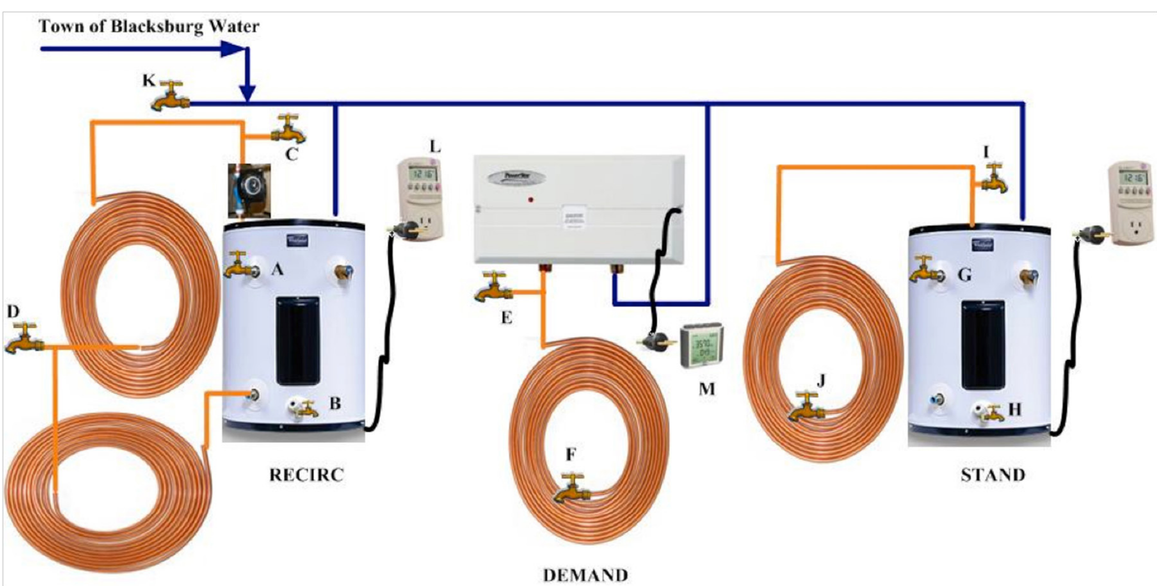
3.2 Water Consumption Profiles

Research was conducted using four different water use patterns: high use, low use, high temperature and low temperature. The high use pattern was determined based on a comprehensive study conducted by Goldner of water heater use patterns in New York. The study showed a high average use was 54 gal/person/day [18]. According to the 2000 census, an average family size is 3.14 which would equate to a total volume of 170 gal/day. If we figure a nominal water heater tank stores about 50 gallons, this would mean that the tank fully empties at least 3 times. Based on these calculations, high use was defined as a system with complete volume turnover 3-times daily with 8-hour stagnation between flow events [19]. Low use represented a situation in which demand was 1/6 of high use with a 25% tank turnover every 12 hours. The high temperature setting is based on the WHO recommended operating temperature of 60°C designed to limit microbial growth [13], while the low temperature setting is based on the United States recommended temperature of 49°C to conserve energy and minimize scalding potential [12]. All pipes were initially insulated with standard self-sealing foam insulation (R = 2) to represent a "best case" for energy efficiency and the pump in the RECIRC system was run continuously to ensure a stable, constant temperature in the pipe network.

3.3 Temperature and Energy Measurements

Total energy ($E_{HEATING}$; Figure 1) measurements were determined using an electric watt meter that measured alternating current (AC) directly and gives cumulative kWh values for the RECIRC and STAND systems as well as the RECIRC pump. To measure the 220 V

FIGURE 2. Experimental design. Experimental design of head-to-head water heaters: A-J) Sample Taps, K) Flush/Waste line, L) 120 V energy meter, and M) 220 V Energy meter. For experiments described in this paper, all copper tube was insulated.



DEMAND system, a wireless energy meter captures the watt-hours via sensors on each of the circuits. The energy delivered ($E_{DELIVERED}$) was defined in terms of hot water yielded (i.e., $q = mc\Delta T$, where q = energy in terms of heat transfer to water = $E_{DELIVERED}$, m = mass, c = specific heat capacity of water, and ΔT = change in temperature; Figure 1). Temperature was measured as follows: 1) 4 gallon cumulative buckets of water from the laboratory tap (as used for energy calculations) was measured using digital thermometers to determine $E_{DELIVERED}$, 2) flushing temperature profiles were measured using automatic loggers and thermocouples that measured temperature every 10 seconds, 3) internal tank temperature was measured by a series of submerged data loggers that automatically logged the internal tank temperature every 30 minutes and 4) room temperature was continually monitored to determine any possible effect on tank or flushing temperature using an electronic thermometer and found to be consistently 25–26°C throughout the course of the experiment.

4. RESULTS AND DISCUSSION

After describing characteristic temperature profiles of water flow from each system and within the storage tanks when present, the overall energy efficiency of each system is quantified. A final section describes the factors affecting the practical performance of on-demand electric heaters.

4.1 Temperature during System Flushing

During flushing, the RECIRC system had less temperature stability during flushing than the STAND configuration. In all cases the RECIRC systems had a short period of stable high temperature followed by a continuous decrease in temperature (Figures 3 and 4). The decrease in temperature was more rapid in the winter months. In contrast, the STAND system was characterized by a brief period in which water temperature rapidly rose as cooled water in the pipes was replaced with the hot water from the tank. Thereafter, the temperature remained stable until the hot water in the tank was completely displaced with cold water. The DEMAND system showed similar pattern to STAND with two key differences: 1) the hot water never "ran out" and was continuous until flushing ended, and 2) the maximum temperature never rose above 37°C or 27°C in the maximum energy and minimum energy settings, respectively. Clearly, from a consumer comfort standpoint, factors such as the length of the time for the hot water to reach the tap, the stability of the water temperature during flushing, and the maximum temperature are going to be important considerations for water heater selection. For example, using the STAND system as a baseline for comparison, both of the "green" models (i.e., RECIRC and DEMAND) had lower delivered water temperatures after 1–2 minutes of flushing. The main concern with the DEMAND system was the limited ability to achieve temperature targets for a comfortable shower. To achieve a temperature of 37°C (warm enough for showering), the flow rate had to be dropped to the minimum flow rate possible (approximately 0.80 gpm). Lower flow rates automatically shut off the heating elements as a safety feature to prevent scalding. Operating the system at the low energy setting was the least desirable condition for a consumer comfort standpoint. Although, this setting uses less energy to run and may be better from a total energy perspective, it does not provide enough power to actually provide hot water (Figure 3).

While the RECIRC system avoided the 50–60 second initial temperature rise in the STAND system, the delivered water temperature declined steadily after the first minutes of flushing. Two possible explanations for this rapid cooling were identified: 1) cold water from

FIGURE 3. Temperature profile during flushing for the low use condition.

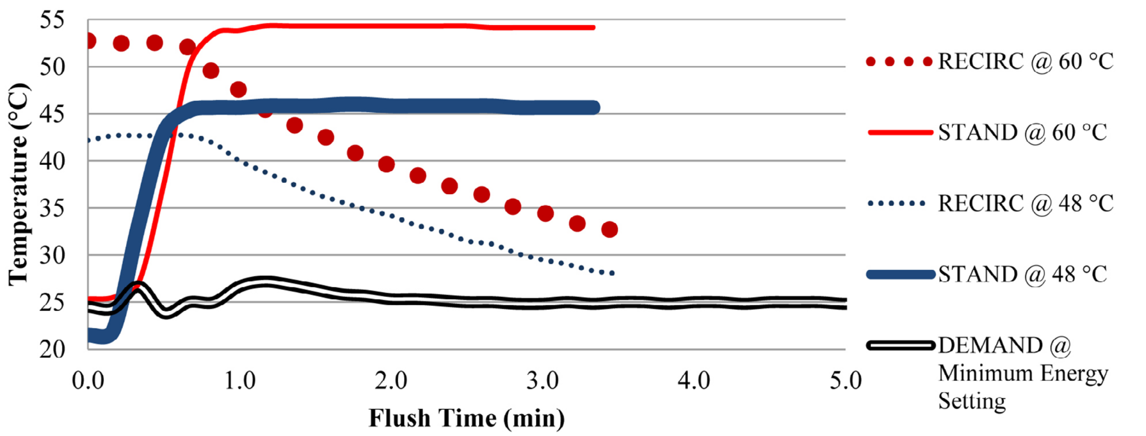
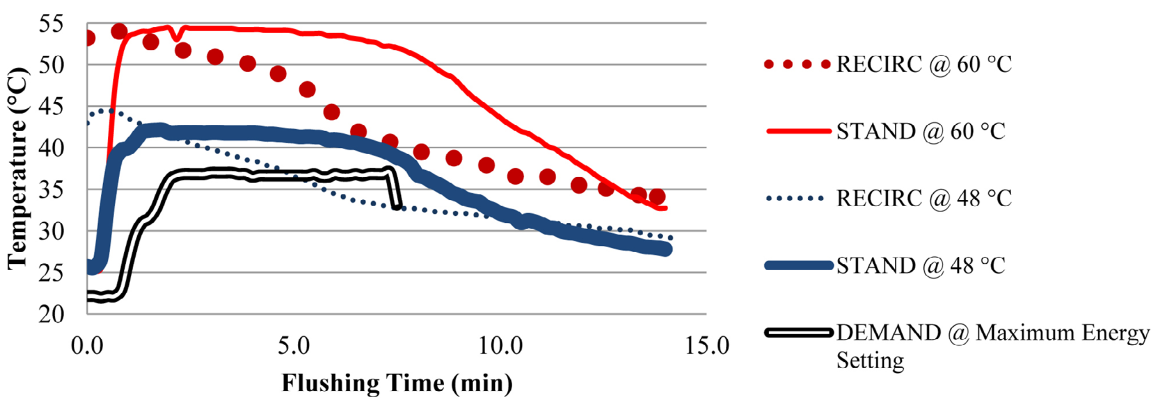


FIGURE 4. Temperature profile during flushing for the high use condition.



the distribution system was instantly mixing in the hot water tank causing a drop in internal temperature throughout the volume, or 2) cold water from the distribution system was short circuiting the tank by back-flowing out of the return line and mixing at a junction upstream of the tap (Figure 1).

A tracer study using a 170 g slug of KCl (39 g as K+) added to the cold water influent pipe before the tank was conducted in the RECIRC system as designed in this study and then again with the installation of a check valve to prevent backflow through the return line (Figure 5). K+ was measured in the effluent water (in a well mixed 4 gallon capture). The extent to which K+ appeared in the delivered water from the tank unambiguously indicates the extent of short-circuiting of cold water that was initially outside the tank. When the check valve was installed, only 9% of the first 4 gallon effluent water was derived from cold influent water initially held outside the tank and that had never been heated (Figure 5), indicating limited mixing of cold water with the hot water stored in the tank in the early phases of showering. In contrast, when the check valve was removed, 4 times more K+ was present in the 4 gallon effluent, indicating 4 times more cold water was present in the delivered water, and confirming that cold water was essentially by-passing the tank via reverse flow through the recirculation return line if the check valve is absent. This issue has important implications for the overall energy efficiency and

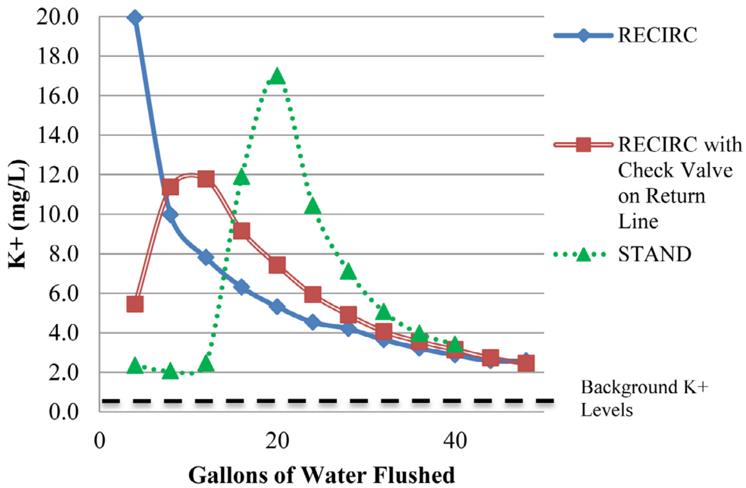


FIGURE 5. KCl tracer study. A slug of KCl was fed into the reactor and K+ was measured in the effluent water to determine how and if mixing was occurring in the recirculation system.

operation of hot water recirculating systems. The STAND system operated closer to a plug flow system, as expected (Figure 5).

4.2 Storage Tank Temperature during Stagnation

The internal temperature of the tanks during stagnation gave insight to the expected energy efficiency of the systems. Standby losses have been cited as being responsible for as much as 50% of the energy demand of storage type water heating systems [20]. These losses are dependent on several factors including the internal temperature and volume of the storage water, the ambient temperature, and the type and amount of installation.

Due to mixing from the pump, the RECIRC system had a consistent, high temperature throughout the entire volume of the storage tank. Temperature recovery from high water demand was essentially complete by 45 minutes after the event throughout the entire volume of the tank. In contrast, the recovery of stable temperature profiles, especially at the bottom of the STAND system for high user pattern, did not occur over the 8 hours of testing. In the low use condition where only 25% of the tank volume turns over each use (50% turn-over per day) the bottom 20% of the STAND storage tank was approximately 12–15°C lower than the top 80% due to temperature stratification within the tank.

The temperature stratification was even larger in the high use STAND condition. Since one tank volume was displaced, 60% of the storage volume was at 10–12°C lower than the temperature setting. This has many implications on standby losses. As previously stated, standby losses are controlled by the temperature differential versus ambient air. The average surface temperature of the tank decreased: RECIRC low use > RECIRC high use > STAND low use > STAND high use. Thus, it would be expected that the RECIRC tank has a greater standby losses than the STAND system in all cases, and low use would always have greater standby losses than high use patterns.

4.3 Energy Efficiency

In all cases, the RECIRC had lower energy efficiency compared to the STAND and DEMAND systems (Table 2). Not only is there added energy consumption for hot water recirculation from the pump (25% net energy increase), but the tank itself requires nearly double the energy to heat water as compared to STAND due to increased standby heat losses from the pipe system and the loss of natural stratification within the tank.

TABLE 2. Energy Efficiency.

Condition	Total Energy Consumption – E_{TOTAL} (kWh/Day)				Energy Out – $E_{DELIVERED}$ (kWh/Day)		Energy Efficiency (%)	
	STAND	RECIRC – TANK	RECIRC – PUMP	RECIRC – TOTAL	STAND	RECIRC	STAND	RECIRC
60°C, High Use	8.1	9.9	0.61	10.5	7.04	5.82	86.9	55.4
49°C, High Use	4.8	6.9	0.61	7.5	4.27	4.12	88.3	55.0
60°C, Low Use	3.2	7.3	0.61	7.9	1.68	1.50	52.2	19.0
49°C, Low Use	2.7	4.9	0.61	5.5	1.47	1.25	55.1	22.7

4.4 Normalized Energy Efficiency and Consumer Use

The total energy demand of the systems (Table 2) appears to indicate that operating at 49°C expends 12–40% less energy than operating at 60°C for the same use pattern, but this is misleading. In the tested scenario, the total energy and output energy of delivered water were calculated without using a mixing valve to temper the hot water with cold water. A higher percentage of cold water would be mixed with water at the 60°C set point to provide a comfortable shower and to prevent scalding. The temperature of a comfortable shower is typically in the range of 32–43°C [21]. Since the temperature and total hot water delivered varies markedly from system to system, calculations were made to normalize the data and estimate energy efficiency if the consumer mixed the hot water with cold water to achieve a fixed volume of water at 37° C (Table 3) [21]. This would reflect the total energy demand on each system if consumers adjusted cold water continuously while showering to maintain 37°C, if a mixing valve made such adjustments automatically, or if volumes of water were drawn for a bath at a constant final temperature. Thus, to normalize the data to account for typical user behavior (assuming a target temperature of 37°C), a normalized "Total Energy" value was determined as follows. The $E_{DELIVERED}$ was fixed in all scenarios such that the total ΔT was predetermined using an average T_{in} of 20°C and final temperature desired of 37°C. Then, using the energy efficiency measured for the systems, a new E_{TOTAL} was calculated and used as the normalized E_{TOTAL} (Figure 1, Table 3). Estimates obtained using calculations (Table 3) had minimal error when compared to confirmation experiments conducted when systems were actually operated to deliver identical quantities of heat (e.g., a fixed volume of water raised to the same temperature).

If the data are normalized for consumer mixing of hot water with cold to hit a target temperature of 37°C, the total extra energy of operating at 60°C versus 49°C is 1–15% higher (Table 3). Thus, while lower temperatures might be necessary and desirable to reduce scaling and scalding potential, in the absence of these considerations overall energy savings from operating at 11°C lower temperature are modest, and the difference is due to reduced standby losses. In situations with water of higher scaling propensity, over the long term, the relative performance advantage of operating at 49°C might increase.

From another perspective the relative energy savings of 49°C vs. 60°C might be eliminated or even reversed if a smaller water heater was operated at the higher temperature. If

TABLE 3. Net Water Consumption and User Costs for Normalized Energy Efficiency.

	60°C, High Use		49°C, High Use		60°C, Low Use		49°C, Low Use	
	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC
Total Energy – E_{TOTAL} (kWh/Day)	8.1	10.5	2.7	5.5	3.2	7.9	2.7	5.5
Normalized Total Energy – E_{TOTAL} (kWh/Day)	5.8	10.2	5.7	10.3	1.6	5.1	1.5	4.3
Water Consumed for Energy Production (Gal/Day)[e]	11.6	20.4	11.4	20.6	3.2	10.2	3.0	8.6
Water Wasted at Tap (Gal/Day)[f]	4.5	0	4.5	0	3	0	3	0
Net Water Consumption (Gal/Day)	16.1	20.4	9.9	11.0	6.2	10.2	6.0	8.6
Annual Consumer Electricity Bill[g]	$233	$410	$229	$414	$64	$205	$60	$173
Additional Costs of Water Due to Waste[h]	$4	$0	$4	$0	$3	$0	$3	$0
Total Cost to Consumer for Water Heating	$237	$410	$233	$414	$67	$205	$63	$173

[e]1 kWh energy produced = 2 gal of water consumed at energy production phase
[f]From Figures 4 and 5 given a flow rate = 1.5 gpm
[g]Given Average Electricity Rate: 1 kWh = $0.11
[h]Given Average Water Rate: 1 gal = $0.0025

the size of the water heater was optimized to provide the same volume of delivered tempered water (e.g. 30 gallons of 37°C tempered water), then less hot water volume would be needed from a system operated at 60°C system (Table 3). Assuming that the surface area of the tank is proportional to standby heat losses, using the example of a target demand of 30 gallons of 37°C delivered tempered water, operation of a water heater at 49°C would require a 20 gallon hot water tank, whereas the same volume of delivered was for a system at 60°C would only require a 14.5 gallon tank with a 17% reduction in surface area. It is conceivable, then, that if water heaters are optimized to minimize tank volume at higher temperature settings, that the benefits of minimizing standby losses would outweigh any increased energy consumption from operating at a higher temperature in non-scaling waters.

Overall, under conditions tested herein, the RECIRC system is still far less energy efficient than the STAND systems. While the RECIRC system will undoubtedly save water at the tap given perfect user conditions (Figures 3 and 4), there is an increased energy consumption of 4–5 kWh daily as compared to STAND. In the model systems, it takes between 45 seconds and 1 minute for the STAND system to run all the cool water to waste (Figures 3 and 4). This equates to approximately 1.2–1.5 gallons conserved in RECIRC as compared to STAND for each flushing event or 3–4.5 gallons of water conserved in RECIRC each day

FIGURE 6. Daily net water consumption for each system and condition given the data and assumptions from Table 3.

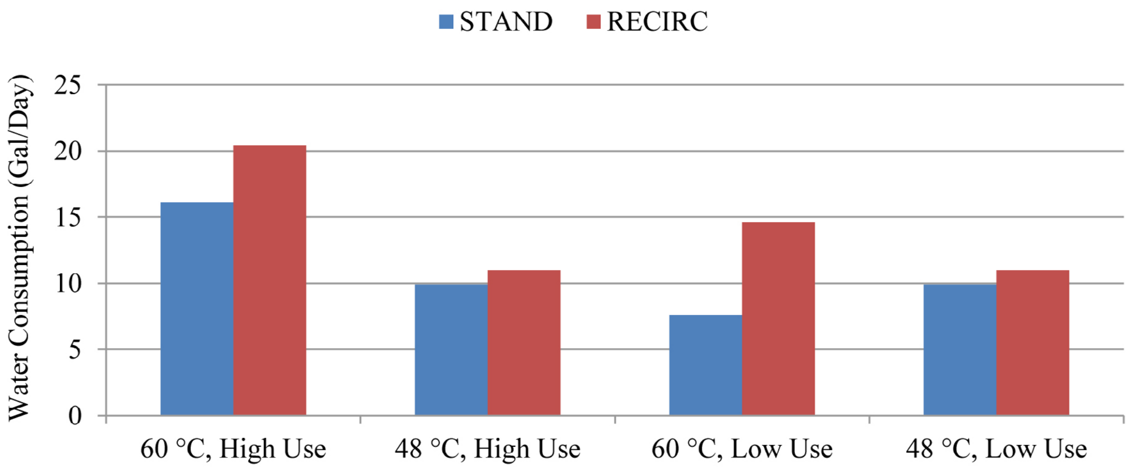
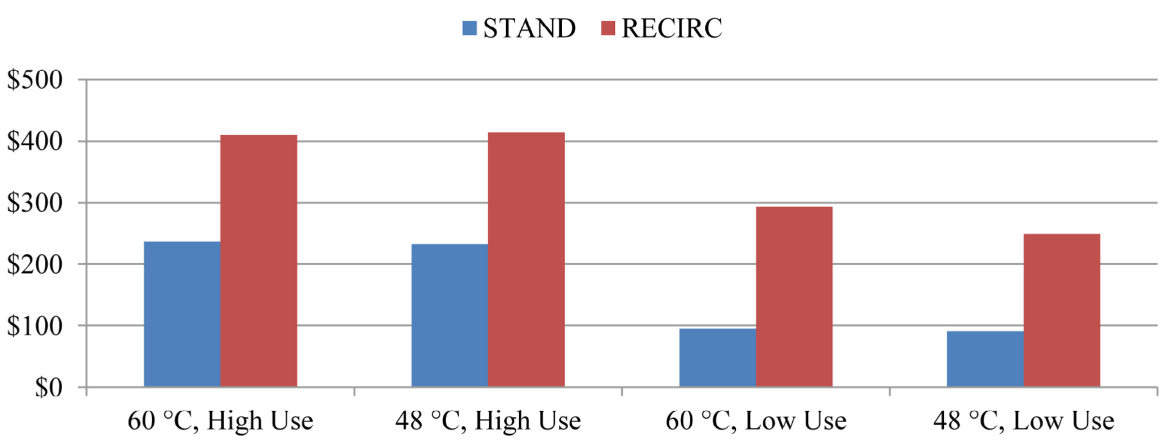


FIGURE 7. Annual consumer utility costs (water and electricity) for water heating based on data and assumptions in Table 3.



(Table 3). Given that it typically takes 2 gallons of water to produce 1 kWh at the energy production phase, the total net water use can actually favor STAND (Table 3, Figure 6) [22]. Thus, this marketed and sometimes mandated "green" system is actually less energy efficient, and is probably less water efficient overall, than the standard system it replaced. When these tradeoffs are compared on the basis of overall consumer costs, a consumer would potentially spend 50–300% more per year to heat water using a RECIRC system as compared to a STAND type heater (Figure 7). To verify this important conclusion for one set of actual operating conditions, the outflow volume of the STAND and RECIRC systems operated at 60°C and low use were operated to provide the same amount of useful product (i.e., 10 gallons/day averaging 1.44 kWh/day for STAND versus 4 gallons/day averaging 1.37 kWh for RECIRC). The measured difference in energy costs was 287% higher for the RECIRC system versus the calculated estimate of 306% in Table 3.

4.5 Point-of-Use DEMAND Water Heaters

Despite achieving nearly 100% energy efficiency the point-of-use DEMAND systems are not always a viable alternative to the STAND system. Specifically, the output temperature is a strong function of the input temperature and flow rate (Figure 8). The net result is that there is a limited range of flow rates at which the system will achieve reasonable temperatures of 32–43°C for the delivered water even when no cold water is used. On average, a "reasonable" shower is in the range of slightly below or above average human body temperature (i.e., 37°C). Not all DEMAND water heaters can meet this minimum temperature. According to the manufacturer specifications for the DEMAND heater used in this experiment, there is a fixed rise in temperature for a given flow rate at the high and low energy settings, respectively (Figure 9). Based on these guidelines, in the winter months in Blacksburg, VA where the influent water is below 10°C, using the high energy setting, a consumer would have to lower the flow rate of the shower to below 1.25 gpm to achieve even a minimum acceptable temperature for showering (note: the minimum temperature defined in this paper is 32°C which may not be adequate for many users). Over 50% of the continental United States (from as far south as North Carolina and parts of Texas and Arizona) has seasonal low temperatures below 10°C, which implies that a substantial fraction of homeowners in these states would need to install low-flow fixtures and/or preheat the influent water to utilize typical electric on-demand systems [23]. On the low energy setting, there is no flow rate that would provide water hot enough for a shower, except if the influent water was above 26° C and a low-flow showerhead with flow rate below 2 gpm is used (Figure 8).

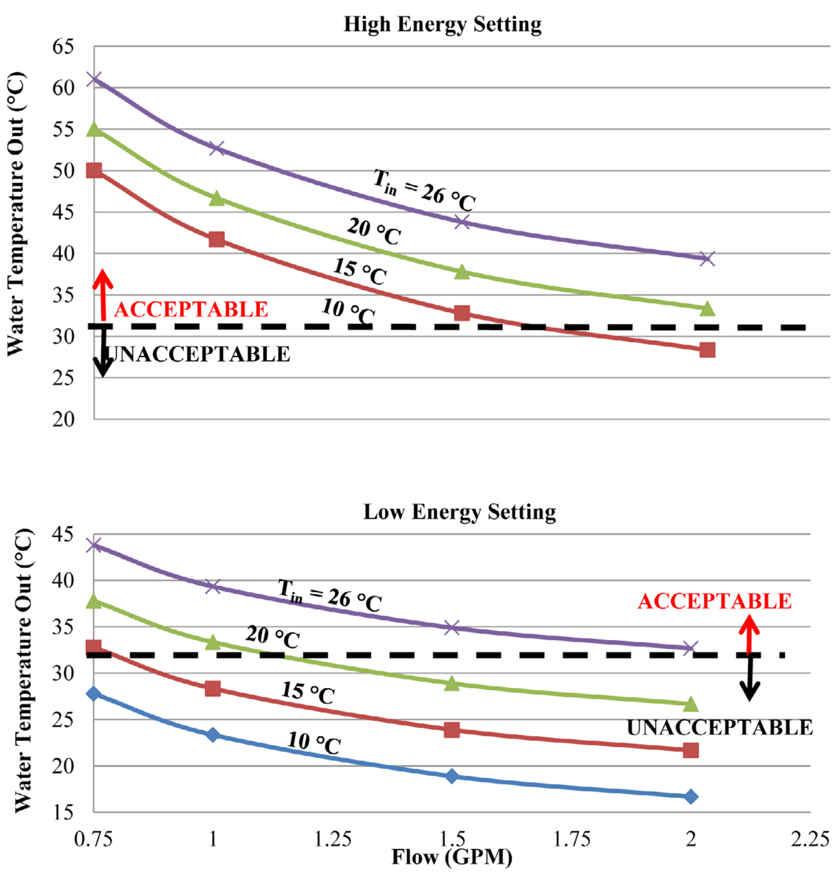


FIGURE 8. Expected output temperatures based on incoming temperature and flow rate from manufacturer specs for the high and low energy settings of the DEMAND system, respectively.

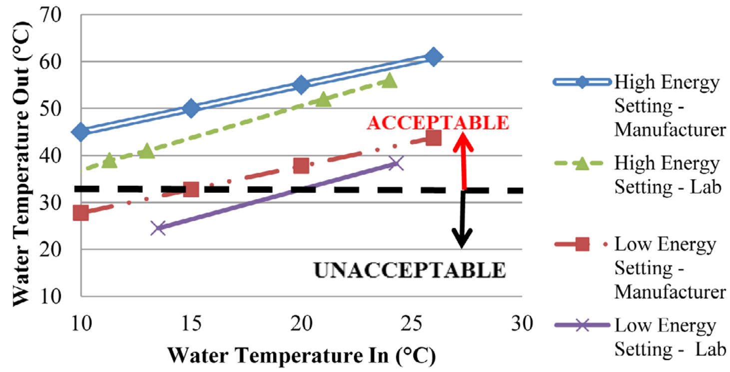


FIGURE 9. Manufacture specs versus laboratory measurements for DEMAND system at 0.75 gpm.

Furthermore, even the smallest DEMAND system available required 220 V electrical connections, and we had to install an $200 voltage booster to upgrade our laboratory's 208 V to 230 V enable the system to heat the water above room temperature during the coldest months. Even with a voltage booster and running at the highest setting, DEMAND only was able to heat the influent water to about 37°C and was lower than the expected manufacturer specs due to a voltage drop when the system is in use (Figure 4 and Figures 8–9). Furthermore, this temperature was only achieved by reducing the flow rate to the lowest possible flow rate of 0.8 gpm. Without the installation of low-flow fixtures at the tap (and even with lower flow fixtures) this flow rate may not be desirable to consumer the coldest winter months and using the low setting, the temperature barely rose above 25°C (Figure 4).

5. CONCLUSIONS

The results of this research provided numerous insights which run contrary to the conventional wisdom and raise significant concerns as to whether certain "green" water heater installations are actually achieving their targeted objectives. From a temperature and energy perspective, the goal of reducing energy demand seems to be in direct conflict with the outcome. The RECIRC system, although mandated by certain municipalities and marketed "green" by manufacture claims, is in fact more detrimental to conservation aims as compared to other systems. The DEMAND system is in fact the most energy efficient, but has issues such as increased power draw during use and inconsistent and undesirable temperature and flow rate. Although additional research is necessary to better understand water heating in the context of the water-energy nexus, this research provides a first step for rational decision making by regulators, public health officials, manufacturers and consumers.

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