OPTIMIZATION OF ELECTRIC HOT WATER RECIRCULATION SYSTEMS FOR COMFORT, ENERGY AND PUBLIC HEALTH

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ABSTRACT

Hot water recirculation systems (RECIRC) are labeled green and are sometimes mandated in local plumbing codes. Previous work conducted under non-optimized operation schemes demonstrated that these systems actually waste energy and water versus standard (STAND) water heater counterparts. Optimization of RECIRC system operation by minimizing pump operation did improve energy efficiency 6–60%, saving consumers 5–140% annually in associated utility costs. However, STAND systems were still more energy efficient than any of the RECIRC systems. With respect to factors that might influence pathogen growth, reducing RECIRC pump operations increased disinfectant residual by as much as 560% as compared to the baseline RECIRC system; however, STAND systems still had 25–250% more total chlorine residual than any of the RECIRC systems. At 60°C operating temperature, STAND systems have 30–230% more volume at risk for pathogen growth (e.g., volume with temp 37–46°C) than any of the RECIRC systems. Thus, in the context of "green" design, RECIRC systems provide a convenience to consumers in the form of nearly instant hot water, at a cost of higher capital, operating and overall energy costs. RECIRC systems have distinct advantages in controlling pathogens via thermal disinfection but disadvantages in control via secondary disinfection residual.

KEYWORDS

Water heaters, energy efficiency, water-energy nexus, green energy, premise plumbing, temperature profiles

1. INTRODUCTION

Potable hot water systems in buildings are a critical part of the water-energy nexus, as water heaters account for the single largest water-related energy consumption in the United States [2]. More recently, hot water recirculation systems have become more common in large single family homes, multi-family structures, hotels and large commercial buildings. These systems are marketed as water-saving, energy efficient, and are mandated in certain municipalities

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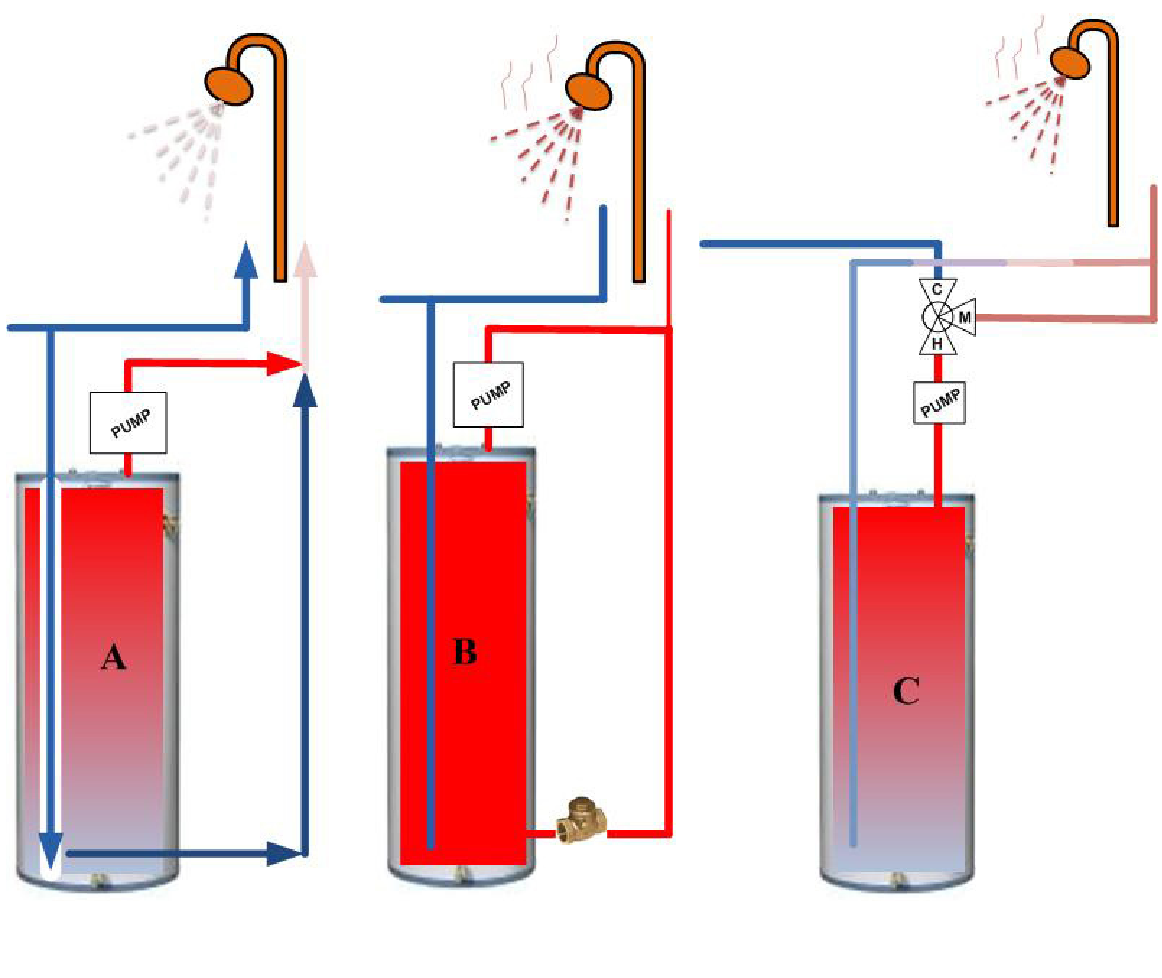
[2–4]. However, a recent head-to-head comparison has demonstrated that these systems actually use more net energy and water than traditional standard water heaters without recirculation [5]. There is also emerging concern that recirculation systems will sometimes increase the occurrence of *Legionella* [1, 6].

This research follows up on work by Brazeau and Edwards [1, 5] which identified several problems associated with continuously operated recirculation systems including reduced energy efficiency, reduced consumer comfort (i.e., temperature of produced water) and reduced levels of disinfectant (Table 1) It was considered likely that some of these concerns could be reduced by operating the pump only for short time periods by the following approaches: 1) turning on the recirculation pump only for a short period with a timer, 2) use of a temperature sensor to turn on the pump when pipes cool below a set point, 3) combination of #1 and #2, or 4) a switch that turns on the pump just before hot water is needed [7]. It is also possible to install systems with a check valve (Figure 1) or placing the pump at the bottom of the heater (always on), which might prevent cold water from short circuiting the hot water tank and passing directly to the shower, a factor which was found to decrease consumer comfort and energy efficiency in prior work. This research will evaluate the potential

FIGURE 1. Various hot water recirculation (RECIRC) systems. A) Dedicated recirculation line with no check valve installed at pipe return, B) Dedicated recirculation line with installation of a check valve, and C) Retro-fit: recirculation line tied into existing cold water line with mixing valve at outlet of storage tank (not tested in this study).



for optimization of recirculating systems, in order to guide improved future design/installation and possible retrofits to improve performance of existing systems (Table 2). Furthermore, a worst case scenario was also analyzed to determine the lowest expected energy efficiency where the insulation was removed from the pipes and the systems were operated in the baseline conditions for high and low use at 60°C. This scenario might best represent a retrofit or a large system in a multi-family residence or hotel.

2. METHODS

Three hot water systems were constructed and operated in parallel to facilitate a "head-to-head" comparison of 1) a standard water heating system with storage (STAND), 2) a "green" water heating storage system with a pump and dedicated hot water recirculation line (RECIRC), and 3) a tankless on-demand system. The "baseline" RECIRC installation operated the recirculation pump continuously and had no check valve on the return line. All pipes were initially insulated with standard self-sealing foam insulation (R = 2). For the worst case no-insulation scenario, all pipe insulation was removed. Additional details on the apparatus design and operation are provided elsewhere [1, 5].

The systems were operated under various conditions including high use, low use, high temperature and low temperature to examine practical extremes encountered in practice. High temperature is 60°C, lower temperature is 48°C, high use involved drawing 100% of the tank volume every 8 hours (3x per day), and low use was a draw of 25% of the tank volume twice daily [1, 5, 8].

In this research, the baseline conditions (RECIRC-Baseline and STAND) were compared to three "optimized" modes of operation including: 1) Pump Optimized—pump operates on a timer set to turn on 15 minutes just prior to flushing, 2) Check Valve—a check valve was installed at the return line to prevent short circuiting and 3) Pump Optimized-Check Valve—a combination of the two strategies. The baseline conditions were also compared to the two systems without insulation: 1) STAND-No Insulation and 2) RECIRC-No Insulation. The conditions with the insulation removed were solely analyzed for energy efficiency comparisons and related costs and water consumption. To compare energy efficiency and consumer comfort, temperature profiles of water heater output and disinfectant decay, "worst" case conditions derived from prior research were selected (Table 1). Since both energy efficiency and chloramine decay were worst in recirculation systems at 60°C, this temperature setting was chosen for evaluation.

Energy efficiency was derived by methods described in Brazeau and Edwards 2012 [5] where energy efficiency = total energy delivered in hot water to the tap/total energy consumption. Total energy was determined using an electric watt meter that measured alternating current (AC) consumption directly and provides cumulative kWh values for the RECIRC and STAND systems as well as the RECIRC pump. The energy delivered in hot water to the tap was based on temperature increase of water from the heater (Figure 1):

$$q = mc\Delta T$$

where, q = energy in terms of heat transfer to water

m = mass

c = specific heat capacity of water

ΔT = change in temperature

TABLE 1. Key Results from Previous Studies to Draw Baseline Comparisons to Optimized Study.

Water Heater Type	Energy Efficiency—High Use		Energy Efficiency—Low Use		Disinfectant Residual—High Use (mg/L)		Disinfectant Residual—Low Use (mg/L)		User Comfort for Shower at 37°C
	60°C	49°C	60°C	49°C	60°C	49°C	60°C	49°C	Figure 4-2
STAND	90%	88%	52%	55%	1.55	2.15	1.30	1.22	Remains above 37°C for length of flush (13.5 minutes)
RECIRC	55%	55%	19%	23%	0.51	1.42	0.19	0.37	Immediately rises above 37°C; but drops below 37°C after 5.5 minutes

ΔT was determined by measuring the initial temperature of influent cold water in 4 gallon buckets of water from the laboratory tap using a digital thermometer. Additional information on temperature profiles within the tank was obtained using a data logger and temperature probes inserted in the tank with every 4" depth, and used to determine the volume of water potentially susceptible to regrowth of pathogens [1, 5].

The "worst" case condition, as determined in a previous study, for disinfectant residual for the RECIRC system was during the 60°C and low use condition (Table 1) [1]. Since chlorine decays with both time and temperature, the longer stagnation period, low volume of water turnover, and higher temperature of this condition makes it the most vulnerable to increased disinfectant decay. Therefore, for the purposes of disinfectant residual, this operation mode was replicated for the "optimized" conditions to analyze chloramine decay. Chloramine residual was analyzed identically to the previous study [1] for continuity using colorimetric methods via a HACH pocket chlorimeter.

3. RESULTS

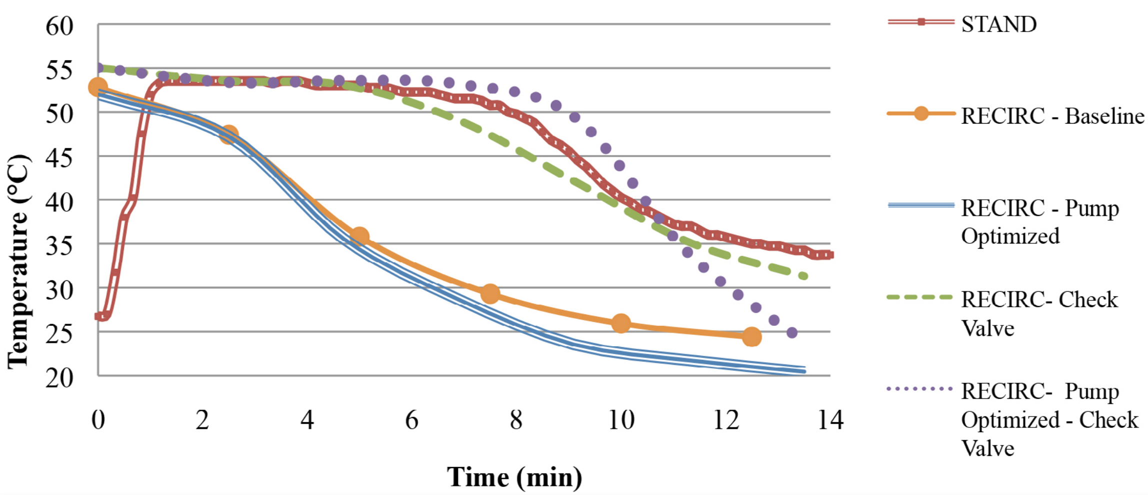
After examining the impacts of optimization on temperature of water delivered to the tap and energy efficiency, effects on internal tank temperature and disinfectant residuals (i.e., total chlorine) are quantified.

3.1 Temperature Profiles during System Flushing

During the baseline mode of operation (60°C and high use), the hot water delivered to the tap from the RECIRC system cooled rapidly after 2 minutes of continuous water flow (i.e., flushing) (Figure 2), whereas the STAND tank remained at a high constant temperature for 8 minutes (i.e., nearly 50% of the flushing time).

It was hypothesized that the rapid decrease in temperature of water flowing from the RECIRC system was due to cold water mixing within the tank due to action of the pump and/or cold water back flowing (i.e., short circuiting) out of the bottom of the tank (reverse flow through the return line). The existence of a short circuiting effect was unambiguously demonstrated previously through a tracer study [5]. Short circuiting through the return line is not possible in the STAND system because there is no return line. Three different modes of operating the RECIRC system were tested to examine optimization approaches to mitigate the drop in temperature.

FIGURE 2. Temperature profiles during flushing.



The RECIRC-Pump Optimized condition, which runs the pump for just 15 minutes before use and then turns the pump off when hot water is drawn from the tank, had no impact on the cooling trend (Figure 2). Clearly, the mixing of hot water with cold is not due to the pump. In contrast, the installation of a check valve and leaving the pump operating continuously, eliminated the cooling problems for water drawn from the tank and operated nearly identical to the STAND system. Likewise, the combination strategy (RECIRC-Pump Optimized-Check Valve) also made the RECIRC system behave nearly like the STAND system in terms of stable, consistent hot water flow (Figure 2). Overall, these results demonstrate that use of a check valve eliminates undesired dropping water temperature during use of a recirculation system.

3.2 Energy Efficiency

Heat losses through the walls of pipes and tanks for the different hot water systems were discussed in detail previously [5]. Losses are exacerbated by continual recirculation of hot water and the electricity consumed by the pump is also significant. Short circuiting, as defined previously in RECIRC systems without a check valve installed, also tends to reduce energy delivery in the form of hot water, reduce daily energy demand, and lower the overall energy efficiency.

Installation of a check valve alone with continuous pump operation, markedly improved the delivery of hot water, but only improved energy efficiency by about 3% (Table 3). Restricting use of the pump to just 15 minutes immediately before water demand events dramatically reduces extra energy losses of RECIRC vs. STAND systems. When the RECIRC-Baseline condition was compared to the RECIRC pump optimized conditions at high use and low use, the energy efficiency improved by 25.8% and 53.1%, respectively. But even with the pump turned off 98% of the day at low and high use, energy efficiency of the RECIRC was still 20–40% lower than the STAND condition. When both check valves and reduced pump demand were used in RECIRC systems, the comparable STAND system was still 5% more efficient than the RECIRC-Pump Optimized-Check Valve system (Table 3). As expected, removing the insulation from the pipes drastically reduced the energy efficiency. When compared to the baseline conditions, the energy efficiency RECIRC-No Insulation system was 79–181% and 26–71% lower for the high and low use conditions, respectively (Table 3).

TABLE 2. Various Modes of Operation and Installation for Hot Water Recirculation Systems.

	Various Pump Operations/Modes					Other Installation Considerations			
ISSUE	**Continuous Pump (Baseline)[1]** Pump installed either at top of tank or bottom of tank and runs continuously	**Timer Controlled Pump[a,b]** Pump only operates at pre-determined times (highly variable) [7]	**Thermostat-Controlled Pump** Pump is triggered on when thermostat in pipes drops below a pre-determined temperature	**Demand Pump[a,b]** Pump is controlled by push-button that is triggered by user	**Thermosiphon** No pump—recirculation is controlled by thermal changes and gravity through a return line	**Check Valve[a]** Installed on return line to prevent backflow from water heater	**Pump Location** Can either be installed at top of tank or bottom of tank	**Recirculation Pipes** **New Construction:** Dedicated Return line **Retrofit:** Can tie into existing cold water line (Figure 1)	**Pipe Insulation** **New Construction:** Pipes typically insulated **Retrofit:** Pipes may not have any insulation
Energy Implications	Increased heat loss due to loss of stratification and through pipes; pump requires energy [5]	Less energy than baseline; Highly dependent on timer set-up	Expected to have greater energy efficiency than continuous pump	Recirculation and pump energy minimized	Much less energy loss than baseline	If not installed: short circuiting of cold water reducing delivered energy [5]	If installed at bottom—similar to check valve	No dedicated cold water line—all water consumption uses some heated water	Tremendous heat loss potential during circulation through pipes
Flushing Temperature Implications	Instant hot water at tap, mixing due to pump may cause rapid cooling [5]	If pump is off during flushing, cooling effects from pump eliminated?	If pump is off during flushing, cooling effects from pump mixing eliminated?	If pump is off during flushing, cooling effects from pump mixing eliminated?	Same as baseline?	If not installed: short circuiting of cold water causing rapid cooling [5]	If installed at bottom—similar to check valve?	Water always warm? No cold water? Water not hot enough?	Same as baseline?
Pathogen Growth Potential	Low disinfectant residual due to pipe contact; nutrients, toxins and disinfectant delivered to biofilm; increased H_2 [1]	Little difference from STAND?	Little difference from STAND?	Little difference from STAND?	Same as baseline?	If not installed: potential reverse flow in pipes [1]	If installed at bottom—similar to check valve?	Cold water line eliminated—warm water through pipes increases pathogen growth?	Same as baseline?

[a]Tested herein
[b]Timer was reduced to lowest possible to represent "best case" for timer controlled and/or a demand controlled pump

TABLE 3. Energy Efficiency Results.

Condition	Total Energy Consumption (kWh/Day)				Energy Out (kWh/Day)		Energy Efficiency (%)	
	STAND	RECIRC–TANK	RECIRC–PUMP	RECIRC–TOTAL	STAND	RECIRC	STAND	RECIRC
Pump On Continuously								
60°C, High Use	8.1	9.9	0.61	10.5	7.04	5.82	86.9	55.4
60°C, Low Use	3.2	7.3	0.61	7.9	1.68	1.50	52.2	19.0
60°C, High Use—Check Valve	9.7	14.3	0.63	14.9	6.47	8.70	67.1	58.3
60°C, High Use—No Insulation	9.1	18.5	0.63	19.1	7.32	5.91	80.9	30.9
60°C Low Use—No Insulation	3.0	13.0	0.63	13.6	1.36	2.06	45.3	15.1
Pump Optimized—On 15 Minutes Prior to Flushing								
60°C, High Use	10.6	7.5	0.03	7.6	9.44	5.27	88.8	69.7
60°C, Low Use	3.3	4.0	0.01	4.0	1.68	1.60	51.2	40.5
60°C, High Use—Check Valve	9.7	11.6	0.03	11.7	8.85	10.22	91.7	87.6

3.2 Internal Tank Temperature

A recommended minimum temperature of 60°C is proposed for pathogen control by the World Health Organization, ASHRAE and others [9–11]. But the tank setting only influences, and does not control, the temperature of the volume of water in pipes and at the bottom of water heaters. If 46°C is considered as a threshold for the termination of Legionella and MAC growth and 30–37°C is an ideal growth range, then weighted daily average volumes of water in each storage tank at risk for potential pathogen growth can be determined using the equation described in Brazeau and Edwards, 2012 (Figure 3, Table 4) [1, 12, 13].

In every condition the STAND system had 30–430% more volume at risk than the RECIRC systems when applying the 46°C threshold for controlling pathogen growth (Table 4). Moreover, the STAND system had 24–577% more volume in the ideal growth range during a 24-hour period. The addition of the check valve to the baseline condition (RECIRC—Check Valve) had nearly 2.5 times less water at risk as compared to the RECIRC-Baseline and represents a "best case" scenario from a temperature perspective on pathogen growth. When the pump was continuously on (Baseline and RECIRC-Check Valve conditions), the RECIRC systems had a high, stable temperature throughout the tank which eliminated stratification (Figure 3). When the pump was optimized (RECIRC-Pump Optimized and RECIRC-Pump Optimized-Check Valve), there was stratification during stagnation

FIGURE 3. Internal tank temperatures for baseline and optimized conditions at 60°C and a high user pattern. Data loggers were inserted the length of the tank as described in Brazeau and Edwards, 2012 [1] with each data logger (Top, 2, 3, 4, and Bottom) being 4” in length.

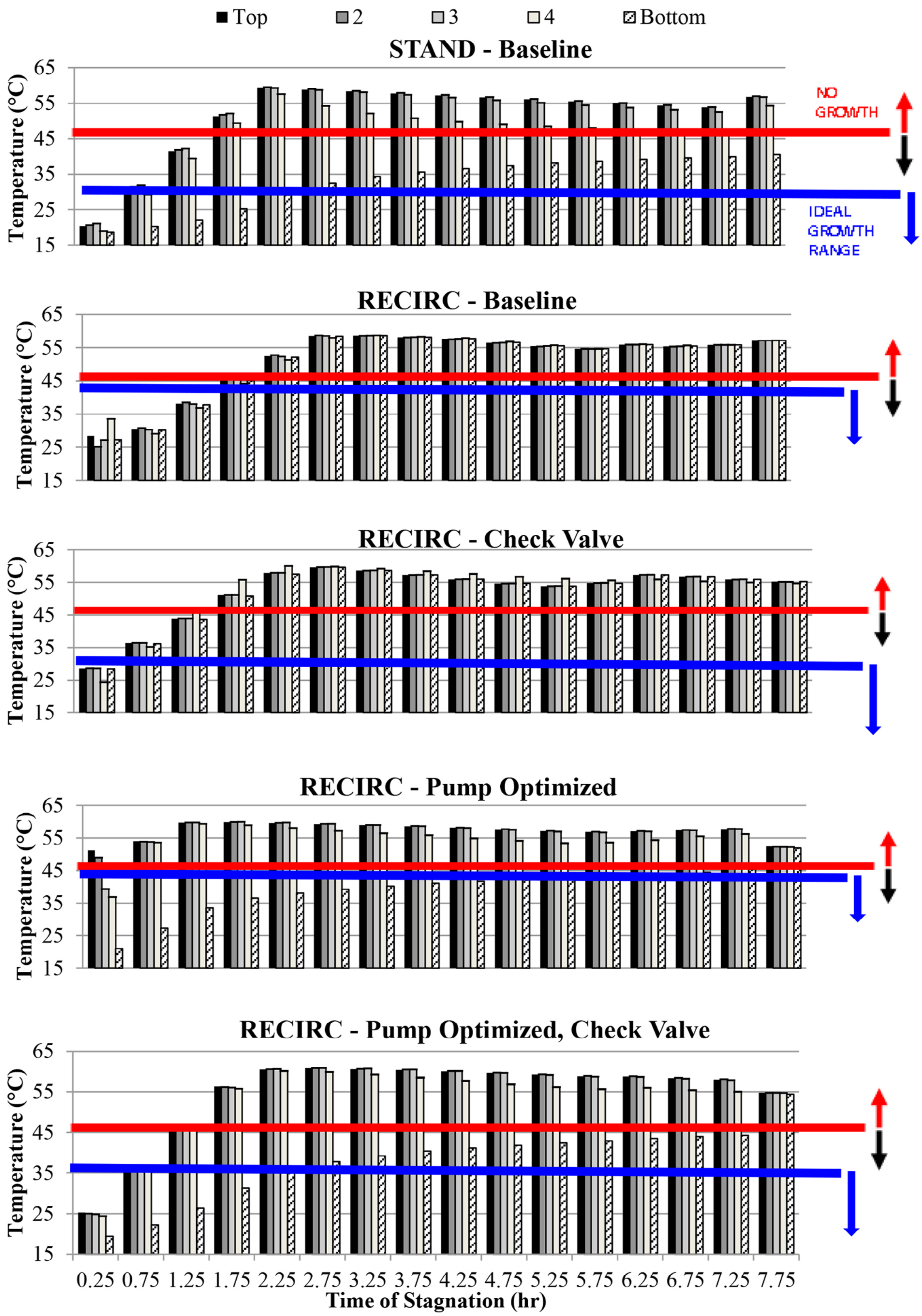


TABLE 4. The average percent of tank volume below key temperatures during a 24-hour period of the baseline conditions as compared to the optimized conditions.

Water Heater Type	Storage Volume (Tank) Below 46°C Per Day High Use (% Tank)	Storage Volume (Tank) Below 37°C Per Day High Use (% Tank)
STAND	31	21
RECIRC	22	16
RECIRC—Check Valve	16	9.4
RECIRC—Pump Optimized	18	6.9
RECIRC—Pump Optimized—Check Valve	24	14

which was broken up just prior to flushing. Since the entire volume of the tanks and pipes were heated prior to flushing (due to recirculation), the RECIRC-Pump Optimized conditions heated faster than the STAND system (Figure 3).

3.3 Disinfectant Residual

As determined by the previous study of the baseline condition, the STAND system had up to 850% more chlorine residual in the bottom of the tank as compared to the RECIRC-Baseline condition (Figure 4-4) [1]. In this optimized study, the RECIRC systems also always had less disinfectant residual than the STAND system (Figure 4). While adding a check valve increased the total disinfectant residual at the end of stagnation as compared to the baseline condition, the STAND system still had up to 260% more residual as compared to this optimized RECIRC condition. This shows that while short circuiting and dilution may be responsible for some of the decrease in total chlorine, even short term pump operation and associated contact additional with premise plumbing is a dominant factor in increased chlorine decay [1, 14].

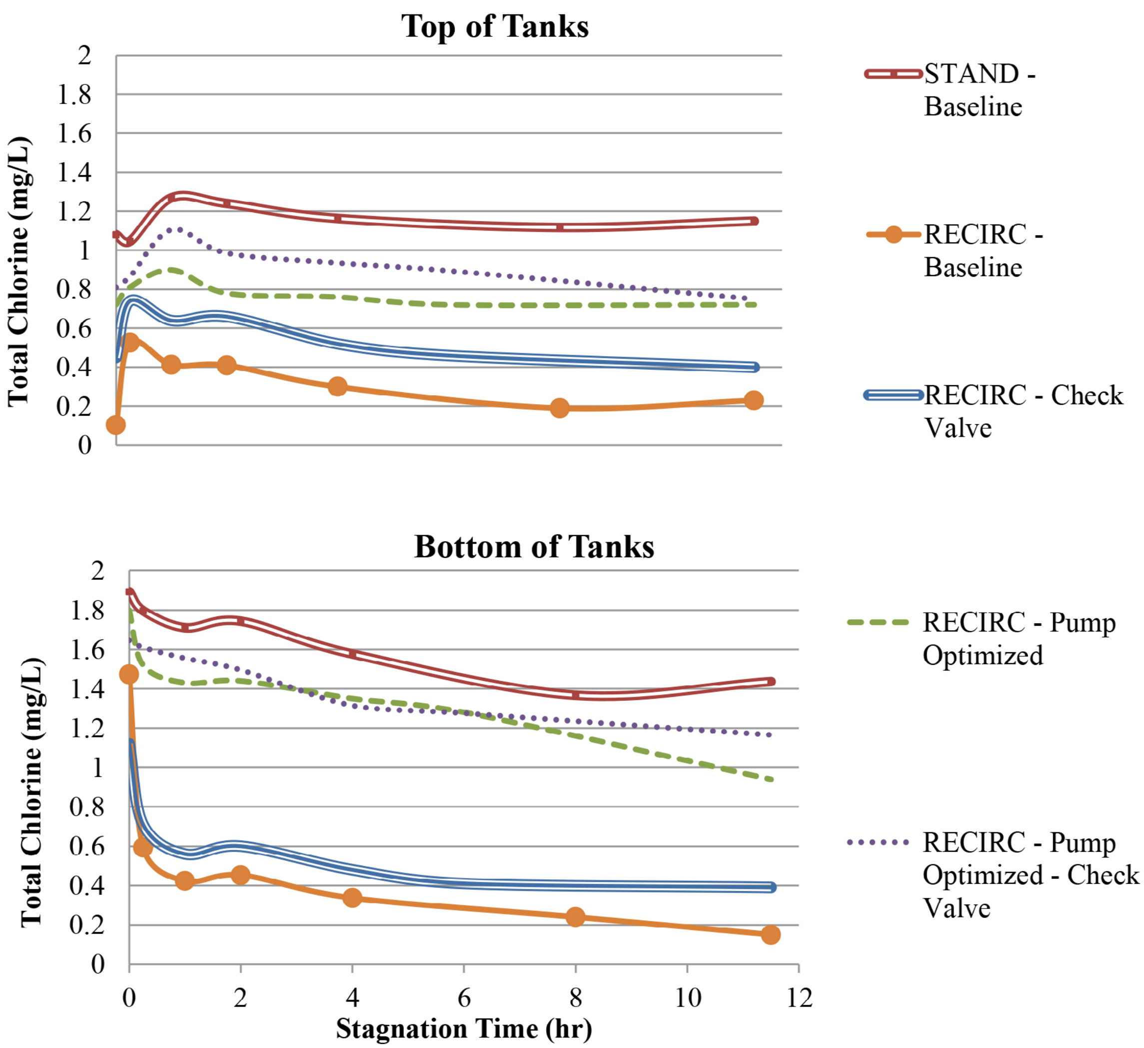
When the pump operation time was minimized, there was 4.5–5.5 times more chlorine residual at the end of stagnation as compared to RECIRC-Baseline (Figure 4). Furthermore, since the system is not completely mixed throughout the stagnation period, there is 1.5 times more chlorine residual at the bottom of the tank, where increased sediment and lower temperatures could facilitate a greater likelihood of biofilm and pathogen growth as compared to the top of the tanks. In the continuously pumped systems, the total chlorine is the same at the top and bottoms of the tank.

4. DISCUSSION

4.1 Energy Efficiency, Water Savings, Costs, and Consumer Concerns

Hot water recirculation is marketed as water and energy saving [4, 15] and while it does in fact save some water at the tap in the consumers home, it inevitably does so at the expense of increased energy use. Under the best scenario optimized RECIRC had 20% more energy consumption and was 3% less energy efficient. Under the worst scenario (low use, no insulation), RECIRC used 353% more energy than STAND and was 200% less energy efficient (Table 3). A more representative analysis from the perspective of a consumer needs to consider that hot water alone is not used, but that hot water will be tempered with cold water to achieve a consistent shower or bath temperature.

FIGURE 4. Total chlorine residual in storage tanks for various operation modes at 60°C and a low user pattern.



4.1.a. Normalized Energy Efficiency

Since the temperature and total hot water delivered varies markedly from system to system, calculations were made to estimate energy efficiency if the consumer mixed the hot water with cold water to achieve a fixed volume of water at 37°C (Table 5) [16]. 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. Prior work demonstrated that the estimates obtained using calculations 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) [5].

Using this normalized result, net water consumption and total annual costs associated with the defined use patterns for each system were compared to the baseline conditions (Table 5, Figure 5, and Figure 6). In all cases, the overall annual water and electricity costs associated with the optimized RECIRC systems were 8.5–66% higher than the baseline STAND

TABLE 5. Net Water Consumption and User Costs for Normalized Energy Efficiency at 60°C for Various Operation Modes.

	High Use		Low Use		High Use—Check Valve		High Use		Low Use		High Use—Check Valve		High Use		Low Use	
	Pump On Continuously[a]						Pump Optimized[a]—On 15 Minutes Prior to Flushing						Pump On Continuously[a], No Insulation			
	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC
Total Energy (kWh/Day)	8.1	10.5	3.2	7.9	3.0	13.6	10.6	7.6	3.3	4.0	9.7	11.7	9.1	19.1	3.0	13.6
Normalized Total Energy (kWh/Day)	**5.8**	**10.2**	**1.6**	**5.1**	**7.6**	**9.7**	**5.7**	**7.9**	**1.6**	**2.1**	**5.5**	**6.1**	**7.0**	**19.6**	**2.1**	**7.9**
Water Consumed for Energy Production (Gal/Day)b	11.7	20.3	3.1	10.1	15.1	19.4	11.4	15.7	3.2	4.2	11.1	12.2	13.9	39.2	4.1	15.8
Water Wasted at Tap (Gal/Day)c	4.5	0	4.5	0	4.5	0	4.5	0	3	0	3	0	4.5	0	4.5	0
Net Water Consumption (Gal/Day)	**16.2**	**20.3**	**7.6**	**10.1**	**19.6**	**19.4**	**15.9**	**15.7**	**6.2**	**4.2**	**14.1**	**12.2**	**18.4**	**39.2**	**8.6**	**15.8**
Annual Consumer Electricity Billd	$234	$409	$63	$203	$303	$390	$229	$315	$64	$85	$222	$244	$279	$787	$83	$316
Additional Costs of Water Due to Wastee	$4	$0	$4	$0	$4	$0	$4	$0	$3	$0	$3	$0	$4	$0	$4	$0
Total Cost to Consumer for Water Heating	**$238**	**$409**	**$67**	**$203**	**$308**	**$390**	**$233**	**$315**	**$67**	**$85**	**$225**	**$244**	**$284**	**$787**	**$87**	**$316**

[a]Since STAND has no pump, pump operation indicated is for RECIRC only
[b]1 kWh energy produced = 2 gal of water consumed at energy production phase
[c]Given a flowrate = 1.5 gpm
[d]Given Average Electricity Rate: 1 kWh = $0.11
[e]Given Average Water Rate: 1 gal = $0.0025

system. While this seriously calls into question the "green" designation for such systems, the use of an optimized recirculation does improve markedly on conditions in previous work, for which RECIRC costs were up to 200% higher than STAND [5]. With the pump continuously running, the RECIRC-No Insulation systems were 178–263% more costly than the relative STAND-No Insulation conditions. In other words, the RECIRC system reduces the consumer wait time for hot water at that tap at the expense of higher energy use and consumer costs between 8–263% more, dependent on use patterns, system design and operation (Table 5).

4.1.b. Net Annual Water Consumption

While the RECIRC system is not energy saving as compared to the STAND system in any scenario, there are probably some net annual water savings accrued from operation of the hot

FIGURE 5. Relative daily water consumption of operating the various water heater systems under the "optimized" conditions at a temperature setting of 60°C. Note: Water consumption includes water used for energy production (Table 5).

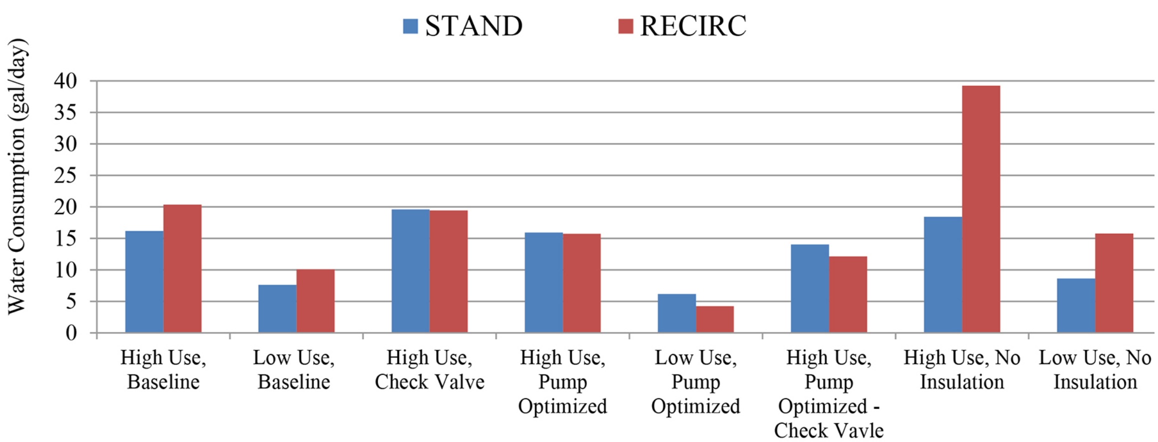
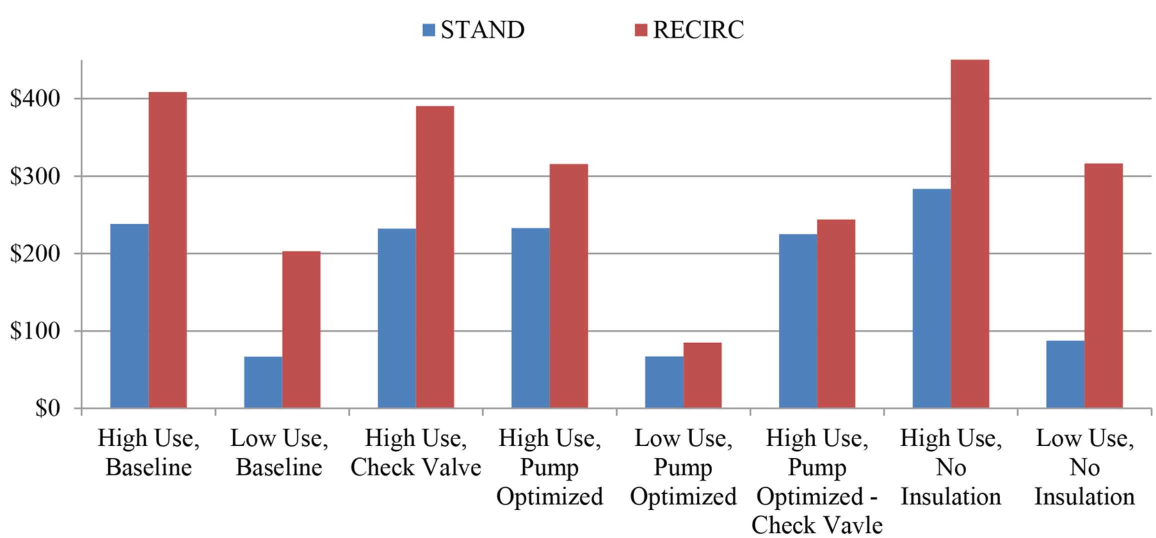


FIGURE 6. Relative annual costs of operating the various water heater systems under the "optimized" conditions at a temperature setting of 60°C.



water system that are projected only if the pump is optimized (Figure 6). These projections require an extreme assumption that all water in STAND systems is wasted down the drain until the temperature of the hot water reaches 37°C and that no water at all is wasted by consumers in the RECIRC system. This extreme assumption is probably close to reality for shower use, but not if a consumer captured all water for bathing and tempered it to a final target temperature. Under this extreme scenario, two of the systems with the RECIRC pump optimized (low use and high use with a check valve) have a projected net water savings of 2 gallons per day compared to the comparative STAND system (Figure 5, Table 5).

4.1.c. Consumer Costs

RECIRC systems always cost more than STAND systems (Figure 5). Even under the best case scenario RECIRC costs 8.5% more to operate than STAND. While this tradeoff obviously depends on the relative cost of water and energy (i.e., in this work $0.11/kWh and $0.0025/gal of water) it is difficult to imagine a scenario when RECIRC would actually save consumers in operating costs. The extra cost of operating a RECIRC system was reduced dramatically by optimizing the pump operation (Figure 6). Installation of the check valve alone reduced operating costs by 4%, whereas optimization of pump operation decreased annual costs by 37% and 45% for the high use and low use conditions, respectively (Table 5). The energy efficiency of installing a check valve was very similar to the baseline condition and thus had an almost negligible effect on total costs when normalized (Table 5, Figure 6).

There are other potential concerns and costs associated with RECIRC systems. First, as noted previously, any cold water mixing due to short circuiting or pump circulation may cause a noticeable difference in user comfort (Figure 2). If a comfortable shower temperature is defined as 37°C, then the STAND system has a capability for 9–260% longer shower times as compared to the various RECIRC systems (Figure 2). In the worst-case baseline condition, the comfortable shower time for RECIRC draws only 20% of the tank volume. Extrapolated to a standard water heater size of 40 gallons and a flow rate of 1.5 gpm, this would equate to a 5.4 minute shower assuming the user steps in immediately after turning on the tap and there is no cold water mixing. If the tank temperature setting was 49°C as recommended by the EPA, this effect would likely be even more noticeable [17]. It is possible, even likely, that a consumer in such situations might terminate their showering more quickly due to discomfort, resulting in actual water and energy savings. Such human behavioral analysis is beyond the scope of the work presented herein.

4.2 Potential Implications on Pathogen Growth in Premise Plumbing

Similarly to the baseline study [1], analysis of factors that might influence pathogen growth are framed in terms of draft proposed ASHRAE standards for Legionella control through: 1) temperature control (> 60°C) and 2) maintaining a disinfectant residual (> 0.5 mg/L Cl) [10].

4.2.a. Pathogen Mitigation through Temperature Inactivation Strategies

From the perspective of temperature control, all of the RECIRC systems outperformed the STAND system with respect to minimizing storage volume at risk for pathogen growth. The RECIRC-Check Valve system shows the greatest potential for pathogen control with the smallest volume at risk (Table 4). The key point is that with recirculation, the internal tank temperature and pipes in the loop are at a constant and high temperature everywhere, which is potentially beneficial in terms of reducing pathogen amplification.

When the pump is optimized and only runs for 15 minutes prior to flushing, stratification occurs during stagnation making these systems more like the STAND system. However, since there is some recirculation prior to flushing which heats the entire volume of the water including near the bottom of the tank, the "recovery time" (i.e., the time it takes for the fresh, cold water to heat to the temperature setting, Figure 3) for the RECIRC-Pump Optimized system is less than both the RECIRC-Pump Optimized-Check Valve and the STAND system given that some volume of cold water short circuits the tank.

The bottoms of water tanks may have a great potential for pathogen growth due to sediment accumulation and temperature stratification in some systems. Both of the continuous pumping conditions (RECIRC-Baseline and RECIRC-Check Valve) have the hottest temperature at the bottom of the tanks, with an average and maximum temperatures well above 46°C (Figure 7). Both of the pump optimized conditions have average temperatures at the bottom of the tank below 40°C which is suitable for pathogen growth. However, the maximum temperature of these systems is above 50°C which can conceivably stop pathogen growth each time the pump mixes the tank. In contrast, the bottom of the STAND system never rises above 40°C, possibly creating conditions suited to sustained pathogen amplification (Figure 7).

4.2.b. Pathogen Mitigation and Disinfectant Residual

Comparing RECIRC to STAND systems, all of the RECIRC systems have less chlorine residual than STAND at all times in the tank (Figure 4). However, it is possible that enhanced transport of chlorine to the biofilm along the tank and pipe walls during the 15 minutes that the pump is on, might be beneficial for biofilm control despite the lower overall disinfectant residual. That is, the extra delivery of disinfectant to the pipe walls during recirculation and resulting benefits in control of biofilm, could outweigh detriments associated with less chlorine in the RECIRC systems.

When comparing one RECIRC system to another, the RECIRC-Pump Optimized conditions had up to 560% more chlorine residual than the RECIRC-Baseline condition (Table 6). The RECIRC-Check Valve system had up to 122% more disinfectant residual than the RECIRC-Baseline condition, but still had far less chlorine residual than the RECIRC-Pump Optimized conditions. Finally, the installation of a check valve prevents short circuiting and any biofilm shearing from reverse flow along the pipe return line. This is another added benefit of installing a check valve on the return line (Table 6).

FIGURE 7. Minimum, average and maximum temperatures at bottoms of tanks during 8-hour stagnation period.

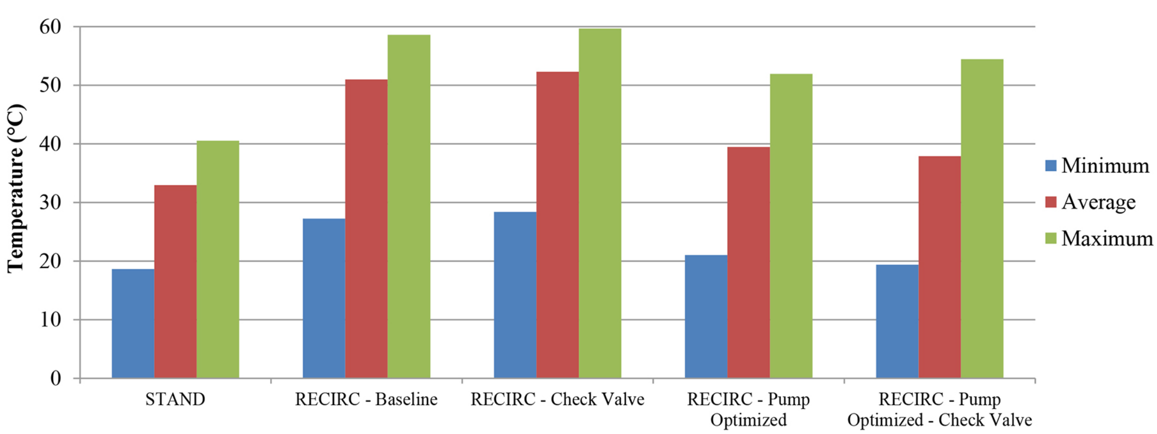


TABLE 6. Summary of Key Results.

SYSTEM	Stagnation Temperature	Energy Efficiency (High Use)	Annual Water Consumption for High Use (gal/yr)	Annual Consumer Cost for Water and Energy for High Use	Volume of Water at Risk for Pathogen Growth (per day)	Total Chloramine Residual	Flow Reversal, Mass Transport to Biofilm
STAND—Baseline	**Tank:** Stratifies; Bottom as much as 25°C cooler than top **Pipes:** Cool to ambient (25°C) in > 4 hours	90%	5700	$238	31%	Up to 860% higher than RECIRC- Baseline in bulk water	None, Low transport
RECIRC—Baseline	**Tank:** Homogenous **Pipes:** Heated to tank temperature	55%	7410	$409	22%	Improved delivery of disinfectant to biofilm	Flow reversal in pipes, high transport
STAND—No Insulation	**Tank:** Stratifies; Bottom as much as 25°C cooler than top **Pipes:** Cool to ambient (25°C) in < 4 hour	81%	6720	$284	Same as baseline	Same as baseline	Same as baseline
RECIRC—No Insulation	**Tank:** Homogenous **Pipes:** Heated to tank temperature but constant heat loss to ambient	31%	14320	$787	Same as baseline	Same as baseline	Same as baseline
RECIRC—Check Valve	**Tank:** Homogenous **Pipes:** Heated to tank temperature	58%	7080	$390	9.4%	Up to 122% higher than RECIRC-Baseline; Delivery to biofilm	None, High transport
RECIRC—Pump Optimized	**Tank:** Stratifies; Bottom as much as 25°C cooler than top; Homogenous 15 minutes prior to flushing **Pipes:** Cool to ambient (25°C)	70%	5730	$315	18%	Up to 400% higher than RECIRC- Baseline; Low delivery to biofilm,	Flow reversal in pipes, low transport
RECIRC—Pump Optimized—Check Valve	**Tank:** Stratifies; Bottom as much as 25°C cooler than top; Homogenous 15 minutes prior to flushing **Pipes:** Cool to ambient (25°C)	88%	4450	$244	24%	Up to 560% higher than RECIRC-Baseline; Low delivery to biofilm	None, low transport

5. CONCLUSIONS

5.1 Comparison of RECIRC-Baseline to the Optimized and No-Insulation RECIRC Systems

In a head to head study evaluating how optimized electric RECIRC systems compared to those without a check valve and continuous pump operation (RECIRC-Baseline), optimization could increase energy efficiency 5.5–60%. This equates to 5–40% cost savings for heating water compared to the typical installation of RECIRC systems. The optimized condition also produced a 560% higher disinfectant residual at the bottom of the tank at the end of the 12-hour stagnation period. In contrast, when insulation is removed, there is a decrease in energy efficiency and increase in cost. In fact, the RECIRC-Baseline Condition has increased efficiency of 79–267% as compared to the RECIRC-No Insulation for the high and low uses, respectively. This relates to 56–74% cost increases in the no insulation condition.

5.2 Comparison of RECIRC Systems to STAND

Despite claims of water savings, the baseline RECIRC systems had a net water consumption (i.e., water saved at tap minus the water needed to produce energy) of 2.5–4.0 gallons per day more than the STAND system. However, when the pump was optimized, under fairly extreme assumptions of consumer waste of water down the drain while temperature rose in a STAND system, the RECIRC system saved up to 2 net gallons per day versus STAND. In the worst-case no insulation conditions, the RECIRC-No Insulation systems used 84–113% more water than the STAND-No Insulation counterparts. On the basis of temperature analysis, the STAND system had 30–230% more volume at risk for pathogen growth as compared to any of the optimized RECIRC systems. The continuous pump operation RECIRC with a Check Valve system had the least amount of volume at risk.

While optimizing the RECIRC system improved total chlorine residuals, the STAND system still had 25–250% more total chlorine residual than the optimized RECIRC systems. STAND systems were between 3–55% more energy efficient and were projected to save consumers between $19–$158 annual on water and electrical costs when compared to any of the RECIRC systems. Thus, in the context of "green" design, RECIRC systems provide a convenience to consumers in the form of nearly instant hot water, at a cost of higher capital, operating and overall energy costs.

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