Role of Hot Water System Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution, and Sediment

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Abstract

Residential water heating is linked to growth of pathogens in premise plumbing, which is the primary source of waterborne disease in the United States. Temperature and disinfectant residual are critical factors controlling increased concentration of pathogens, but understanding of how each factor varies in different water heater configurations is lacking. A direct comparative study of electric water heater systems was conducted to evaluate temporal variations in temperature and water quality parameters including dissolved oxygen levels, hydrogen evolution, total and soluble metal concentrations, and disinfectant decay. Recirculation tanks had much greater volumes of water at temperature ranges with potential for increased pathogen growth when set at 49°C compared with standard tank systems without recirculation. In contrast, when set at the higher end of acceptable ranges (i.e., 60°C), this relationship was reversed and recirculation systems had less volume of water at risk for pathogen growth compared with conventional systems. Recirculation tanks also tended to have much lower levels of disinfectant residual (standard systems had 40–600% higher residual), 4–6 times as much hydrogen, and 3–20 times more sediment compared with standard tanks without recirculation. On demand tankless systems had very small volumes of water at risk and relatively high levels of disinfectant residual. Recirculation systems may have distinct advantages in controlling pathogens via thermal disinfection if set at 60°C, but these systems have lower levels of disinfectant residual and greater volumes at risk if set at lower temperatures.

Key words: *Legionella pneumophila*; *Mycobacteria avium* complex; pathogen control; premise plumbing; water heaters

Introduction

CONTROL OF WATERBORNE DISEASE from fecal-derived pathogens has been achieved from source water protection, primary disinfection, and removal of particulates before distribution of water to homes (NRC, 2006). Mitigating emerging problems of human pathogens that colonize premise plumbing systems will require new control paradigms, which include an improved understanding of how selection and operation of building water systems can either increase or decrease the risk of pathogen propagation (Pryor *et al.*, 2004; Liu *et al.*, 2006; CDC, 2008a, 2008b). For instance, use of home filtration devices that remove chlorine disinfectants, certain metered faucets and lowering water heater temperatures to <49°C (for energy savings and reduce likelihood of scalding) (EPA, 2009) can sometimes encourage

pathogen growth, but increasing water heater temperatures to >60°C may decrease pathogen growth (Mauchline *et al.*, 1992; Pryor *et al.*, 2004; Berry *et al.*, 2006; Moore *et al.*, 2006; CDC, 2008a; Brazeau and Edwards, 2011). Two studies reported higher incidence of *Legionella pneumophila* in buildings with hot water recirculation systems or when continuous flow conditions were present—a potentially worrisome development given that certain municipalities require installation of such systems for water conservation and purported energy efficiencies (Pryor *et al.*, 2004; Liu *et al.*, 2006).

Concern over public health implications of pathogens in premise plumbing is currently increasing. The Centers for Disease Control and Prevention (CDC) estimates that between 8000 and 18,000 people in the United States are hospitalized each year with Legionnaires' disease due to infection by *L. pneumophila*. Legionellosis is responsible for the most cases of waterborne disease and deaths associated with potable water in the U.S. (CDC, 2008a; Pruden *et al.*, 2013). Other pathogens of concern such as *Acanthamoeba*, *Mycobacterium avium* complex (MAC), and *Pseudomonas aeruginosa* can also grow within water heating systems and cause thousands of

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cases of infections annually (Lyytikainen *et al.*, 2001; Marras *et al.*, 2005, 2007; Aumeran *et al.*, 2007; Falkinham *et al.*, 2008; CDC, 2008a, 2008b; Brazeau and Edwards, 2011).

This research is aimed at providing fundamental insights into the role of water heater systems in the creation of microclimates suitable for pathogen growth. That is, growth of premise plumbing pathogens can be strongly influenced by complex interactions between temperature, chloramine/chlorine residual, hydrogen availability, dissolved oxygen (DO), chlorine, and sediment—this is the first study to directly compare performance of representative systems found in buildings (Table 1). Results will help formulate rational decision making relative to the important, yet sometimes synergistic and occasionally antagonistic goals, of water conservation, energy conservation, and public health protection. This is also the first study to quantify hydrogen concentrations in hot water systems, which is of future interest given that hydrogen is an important energy source allowing virulence gene activation of *Salmonella* and other human pathogens (Maier, 2003; Carlyle, 2002). Hydrogen can also support autotrophic hydrogen-oxidizing bacteria growth that can support food webs (e.g., protozoan grazing) and certain pathogens (Aragno and Schlegel, 1992; Morton *et al.*, 2005; Gomila *et al.*, 2008).

Experimental Methods

Three hot water systems were constructed and operated in parallel to facilitate a direct comparison of a standard water heating system using a 20-gallon storage tank (STAND; 1 gallon = ~3.8 L) to “green” water heating systems including (1) a 20-gallon storage system with a pump and hot water recirculation system (RECIRC) and (2) an on-demand system with no storage and no recirculation line (DEMAND; Fig. 1).

The three systems were designed to operate under four representative consumer use conditions: (1) high temperature and high use, (2) high temperature and low use, (3) low temperature and high use, and (4) low temperature and low

use. “High use” is based on a comprehensive study of domestic hot water use in New York apartments that determined average demand as high as 100–200 L per day, which translates to three complete water tank turnovers per day assuming a typical tank size of 189 L and about three people/household (Goldner, 1994; United States Census Bureau, 2000). To provide regular water changes and stagnation events “high use” flushed one water tank volume every 8 h. “Low use” was defined herein as 1/6 of high use (i.e., 25% tank turnover every 12 h). The high temperature setting is based on WHO recommended operating temperature of 60°C designed to limit *L. pneumophila* growth (NRC, 2006; Bartram *et al.*, 2007), while the low temperature setting is based on the U.S. Environmental Protection Agency (EPA) recommended temperature of 49°C to conserve energy and minimize scalding potential (Levesque *et al.*, 2004; NRC, 2006).

The influent water was relatively soft, Blacksburg tap water with a typical residual of 2.5 mg/L monochloramine. Influent to the water heaters was flushed to waste for a period of 15 min, before drawing water into and through the heater. Additional details regarding operation and energy efficiency during testing are presented in previous work (Brazeau and Edwards, 2013).

Water quality parameters (i.e., total chlorine, DO, and metal concentrations) were measured in accordance with Standard Methods (APHA *et al.*, 1998). Samples were collected (unless otherwise indicated) from the bulk water at the top and bottom of the tanks and the outflow of the DEMAND system (sample taps A, B, E, G and H; Fig. 1). The test waters were analyzed for metal concentrations using a Thermo Electron X-Series inductively coupled plasma mass spectrometer per Standard Method 3125-B (APHA *et al.*, 1998). Internal tank temperature was measured using a series of wireless data logger temperature probes that were inserted in the tank at various depths and temperature was automatically recorded every 30 min (Fig. 2). Hydrogen was measured using a residual gas analyzer type gas chromatograph, after collecting samples at taps C, E, and I (Fig. 1) in glass vials

TABLE 1. PHYSICAL WATER SYSTEM VARIABLES FOR REPRESENTATIVE PATHOGENS

Issue		<i>Legionella</i> ^{a,c,d,h,j-n,p}	<i>Mycobacteria avium complex (MAC)</i> ^{b,e-g,i,j,l,n,o}
Temperature	Controls volume of system in which pathogen growth and death occurs	Ideal growth range: 30–37°C Growth impeded: >46°C	Growth range: 15–45°C Growth impeded: >53°C
Total chloramine residual	Controls many pathogens but can select for others	High chloramine seems to control problem	High chloramine does not control and may increase
Hydrogen evolution	Potential nutrient and AOC source	Unknown effects	Some MAC are hydrogen oxidizing
Dissolved oxygen (DO)	Requirement, but if too high may inhibit growth	Microaerophile—higher growth rate in lower oxygen environment	Microaerophile—higher growth rate in lower oxygen environment
Copper	In soluble form, may be toxic to pathogens	Suspected to inhibit growth above 50 ppb; can increase disinfectant decay rate	Much more resistant to copper than <i>Legionella</i>
Sediment	Provides surface for detachment, biofilms	Suspected to assist growth	Suspected to assist growth

References: ^aDewailly and Joly, 1991; ^bKirschner *et al.*, 1992; ^cMauchline *et al.*, 1992; ^dZacheus and Martikainen, 1994; ^eLin *et al.*, 1998; ^fMomba *et al.*, 2000; ^gFalkinham *et al.*, 2001; ^hBorella *et al.*, 2004; ⁱNorton *et al.*, 2004; ^jPryor *et al.*, 2004; ^kLeoni *et al.*, 2005; ^lBerry *et al.*, 2006; ^mLiu *et al.*, 2006; ⁿMoore *et al.*, 2006; ^oGomila *et al.*, 2008; ^pBuse and Ashbolt, 2011.

AOC, assimilable organic carbon.

FIG. 1. Experimental design of head-to-head water heaters: A–J, sample taps; K, flush/waste line; L, 120 V energy meter; M, 220 V energy meter; N, gate check valve; O, pressure gauge. For experiments described in this article, copper tube was insulated. Picture modified from photo published in Brazeau and Edwards, 2013.

using a 50% air and 50% water volume with an airtight septum for head space sampling after shaking and equilibration. Henry's Law, using readily available hydrogen gas constants, was used to back calculate aqueous total dissolved hydrogen concentrations originally present in water sample, which represents a lower bound to actual concentration given some unavoidable H_2 losses during collection.

A series of bench top studies using glass containers were conducted to evaluate factors (temperature, sediment, and copper surfaces) that might affect chloramine decay rates in the different water heaters. The effect of slightly higher temperatures was evaluated in one set of tests using Blacksburg tap water, and qualitative effects of sediment were examined by spiking in sediment collected from the bottom of water heaters and concentrated into a pellet by centrifugation. A final test attempted to examine the effects of exposure to copper tubing, by adding copper pipe to the glass container at copper surface area to water volume ratios (SA:V) identical to that present in the RECIRC system at 55°C, while stirring with a magnetic stir rod at a moderate rate.

Hot water heaters were the smallest available retail residential units (20 gallons) and lengths of plumbing were also deemed near the minimum lengths commonly observed in practice. Field observations confirmed similar trends to those

observed in the lab (Fig. 3). Use of larger heaters and longer lengths of pipe used in practice, would tend to increase the impact of the hot water system on water chemistry and the extent of stratification, relative to results presented herein. All three systems were connected to a central line fitted with gate check valves to prevent backflow and cross contamination of the systems. Moreover, pressure gauges were fitted on each system to verify that pressure was maintained on stagnate systems during flow events of other rigs. The water heaters were installed according to manufacturer specifications with

FIG. 2. To measure the internal temperature of the tanks, data loggers (1–5) were installed that automatically measured temperature every 30 min.

Field Observations - Large Scale Systems

Laboratory Measurements - Small Scale Systems

FIG. 3. Temperature profiles during flushing for field observations of 50 gallon plus tanks and large-scale plumbing systems versus laboratory controlled measurements of 20 gallon tanks and small-scale plumbing systems.

FIG. 4. Internal tank temperature with depth for RECIRC and STAND systems at 60°C and low volume use.

only manufacturer options included. Additional details on system setup have been previously published (Brazeau and Edwards, 2013).

Results

After describing characteristic temperature profiles of internal tank temperatures within the STAND and RECIRC systems, the impacts of water heater type and operation on water chemistry (total chlorine, DO, metal concentrations, hydrogen generation, and sacrificial anode rod depletion) are quantified. After bench scale tests isolated important mechanisms of chloramine decay, performance of DEMAND systems is considered.

Storage tank temperature during stagnation

Profiles of internal temperature within each tank during stagnation (Figs. 4–7) reveals complexities of controlling pathogens by temperature alone, and the over-simplification of characterizing system temperature using a single water heater setting. There is evidence to suggest that 46–53°C may

be the upper range of growth for key pathogens such as *L. pneumophila* and MAC, with upward of 60°C needed to kill the bacteria and the ideal growth range being somewhere between 37°C and 30°C (Table 1). A weighted average was calculated to compare the relative volume of each tank below identified temperature thresholds (Table 2). For example, in the case of 60°C low use, to calculate the percentage volume at risk due to temperatures below 46°C, it was determined that an average of 8 gallons of water were below 46°C for 1.25 h and 4 gallons were below the trigger temperature for 6 h during each 12 h cycle (Fig. 3). This translates to a weighted average of 2.8 gallons per day below the threshold of 46°C, which in a 20-gallon tank is equal to 14% of the tank per day [i.e., (8 gallons $\times$ 1.25 h/cycle + 4 gallons $\times$ 6 h/cycle)/24 h/day $\times$ 2 cycles/day = 2.8 gallons weighted average at risk; (2.8 gallons)/20 gallon/tank $\times$ 100 = 14% tank]. The same calculation was repeated for all conditions at 46°C and 37°C (Table 2).

In both the high use and low use conditions, due to constant mixing, the RECIRC system had a relatively consistent, high temperature throughout the entire volume of the storage tank. Temperature recovery from high water demand events was

FIG. 5. Internal tank temperature with depth for RECIRC and STAND systems at 49°C and low user pattern.

FIG. 6. Internal tank temperature for RECIRC and STAND systems at 60°C and high user pattern.

essentially complete within 45 min throughout the entire volume of the tank. In contrast, due to stratification, a consistent temperature profile with depth was never achieved in the STAND system, especially under high use conditions, over the 8 h of testing. The DEMAND system has minimal storage volume (~ 0.03 gallons), which cools to room temperature when not in use.

Considering a threshold of 46°C as a representative temperature cutoff that would allow *L. pneumophila* growth (Table 1), a target EPA-recommended water heater temperature setting of 49°C results in large volumes of water suitable for pathogen growth under the two different operating regimes (Table 2; Figs. 5 and 7). In fact, compared with the STAND system, the RECIRC system had nearly 30% more storage volume below 46°C in the high use condition and 130% more in the low use condition. From this perspective, the STAND system would seem to be more conducive to *L. pneumophila* inactivation due to larger volumes at higher temperatures. However, when considering the volume of water in a more

ideal *Legionella* growth range using a 37°C criteria, the RECIRC system has very little suitable volume (2.5% in high and 0% in low use), whereas the STAND system has up to 25 times greater volume (62% in high and 13% in low use). Ultimately, a much better understanding of microbial ecology, pathogen growth, and inactivation rates would be needed to determine which of these systems is actually more conducive to pathogen growth. But the key point is that the two systems are very different in terms of respective water volumes in temperature ranges causing growth and inactivation.

Using a temperature setting of 60°C yields dramatic improvements for both systems (Table 2; Figs. 4 and 6); however, even in the best case scenario of high temperature and low use, 14% of the STAND volume still remains below the critical temperature required for inactivation over a 24 h period (Fig. 6). At 60°C the RECIRC system outperforms the STAND system, in terms of minimizing water volume below 37°C and maximizing water volume above 46°C. At low use the entire volume of the RECIRC tank is above 46°C while only 86% of

FIG. 7. Internal tank temperature for RECIRC and STAND systems at 49°C and high user pattern.

TABLE 2. AVERAGE PERCENT OF TANK VOLUME BELOW KEY TEMPERATURES DURING A 24-HOUR PERIOD UNDER VARIOUS TEST CONDITIONS

		Water heater type	
	Tank setting	STAND	RECIRC
Storage tank volume below 46°C (% tank)			
Per day high use	60°C	31	22
	49°C	78	100
Per day low use	60°C	14	0
	49°C	38	88
Storage tank volume below 37°C (% tank)			
Per day high use	60°C	21	16
	49°C	62	2.5
Per day low use	60°C	<1	0
	49°C	13	0

the STAND tank is above this mark. For high use both tanks have volume below 46°C during the 24-h period, but there is still 40% less volume below 45°C in RECIRC than in the STAND tank (Table 2). Thus, at a temperature setting of 60°C if temperature alone is considered, a RECIRC system would appear to be less likely to support pathogens than the STAND system. This is the opposite trend for relative risk of STAND versus RECIRC at the 49°C set point based on weighted average water volumes below 46°C.

Water quality parameters: oxygen, sediment, metals, and hydrogen

In addition to temperature, other water quality parameters were measured including DO (Fig. 8), soluble and total metal concentrations, and hydrogen gas in the bulk water. The pH of the water was monitored throughout the experiment and remained fairly consistent in the 7.7–8.0 range. Typical influ-

FIG. 8. Dissolved oxygen (DO) concentrations at various sample ports (Fig. 1) in the bulk water of the systems taken at 60°C and high use.

TABLE 3. INFLUENT WATER PARAMETERS IN TOWN OF BLACKSBURG WATER

Season	Temperature (°C)	pH	DO (mg/L)	H ₂ (ppb)	Al (ppb)	Cu (ppb)	Total Cl (mg/L)
Summer	26	7.4	11	1500	45	15	2.5
Winter	13	7.4	13	2800	25	6.5	2.4

ent values over the duration of the study were recorded (Table 3) and were generally very similar to values observed in the demand system that had no storage or anode rod (Table 4).

With respect to DO, the RECIRC system and the top of the STAND system were similar with medians between 4.9 and 5.5 mg/L, although the STAND system tended to have average DO that was up to 65% higher throughout the system (Fig. 8; Table 4). The RECIRC system also showed the most homogeneity with the lowest measured DO (4.9 mg/L) at both the top and bottom of the tank. The STAND system, however, showed heterogeneity with the top of the tank at 5.5 mg/L DO and 8.1 mg/L at the bottom of the tank where the temperatures were cooler. The DEMAND system had the highest level of DO with a median twice that of the higher temperature STAND and RECIRC systems (Table 4). These results might be important given reports that *Legionella* is a microaerophile (Mauchline *et al.*, 1992).

Both the STAND and the RECIRC system had suspended sediment in the bulk water, and it was visually obvious that the RECIRC system had more turbidity in the bulk samples compared with the STAND system. Samples were acidified to dissolve the suspended sediment and analyzed on an inductively coupled plasma mass spectrometer. Samples were also filtered

TABLE 4. WATER QUALITY PARAMETERS

	Water heater type		
	STAND	RECIRC	DEMAND ^a
DO (mg/L) ^b			
Top of tank	5.5	4.9	N/A ^d
Bottom of tank	8.1	4.9	10
Al (ppb) ^c (total)			
60°C	1034	3467	20
49°C	126	2676	38
Al (ppb) ^c (soluble)			
60°C	36	174	18
49°C	80	294	38
Cu (ppb) ^c			
60°C	130	751	170
49°C	24	310	20
Cu (ppb) ^c (soluble)			
60°C	14	32	62
49°C	12	56	12
H ₂ (ppm)			
High use	210	1240	80
Low use	580	2360	0.7
Anode rod, weight loss (%)	13	24	N/A

^aFor DEMAND system: 60°C = high setting; 49°C = low setting.

^bDEMAND DO data taken from just below heating system.

^cValue represents an average of the concentration in the top and bottom of the tank (Fig. 1).

^dN/A = not applicable to DEMAND system.

FIG. 9. Total metal concentrations in bulk water samples for the RECIRC and STAND systems.

to determine the contribution of particulate versus dissolved concentrations. In the RECIRC system, 8–23% of the total metal was dissolved, there was 2–3 times higher aluminum and 2–4.5 times more copper particulates than in the standard system. It has been suggested that copper levels above ~100 parts per billion may inhibit microbial growth, and in this study total copper was much higher than these levels but soluble copper was much lower (Zacheus and Martikainen, 1994; Lin *et al.*, 1998; Zhang *et al.*, 2009). Future research needs to distinguish which forms of copper may control pathogens, since the active form of metal has been identified as soluble Cu^{+2} in prior research for microbes such as nitrifiers (e.g., Zhang *et al.*, 2009). There was no clear trend in soluble copper levels with higher temperature, although total copper was much higher at 60°C than at 49°C (Table 4).

The primary source of aluminum in the water was the sacrificial anode rod (Table 3), and consistent with expectations based on measurements in Fig. 9, at the end of the experiment the RECIRC anode rod was much more corroded as evidenced by higher weight loss (Table 4). Over the 19 month duration of this experiment, 24% of the RECIRC anode disappeared versus 13% of the STAND anode, raising the possibility that a water heater would have a shorter service life if used in a recirculation mode if the anode is not changed more frequently. Moreover, since anode rod corrosion can cause hydrogen evolution, it was not surprising that the RECIRC system had 4–6 times higher ambient H_2 than the STAND system (Table 4). Aside from rare cases in which H_2 evolved from potable water heating systems caused serious explosions (WSOCTV, 2007), higher levels of H_2 might fuel microbial regrowth (Maier, 2003; Morton *et al.*, 2005; Gomila *et al.*, 2008). While there was significantly more H_2 in the RECIRC system, the value of hydronium produced was still a factor of 100 below the amount the amount needed to exceed the buffering capacity of water. Thus, the hydrogen gas did not affect pH in the system.

Disinfectant residual

Low disinfectant residuals in water systems have been linked to higher incidence of *L. pneumophila* and lower incidence of MAC (Falkinham *et al.*, 2001; Pryor *et al.*, 2004; Moore *et al.*, 2006). Each hot water configuration and operating condition differed markedly in profiles of chlorine residual

during operation. In all conditions, the total chlorine residual was 1.5–10 times higher in the STAND system as compared to the RECIRC system (Fig. 10; Table 5), whereas DEMAND systems showed negligible decay since influent water flows directly through the system. Since each tank received identical inputs of total chlorine, it is clear that there is much more chlorine decay in the RECIRC than in the STAND system, prompting bench tests to isolate sources of the demand.

Bench-top chlorine decay tests

Results of the bench test examining effects of higher temperature (Fig. 11) indicated that chloramine at 55°C

FIG. 10. Total chlorine decay during stagnation for the low use conditions.

TABLE 5. CHLORINE RESIDUAL AFTER STAGNATION

	Water heater type		
	Temperature setting	STAND	RECIRC
Disinfectant residual after 8 h stagnation high use (mg/L)			
Top of tank	60°C	1.4	0.6
	49°C	2.1	1.5
Bottom of tank	60°C	1.7	0.5
	49°C	2.2	1.4
Disinfectant residual after 12 h stagnation low use (mg/L)			
Top of tank	60°C	1.2	0.2
	49°C	1.1	0.4
Bottom of tank	60°C	1.4	0.2
	49°C	1.3	0.4

disappeared 1.5 and 2 times faster than at 45°C and 25°C, respectively. The lower temperatures in the STAND versus RECIRC tank are therefore qualitatively consistent with the observation of higher chlorine levels, but calculations indicate that higher temperature could only be responsible up to 20% of the observed difference, leading to additional bench top studies of chlorine demand from sediment and copper pipe as described below.

Presence of sediment did not affect the rate of chlorine decay when compared with the control sample without any sediment added. Similar testing using a piece of aluminum anode rod selected to achieve the same SA:V ratio present in the water heater also illustrated no significant chloramine demand versus a control. Conversely, in 4 h, glass bottles with a new copper surface had undetectable chlorine, whereas the control without copper only decayed slightly (Fig. 12). Nguyen *et al.* (2012) observed this mechanism for chloramine decay in cold water and determined that new copper showed a chlorine decay rate much higher than older copper. Thus, the aged copper is probably why some chloramine residual was present in the pilot test apparatus versus the undetectable chlorine after a few hours in the bench test with new copper, but it seems likely that the lower disinfectant residual in RECIRC tanks is due to constant flow through the aged copper pipe.

Discussion: Implications for Pathogen Control

There are numerous important implications of this research for scientific evaluations of opportunistic premise plumbing pathogen growth in field and laboratory settings, projected

comparisons of water heater system performance relative to factors influential to pathogen growth, and for considering interventions that might be used to control pathogens in buildings. At present, the data appear insufficient to draw definitive conclusions, but it is nonetheless useful to highlight the likelihood that there would sometimes be profound differences between pathogen growth in STAND versus RECIRC and DEMAND systems. Given variations expected with water chemistry and operation conditions, the differences between STAND and RECIRC do not always unambiguously favor one system or another in terms of pathogen regrowth. Discussion below is framed in terms of draft proposed American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) standards for *L. pneumophila* control through (1) temperature control (>60°C) and (2) maintenance of a disinfectant residual (>0.5 mg/L Cl) (ASHRAE, 2011).

Electric DEMAND systems and pathogen control

Since the DEMAND system has nearly no storage volume and has negligible disinfectant decay, it has major advantages relative to STAND or RECIRC systems. But for the device tested, in winter the DEMAND system never heated the water above the 25–30°C (Brazeau and Edwards, 2013) threshold necessary for consumer comfort, much less thresholds necessary for thermal disinfection of pathogens (>70°C), which were never achieved anywhere in the system. To address the comfort issue consumers have been instructed by manufacturers to purchase a STAND system to preheat the water, in which case the temperature setting of that tank preheater is likely to be critical.

STAND versus RECIRC systems

In the subsequent sections, the effects of the various metrics measured in this study will be discussed with respect to pathogen growth and mitigation in the STAND system as compared to RECIRC.

ASHRAE temperature standards for pathogen control versus standard EPA temperature recommendations. The new ASHRAE draft standards propose a minimum outflow temperature of 60°C from the water heater and maintaining 51°C through the entire tank and pipe infrastructure (ASHRAE, 2011). From the perspective of a temperature set point of 60°C and maintaining high temperatures throughout the hot

FIG. 11. Total metal concentrations in bulk water samples for the RECIRC and STAND systems.

FIG. 12. Bench-top experiment results determining chlorine decay when mixed with a copper coupon.

water system, the conventional wisdom that RECIRC systems would be expected to have a lesser likelihood for pathogens such as *L. pneumophila* than stratified tank electric water heaters was validated in this work (Lacroix, 1999). But if temperature settings are at or below 49°C, the opposite trend seems to be true, since STAND had somewhat less volume susceptible to regrowth than RECIRC.

Water quality parameters influential to pathogen growth. Without the installation of a check valve on the RECIRC system, water actually short circuited the tank during flushing causing a reversal of flow in the return line that might cause problematic shearing of biofilm containing pathogens from pipes and aerosolizing them downstream at the showerhead (Brazeau and Edwards, 2013).

There are a host of water quality parameters that could influence pathogen growth positively or negatively. Increased levels of metals could act as a nutrient source or toxin for bacteria (Table 1). The extent to which soluble metals such as copper are toxic to pathogens needs to be explored more fully, along with possible differences in soluble and total metal concentrations in STAND and RECIRC systems, given that temperature varied slightly and total metal concentrations

varied markedly (Table 2). DO has also been implicated as an important factor in bacteria growth, in that both *L. pneumophila* and MAC have been described as a microaerophile, suggesting that the lower levels of DO found in the entire storage volume of the RECIRC tank may be more supportive of their growth (Tables 1 and 6; Fig. 8).

Recently, there has been discussion of controlling pathogens by removing assimilable organic carbon (AOC) at the treatment plant and limiting the potential for microbial growth. While it is known that humic substances and organic carbon are essential for heterotrophic bacteria to grow (Camper, 2004), unfortunately there are a variety of mechanisms by which AOC can be created in premise plumbing. For example, it has been suggested by Martin (2012) that carbon can be generated in water heaters from hydrogen evolution due to decay of the anode rods at a rate of 0.2 mg C/mg evolved H₂ and another work has demonstrated that sorption of humic substances to rust sediment might increase fractions of bioavailable carbon (Butterfield *et al.*, 2002; Morton *et al.*, 2005; Lieberman *et al.*, 2011; Martin, 2012). The RECIRC system had more corrosion of the anode rod and also much higher concentrations (4–6 times) of H₂ in the tank (Table 3), which could ultimately lead to more AOC generation or available nutrients within the RECIRC system compared with the STAND system (Table 6), since certain species of MAC may be able to utilize H₂ directly as a nutrient source leading to potential increased pathogen growth from anode decay products directly (Gomila *et al.*, 2008). In our experience, anode rods are rarely replaced when consumed, unless there are odor issues in which case consumers can find publicly available materials citing replacement as a remedial measure (MRWA, 2005; Navajo County Health Department, 2012; Water Heater Rescue, 2012). However, once the anode rod disappears, AOC generation from anode decay would cease, and this would occur more quickly in the RECIRC tank. Thus, while the RECIRC may have more hydrogen in the short term, theoretically, the STAND system has potential to produce hydrogen over the longer period of the anode life. This assumes that the anode rod is not replaced in the RECIRC system and the tank does not fail due to corrosion.

This work is the first to document the complex relationships between temperature, disinfectant decay, and possible

TABLE 6. KEY DIFFERENCES BETWEEN PHYSICAL PARAMETERS THAT MAY INFLUENCE PATHOGEN PROPAGATION

	System		
	STAND	RECIRC	DEMAND
Temperature	Tank: Stratifies; bottom as much as 25°C cooler than top Pipes: Cool to ambient (25°C)	Tank: Homogenous Pipes: Heated to tank temperature	Tank: Not Applicable Pipes: Cool to ambient (25°C)
Total chloramine residual	24–66% higher than RECIRC in bulk water	Improved delivery of disinfectant to biofilm	Virtually no decay from distribution system levels
Hydrogen; sediment	H ₂ lower than RECIRC	Circulation delivers H ₂ directly to pipe biofilm	Extremely low H ₂ ; no sediment accumulation
DO	Overall higher than RECIRC	Lower DO leads to increased growth of microaerophile	Highest levels of DO
Total copper	6–13 times lower than RECIRC	310–750 ppb	Similar to STAND
Flow reversal; mass transport to pipe wall	None, low transport	Flow reversal in pipes, high transport	None

nutrients as a function of full-scale water heater system design and operation, and it considers implications of these environmental factors for pathogen growth. While the scope, budget, and duration of tests at each condition did not allow quantification of impacts on actual pathogen levels, future testing can do so.

Conclusions

In a controlled, direct comparison in a system with copper plumbing, continuous hot water recirculation maintained much lower levels of disinfectant residual than standard systems. Standard systems without hot water recirculation had 40–600% higher concentrations of total chlorine in the tank (i.e., up to seven times more chlorine). There was no instance when the bulk water in the standard tank dropped below a disinfectant residual of 1 mg/L, whereas levels below 0.5 mg/L were not uncommon in the recirculating system. Systems with hot water recirculation also had 4–6 times higher hydrogen and 3–20 times more suspended metal hydroxide sediment compared with standard tanks without recirculation. On demand, tankless systems had very small volumes (~0.03 gallons) of water at risk and relatively high levels of residual disinfectant. When run at a temperature of 49°C the water volume at risk for *L. pneumophila* growth was up to 130% higher for recirculating tanks versus standard tanks, but when run at a temperature of 60°C the volume of water at risk in the recirculation system was 0% compared with 14% in the standard tank.

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Author Disclosure Statement

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References

- APHA, AWWA, and WEF. (1998). *Standard Methods for Examination of Water and Wastewater*, 20th edition. Washington, D.C.: APHA.
- Aragno, M., and Schlegel, H.G. (1992). In A. Balows, H.G. Trüper, M. Dworkin, W. Harder, and K.H. Schleifer, Eds., *The Prokaryotes*, 2nd ed. New York: Springer-Verlag, Vol. 1, p. 344.
- ASHRAE. (2011). *Proposed New Standard 188, Prevention of Legionellosis Associated with Building Water Systems*. Atlanta, GA: ASHRAE.
- Aumeran, C., Paillard, C., Robin, F., Kanold, J., Baud, O., Bonnet, R., Souweine, B., and Traore, O. (2007). *Pseudomonas aeruginosa* and *Pseudomonas putida* outbreak associated with contaminated water outlets in an oncohaematology paediatric unit. *J. Hosp. Infect.* 65, 47.
- Bartram, J., Chartier, Y., Lee, J., Pond, K., and Surman-Lee, S., Eds. (2007). *Legionella and the Prevention of Legionellosis*. Geneva: WHO Press.
- Berry, D., Xi, C.W., and Raskin, L. (2006). Microbial ecology of drinking water distribution systems. *Curr. Opin. Biotech.* 17, 297.
- Borella, P., Montagna, M.T., Romano-Spica, V., Stampi, S., Stancanelli, G., Triassi, M., Neglia, R., Marchesi, I., Fantuzzi, G., Tato, D., Napoli, C., Quaranta, G., Laurenti, P., Leoni, E., De Luca, G., Ossi, C., Moro, M., and D'Alcala, G.R. (2004). *Legionella* infection risk from domestic hot water. *Emerg. Infect. Dis.* 10, 457.
- Brazeau, R.H., and Edwards, M.A. (2011). A review of the sustainability of residential hot water infrastructure: Public health, environmental impacts, and consumer drivers. *J. Green Build.* 6, 77.
- Brazeau, R.H., and Edwards, M.A. (2013). Water and energy savings from on-demand and hot water recirculating systems. *J. Green Build.* 8, 75.
- Butterfield, P.W., Camper, A.K., Biederman, J.A., and Bargmeyer, A.M. (2002). Minimizing biofilm in the presence of iron oxides and humic substances. *Water Res.* 36, 3898.
- Camper, A.K. (2004). Involvement of humic substances in regrowth. *Int. J. Food Microbiol.* 92, 355.
- Carlyle, K. (2002) New UGA Study Demonstrates Bacterial Pathogens Use Hydrogen as Energy Source in Animals. Available at: www.eurekalert.org/pub_releases/2002-11/uog-nus112502.php (accessed June 25, 2012).
- CDC. (2008a). Possible Link of Poor POU Devices, Plumbing to Disease. *AWWA Annual Conference and Exposition*. Atlanta, GA.
- CDC. (2008b) Patient Facts: Learn More about Legionnaires' Disease. Available at: www.cdc.gov/legionella/about/index.html (accessed June 27, 2008).
- EPA. (2009). Lower Water Heating Temperature for Energy Savings. Available at: www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=13090 (accessed July 28, 2010).
- Dewailly, E., and Joly, J.R. (1991). Contamination of domestic water-heaters with *Legionella-pneumophila*—Impact of water temperature on growth and dissemination of the bacterium. *Environ. Toxic. Water* 6, 249.
- Falkinham, J.O., Iseman, M.D., de Haas, P., and van Soolingen, D. (2008). *Mycobacterium avium* in a shower linked to pulmonary disease. *J. Water Health* 6, 209.
- Falkinham, J.O., Norton, C.D., and LeChevallier, M.W. (2001). Factors influencing numbers of *Mycobacterium avium*, *Mycobacterium intracellulare*, and other mycobacteria in drinking water distribution systems. *Appl. Environ. Microb.* 67, 1225.
- Goldner, F. (1994). *Energy Use and Domestic Hot Water Consumption*. New York: Energy Management and Research Associates.
- Gomila, M., Ramirez, A., Gasco, J., and Lalucat, J. (2008). *Mycobacterium llatzerense* sp. nov., a facultatively autotrophic, hydrogen-oxidizing bacterium isolated from haemodialysis water. *Int. J. Syst. Evol. Microbiol.* 58, 2769.
- Kirschner, R.A., Parker, B.C., and Falkinham, J.O. (1992). Epidemiology of infection by nontuberculous mycobacteria—*Mycobacterium-avium*, *Mycobacterium-intracellulare*, and *Mycobacterium-scrofulaceum* in acid, brown-water swamps of the Southeastern United-States and their association with environmental variables. *Am. Rev. Respir. Dis.* 145, 271.
- Lacroix, M. (1999). Electric water heater designs for load shifting and control of bacterial contamination. *Energ. Convers Manage.* 40, 1313.
- Leoni, E., De Luca, G., Legnani, P.P., Sacchetti, R., Stampi, S., and Zanetti, F. (2005). *Legionella* waterline colonization: Detection of *Legionella* species in domestic, hotel and hospital hot water systems. *J. Appl. Microbiol.* 98, 373.
- Levesque, B., Lavoie, M., and Joly, J. (2004). Residential water heater temperature: 49 or 60 degrees Celsius? *Can. J. Infect. Dis.* 15, 11.

- Lieberman, R.H., Martin, A., and Edwards, M.A. (2011). *Mitigation Practices and the Practical Aspects of Premise Plumbing Problems Relative to Control of Pathogens*. Phoenix, AZ: AWWA-WQTC 11.
- Lin, Y.-s.E., Vidic, R.D., Stout, J.E., McCartney, C.A., and Yu, V.L. (1998). Inactivation of *Mycobacterium avium* by copper and silver ions. *Water Res.* 32, 1997.
- Liu, Z., Lin, Y.E., Stout, J.E., Hwang, C.C., Vidic, R.D., and Yu, V.L. (2006). Effect of flow regimes on the presence of *Legionella* within the biofilm of a model plumbing system. *J. Appl. Microbiol.* 101, 437.
- Lyytikäinen, O., Golovanova, V., Kolho, E., Ruutu, P., Sivonen, A., Tiittanen, L., Hakanen, M., and Vuopio-Varkila, J. (2001). Outbreak caused by tobramycin-resistant *Pseudomonas aeruginosa* in a bone marrow transplantation unit. *Scand. J. Infect. Dis.* 33, 445.
- Maier, R.J. (2003). Availability and use of molecular hydrogen as an energy substrate for *Helicobacter* species. *Microb. Infect.* 5, 1159.
- Marras, T.K., Chedore, P., Ying, A.M., and Jamieson, F. (2007). Isolation prevalence of pulmonary non-tuberculous mycobacteria in Ontario, 1997–2003. *Thorax* 62, 661.
- Marras, T.K., Wallace, R.J., Koth, L.L., Stulbarg, M.S., Cowl, C.T., and Daley, C.L. (2005). Hypersensitivity pneumonitis reaction to *Mycobacterium avium* in household water. *Chest* 127, 664.
- Martin, A. (2012). *Organic carbon generation mechanisms in main and premise distribution systems* [M.S. thesis]. Blacksburg, VA: Civil and Environmental Engineering, Virginia Polytechnic Institute and State University.
- Mauchline, W.S., Araujo, R., Wait, R., Dowsett, A.B., Dennis, P.J., and Keevil, C.W. (1992). Physiology and morphology of *Legionella-pneumophila* in continuous culture at low oxygen concentration. *J. Gen. Microbiol.* 138, 2371.
- Momba, M.N.B., Kfir, R., Venter, S.N., and Cloete, T.E. (2000). An overview of biofilm formation in distribution systems and its impact on the deterioration of water quality. *Water SA* 26, 59.
- Moore, M.R., Pryor, M., Fields, B., Lucas, C., Phelan, M., and Besser, R.E. (2006). Introduction of monochloramine into a municipal water system: Impact on colonization of buildings by *Legionella* spp. *Appl. Environ. Microb.* 72, 378.
- Morton, S.C., Zhang, Y., and Edwards, M.A. (2005). Implications of nutrient release from iron metal for microbial regrowth in water distribution systems. *Water Res.* 39, 2883.
- MRWA. (2005). MDH Fact Sheet/Brochure: Why Does My Water Smell Like Rotten Eggs? Available at: www.mrwa.com/water-smellrotteneggs.htm (accessed July 11, 2012).
- Navajo County Health Department. (2012). *My Water Smells Like Rotten Eggs!* Holbrook, AZ: P.H. Services.
- Nguyen, C., Elfland, C., and Edwards, M. (2012). Impact of advanced water conservation features and new copper pipe on rapid chloramine decay and microbial regrowth. *Water Res.* 46, 611.
- Norton, C.D., LeChevallier, M.W., and Falkinham, J.O. (2004). Survival of *Mycobacterium avium* in a model distribution system. *Water Res.* 38, 1457.
- NRC. (2006). Alternatives to premise plumbing. *Drinking Water Distribution Systems: Assessing and Reducing Risk*. Washington, DC: The National Academies of Science, p. 316.
- Pruden, A.J., Edwards, M.A., and Falkinham, J.O. III. (2013). *Research Needs for Opportunistic Pathogens in Premise Plumbing*. Denver, CO: Water Research Foundation.
- Pryor, M., Springthorpe, S., Riffard, S., Brooks, T., Huo, Y., Davis, G., and Satter, S.A. (2004). Investigation of opportunistic pathogens in municipal drinking water under different supply and treatment regimes. *Water Sci. Technol.* 50, 83.
- United States Census Bureau. (2000). Census 2000 Demographic Profile Highlights. Available at: www.factfinder.census.gov/servlet/SAFFacts (accessed September 13, 2011).
- Water Heater Rescue. Trouble Shooting: Smelly Water. Available at: www.waterheaterrescue.com/pages/WHRpages/English/Troubleshooting/stinky-water-in-hot-water-heaters.html (accessed July 17, 2012).
- WSOCTV. (2007). *Water Heater Explosion Shatters Kannapolis House*. News Report. Kannapolis, NC.
- Zacheus, O.M., and Martikainen, P.J. (1994). Occurrence of *Legionellae* in hot water distribution systems of Finnish apartment buildings. *Can. J. Microbiol.* 40, 993.
- Zhang, Y., Love, N., and Edwards, M. (2009). Nitrification in drinking water systems. *Crit. Rev. Environ. Sci. Tec.* 39, 153.