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Investigative approach to improve hot water system hydraulics through temperature monitoring to reduce building environmental quality hazard associated to *Legionella*

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ABSTRACT

Several countries have promulgated control measures and design guidelines to limit the proliferation of *Legionella* within hot water distribution systems (HWDS). However, there is little information on how to assess and improve existing HWDS unable to maintain water temperatures $\geq$55 °C throughout the system. A 50-year old hot water system of a 10 story hospital was investigated in terms of temperature distribution and *Legionella pneumophila* prevalence. Concentrations of *L. pneumophila* were correlated with the maximum temperature reached at the tap, with a significant decrease observed at $T \geq 55$ °C. Continuous temperature and flow monitoring was performed on the overall HWDS, characterizing the principal and secondary horizontal return loops for all 9 wings, and detailed investigations of the secondary vertical return loops was completed in Wing 3. Results indicated the system inability to systematically maintain desired operating temperatures of 55 °C. The deficient hydraulic distribution was the root cause of the poor temperature maintenance throughout the secondary loops, but defective devices were also identified as playing an important role in sectorial temperature failure. A simple stepwise investigative approach was developed to identify hydraulic deficiencies. The implementation of flow restrictions on identified recirculation loops and increased pumping efficiency was conducted within a short period of 2 months, with no major system upgrade. These corrective measures resulted in a balanced system with increased flow velocities (>0.2 m/s). As a result, the proportion of taps achieving 55 °C within 2 min increased from 11% to 74% and *L. pneumophila* prevalence decreased from 93.1% to 46.1% after 4 weeks.

1. Introduction

Proliferation of *Legionella pneumophila* in water distribution systems causes an important number of infections with high mortality levels [1] estimated to cost 33 366 US$ per hospitalization in the United States [2]. In the United States, between 2011 and 2012, *Legionella* was responsible for 66% of drinking-water associated infectious outbreaks [3]. The presence of *Legionella* in hot water distribution systems from large buildings can lead to environmental quality issues, especially within healthcare settings. Immuno-compromised patients and vulnerable population can be exposed to *Legionella* via the inhalation of contaminated aerosols generated by equipment such as showers, faucets, air-cooling towers and toilets [4]. Premise plumbing from large buildings often provide multiple favorable conditions for the development of biofilm and *L. pneumophila* [5]. Biofilm offers protection against

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disinfection and can harbor amoebas, a growth vector for *L. pneumophila* [6]. The presence of stagnation related to dead legs or inadequate system hydraulic balancing also reduces the disinfectant efficiency in these areas [7]. In addition, bacteria exposed to sub-optimal disinfection and low nutrient environmental conditions can enter a viable but not culturable state (VBNC). Although undetected by standard culture methods [8], VBNC cells can recover culturabilty when they are provided with favorable conditions (lower water temperature, loss of disinfectant, presence of biofilm) [9] [10].

Several regulations, guidelines and recommendations identify design, operating conditions and monitoring frequency required in hot water distribution systems to prevent and control the proliferation of *L. pneumophila* [11]. Typically, they include control measures such as maintaining a water temperature ≥60 °C at the outlet of the water heater and ≥55 °C in the main recirculation loop [12,13]. Furthermore, a temperature of at least 55 °C should be maintained in the HWDS and reached within 1–2 min of flushing at each point of use [12–15]. Extended periods of stagnation and the presence of dead legs should be avoided and minimal water velocity should be maintained at all times within the recirculation pipes. A French technical guideline suggests to define the minimum water velocity as the greatest value between 0.2 m/s and the velocity required to maintain heat loss below 5 °C [13,16]. However, the maximum water velocity suggested is 0.5 m/s to protect the pipes from premature wear.

Periodic monitoring is required to confirm that the control measures described previously are efficient to maintain *L. pneumophila* load below action and alert levels. In European countries like Austria, France, Germany, Netherlands and United Kingdom, periodic monitoring of *Legionella* and temperature is mandatory with a frequency varying from continuous to weekly or annually depending on the parameters, the risk classification and the location of the point of use [12,17–20]. Results from the periodic monitoring are interpreted against established target levels that vary between 1000 and 10000 CFU/L, above which corrective and preventive actions should be undertaken to reduce the risk of infection [12,17–19,21–23]. While maintaining temperatures is considered the first line of defense to limit the growth of *L. pneumophila*, complete eradication is often not possible, especially in systems already contaminated or where adequate control conditions cannot be maintained throughout the systems [24,25]. A single piece of deficient equipment can influence the hot water temperature distribution within an entire wing, causing hot water temperature decrease in those sectors [11].

The *Legionella* risk associated to a large building HWDS can be evaluated using a temperature-based diagnostic approach [11]. Systems that are unable to maintain control temperatures at the point of use despite adequate water heater temperatures are considered at risk and hydraulically deficient. A hot water system that is not hydraulically balanced can lead to higher flowrates in loops with lower head loss and poor circulation or even stagnation in high restriction loops. There are few methodologies that are proposed to perform a detailed assessment of hydraulic deficient areas within an existing HWDS. A technical document suggests the investigation of the following issues: valve obstructions (leading to stagnation or reduced water velocity within the return loop), the type of control elements installed, the recirculation pump design/operation or the lack of balancing between the different secondary flow and return loops [13,16]. Applied investigation approaches are needed to identify corrective actions and ensure an adequate first line thermal control for *Legionella*.

This study presents an investigation approach to evaluate and correct the hydraulics of an existing hot water system based on detailed thermal monitoring. This approach can be implemented promptly to obtain required temperatures at points-of-use as well as recommended minimal flow velocities. The objectives of this study were to: 1) identify malfunctioning zones in the water distribution network using temperatures and flowrates analysis 2) quantify the impact of unfit equipment (pump, faucets, showers) on temperatures and flowrates within a sector of the HWDS 3) propose an investigative procedure to identify and correct the causes of inadequate temperature distribution and 4) investigate the effect of distal temperature on the prevalence and concentrations of *Legionella* and *L. pneumophila*.

2. Methods

2.1. Description of the study site

The study was conducted prospectively, in absence of nosocomial cases of legionellosis in a 450-bed healthcare facility in Québec, Canada. The hot water system investigation was conducted using a temperature diagnostic approach [11]. The 50-year-old hospital is supplied with treated chlorinated surface water. The main hot water network supplies water to nine 10-story wings and copper piping (type K) is the material used for all principal, secondary and tertiary flow and return loops [11]. Copper and flexible braided elastomeric hoses are used for connecting pipes at points of use. Hot water is produced by a steam heat exchanger with a temperature set point of 60 °C. The HWDS has a vertical architecture where the main horizontal flow and return loop supplies water to each wing through horizontal secondary flow and return loops, that feed water to between 9 and 21 secondary vertical flow and return loops depending on the wing (Fig. 1). There are 2–4 devices connected on a riser at each floor and each equipment is connected on the recirculation loop [11]. A detailed study of the secondary and tertiary hot water distribution systems was carried out in Wing 3, supplied by 10 risers. This wing was selected for detailed investigation due to recurrent user complaints about hot water temperatures being unusually low at the point-of-use.

2.2. Water sampling approach for L. pneumophila and physico-chemical evaluation

A one-liter sample of water was collected at the water heater outlet and on the principal return loop pipe after the sampling port was cleaned with alcohol and ultrapure water, and flushing for one minute. For points of use, the first liter of hot water was collected into sterile polypropylene bottles from taps and showers. No prior cleaning or flushing were carried out in order to get a sample representative of the point of use. In total, 29 points of use were selected for sampling, of which 17 were located in Wing 3. Microbiological sampling was conducted once in Wing 3 prior to the implementation of corrective measures. The water heater outlet, recirculation loop and the points of utilization throughout the hospital were sampled twice prior to and once 4 weeks following the implementation of corrective measures. Water samples were cultured according to the quantitative method AFNOR NF T90-431 *Legionella* procedure [26]. Different volumes of water were filtered through sterile 47 mm diameter and 0.45 μm mixed ester cellulose membranes (Millipore, Germany) and an acid untreated sample volume of 0.2 mL were plated on Glycine-Vancomycin-Polymyxin-Cycloheximide (GVPC) selective agar (Biokar diagnostics, France). Before plating, acid treatment was applied to filtered samples ($pH = 2$; 5 min). All plates were then incubated at 36 °C for 10 days. Typical colonies that developed after 4–10 days were sub cultured on confirmation plates for 2–4 days at 36 °C. Resulting colonies that developed on BCYE agar, but not on BCYE without cysteine, were considered as *Legionella* spp. The *Legionella* latex test (M45,

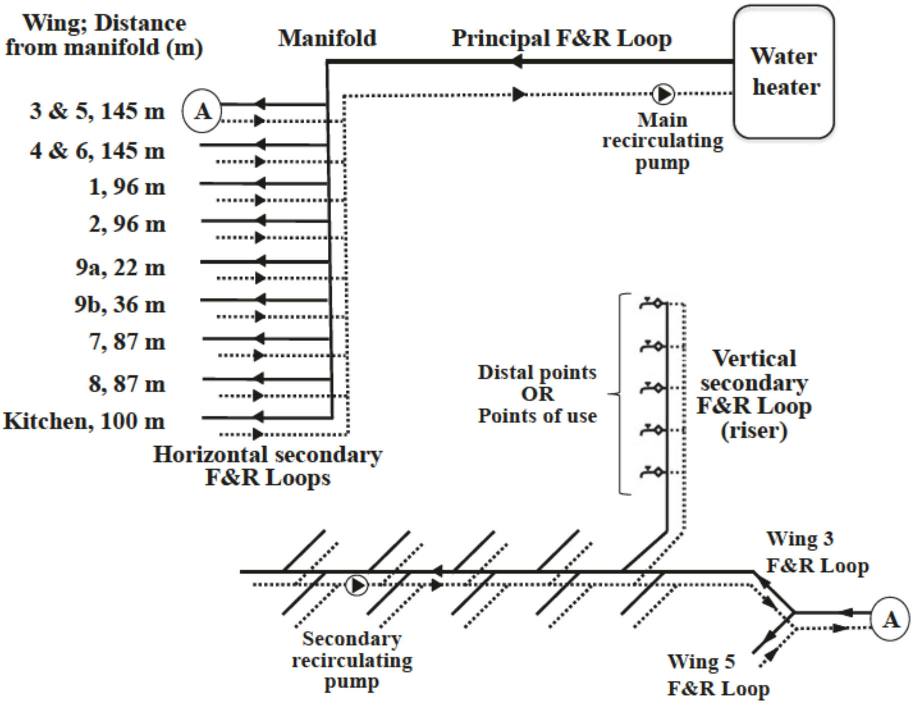

Fig. 1. Hot water distribution system schematic, including pumps location, wing(s) supplied by each horizontal secondary flow and return (F&R) loops, distance from the manifold, and riser configuration within Wing 3.

Microgen bioproducts) was used for *L. pneumophila* confirmation. The detection limit for the culture method was 10 CFU/L for both *Legionella* spp. and *L. pneumophila*. Water physico-chemical parameters were evaluated for each tap at each sampling event using 500 mL collected immediately after the first liter. The following parameters were evaluated on-site: pH, dissolved oxygen, free and total chlorine, turbidity and temperature. Residual and total chlorine were measured using a Pocket Colorimeter™ II (Hach, Loveland, CO, USA), turbidity with a Hach 2100Q (Hach, Loveland, CO, USA) while pH and dissolved oxygen were measured using a Hach Multi-Parameter HQ40d tool with a pH probe PHC301 and dissolved oxygen probe LDO101 (Hach, Loveland, CO, USA).

2.3. Continuous measurements across the hospital and temperature profiles

Temperature at the water heater outlet as well as cold and hot water pressures were monitored at all times by the hospital building management system at 5-min intervals. In addition, water flow rates and temperatures were recorded in selected locations throughout the system at 5-min intervals using non-intrusive portable ultrasonic flowmeters (Greyline PTFM 1.0) and portable datalogger RDXL4SD with self-adhesive thermocouples SA1XL (Omega, Laval, QC, Canada). Water flow rates were monitored between 2016/03/24 and 2016/04/08 on the horizontal secondary pipe and at the base of hot water risers located in Wing 3. Temperature was monitored at the inlet of each wing (03/18 to 03/22 and 05/06 to 05/16) and at the base of each secondary vertical flow and return loop (riser) in Wing 3 (01/10 to 01/16 and 05/17 to 05/22). All the monitoring points were located at the lowest building level. The dataloggers had a 0.1 °C resolution and an accuracy of ±0.4%.

Temperature profiles were carried out between 2012 and 2016 in all wings of the hospital, to determine the temperature evolution as a function of flushed water and the maximum temperature reached. The temperature was measured in 250 ml polypropylene bottles for the first half-liter, in 500 ml bottles between the first and the second liters, and in 250 ml bottles for the remaining samples, for a total duration of 20 min.

2.4. Detailed investigation of shower valves

Trials were conducted from 2016/03/24 to 2016/04/08 on 4 shower mitigating valves periodically allowing integrity breech between hot and cold water systems and one control shower where no breech was possible. All showers were located in Wing 3, seven floors above the secondary horizontal pipe and each supplied by different risers. In addition to the temperature control knob on the mitigating valve (Figure S1a), the tested showers had separate valves to control the water supply to the shower head and to the lower faucet (Fig. S1). In this type of shower equipment, water flow can be interrupted by closing the lower faucet control knob and the shower faucet control knob while leaving the mitigating valve opened, thus creating a connection or integrity breech between the hot and cold water systems. Hot water temperature and flow rate were recorded at 5-min intervals at the bottom of each associated riser using devices described in section 2.3. The temperature was also monitored for corresponding return pipes and on the horizontal secondary flow and return loop feeding into Wing 3. During the trial, the shower mitigating valve was opened from 03/25 to 03/28 (water flow interrupted through the lower faucet and shower faucet control knobs), and again, from 04/01 to 04/04. The mitigating valve was closed appropriately from 03/29 to 03/31, although only periodical control could be performed after shower usage by patients. Design of the control shower did not allow mixing of hot and cold water.

2.5. Statistical analysis

Statistical analysis (Kruskal-Wallis and multivariate adaptative regression spline [MARSpline]) were performed with Statistica10 (StatSoft). Culture results for *L. pneumophila* were considered as

Table 1
Positivity of *L. pneumophila* (% or CFU/L) compared to physicochemical results in all wings and particularly in wing 3.

	All wings excluding wing 3					Wing 3				
Number of samples	26					18				
L. pneumophila positivity	83.3%					100%				
Legionella spp positivity	87.5%					100%				
	Mean	2*SD	Median	Min	Max	Mean	2*SD	Median	Min	Max
L. pneumophila levels in positive samples (CFU/L)	3639	8525	3050	20	15000	12211	26970	5500	1000	40000
Legionella levels in positive samples (CFU/L)	6979	22920	5000	20	35000	12489	26757	6400	1000	40000
pH	7.8	0.2	7.8	7.6	8.0	7.5	0.4	7.5	7.2	7.8
Turbidity (NTU)	0.38	0.78	0.28	0.04	2.13	0.30	0.11	0.31	0.21	0.41
Dissolved Oxygen (mg/L)	8.1	2.1	8.1	6.3	10.0	7.3	1.5	7.1	6.1	8.7
Maximum temperature at point of use	54.9	6.6	55.2	48.6	59.7	49.6	5.54	49.4	44.1	54.9

SD: Standard deviation.

non-parametric. MARSpline regression is a nonparametric analysis in which continuous, categorical, and nominal variables are considered to define a predictive equation with the best fit between predicted and observed data. The Kruskal-Wallis test was used to determine if there was a significant change in levels of *L. pneumophila* contamination before and after the interventions, and to evaluate if there was a statistical difference in level of *L. pneumophila* between the different temperature groups. Results were considered significant if $p \leq 0.05$.

3. Results and discussion

3.1. Monitoring of temperature in the HWDS

Temperature distribution in the primary and secondary return loops was first assessed to evaluate the overall *Legionella* risk. Water temperatures at the water heater outlet and at the main recirculation loop were monitored over a 3-week period (2015/11). Although the mean hot water temperature was above the 60 °C set point (61.1 °C ± 3.0 °C), important temperature variations were observed throughout the day and continuous monitoring revealed that the 60 °C was met only 85% of the time. As an example, the hot water temperature lowered to 37.4 °C during a high demand event and the temperature remained below 60 °C for a period of 30 min. In addition, the mean temperature in the main recirculation loop (52.9 ± 0.9 °C) did not meet the recommended 55 °C [12,16]. Mean recirculation temperatures below 50 °C were also observed for secondary horizontal pipes [11]. An earlier study revealed that mean hot water temperature after 5 min of flushing at the tap was below 50 °C (45.5 ± 6.6 °C) and more than 80% of sampled faucets (53/63) did not reach 55 °C after 15 min of flushing [11]. In addition, pressure recorded at the principal flow and return loop prior to distribution into the secondary flow and return loops revealed the absence of a pressure differential between the hot water and the recirculation systems. Prior to the start of this study, secondary pumps were installed on the recirculation loop of wings 3, 4, 5 and 6, as an attempt to compensate for the lack of recirculation observed in those wings. However, poor water recirculation in sectors of a large building HWDS is often associated to a lack of hydraulic balance between the different secondary loops and should be addressed. The use of local pumps on selected secondary horizontal loops can drive local internal loops, creating flow inversions between hot water and recirculated water during or in between periods of water usage. In addition, the presence of a connection between the hot water and the recirculated water at each point-of-use (Fig. 1) increased the number of locations where flow inversions could occur. This phenomenon will be discussed in greater details in section 3.3 and is likely one of the reason why temperatures of 55 °C cannot be reached after prolonged flushing at some points of use despite production of hot water at or above 60 °C. In light of these results and according to the risk classification approach proposed by Bedard et al., the principal flow and return loop system was rated at risk, with hot water temperature ≥60 °C less than 90% of the time and the principal recirculation loop temperature below 55 °C. The secondary and tertiary flow and return loops were at high risk, with secondary return loop temperatures below 50 °C in several wings and at the tap after 5 min [11].

3.2. Detection of *Legionella pneumophila* in the HWDS

Monitoring of *Legionella* spp., *L. pneumophila* and water quality was conducted on the system (water heater outlet and the recirculation loop) and points of use before the start of the hydraulic investigation (Table 1). The selected points of use included showers (9), manual faucets (12) and foot-operated faucets (8), and were located throughout the hospital, with 17 points located in Wing 3. The *Legionella* population was clearly dominated by *L. pneumophila* and given the observed similarities between both datasets, the discussion mainly focuses on *L. pneumophila* results. High positivity for *L. pneumophila* (90.5%) was observed throughout the hospital, with 100% contamination and maximum bacterial loads observed in Wing 3. This wing was selected as representative of a hospital sector with poor hot water recirculation and unable to achieve recommended control temperatures. More specifically, mean bacterial loads for *L. pneumophila* positive samples in Wing 3 were more than 3X higher than in all other wings and all positive samples from Wing 3 were at or above an established action level of 1000 CFU/L [12]. The lower temperature results observed in Wing 3 also confirmed the presence of water circulation issues. Although the variability was comparable, the mean temperature was 5.3 °C lower in Wing 3, a trend also observed for minimum and maximum values. Overall, the prevalence and bacterial load of *L. pneumophila* measured in hot water samples of the studied HWDS confirmed the high level of risk for *Legionella* proliferation that was assigned based on temperature data (section 3.1).

The distribution of *L. pneumophila* counts were investigated as a function of the maximum temperature reached after flushing the point of use for at least 10 min (2016/01 to 2016/05). Fig. 2 clearly shows that the counts are systematically higher between 40 and 55 °C and that they decrease substantially and significantly ($p < 0.005$) for water samples collected at points of use where maximum temperature exceeded 55 °C. More specifically, the median decreased by 2.1 log when temperatures were above 55 °C, and an important decrease in *L. pneumophila* positivity was observed (Fig. 2). According to these results, a relationship between the temperature at the point of use and the percent positivity can be suspected. Although a decrease in positivity is already observed between 50 and 55 °C, it should be noted that the only two points

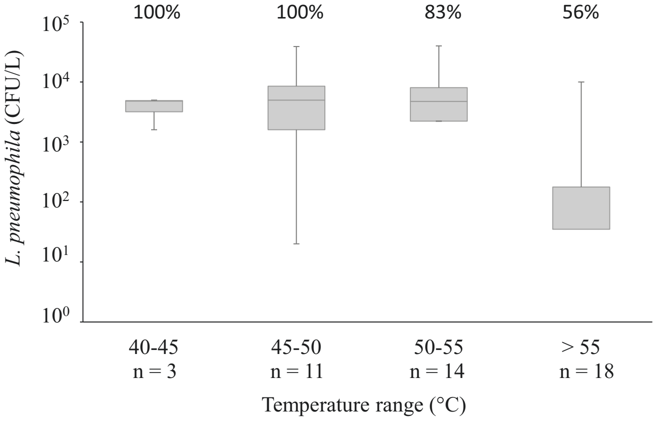

Fig. 2. Variation of *L. pneumophila* (CFU/L) as a function of the maximum hot water temperature measured at the point of use for positive samples. *L. pneumophila* percent positivity for each temperature range is indicated above the box. Samples were taken between January 18th and April 25th prior to hydraulic corrective measures. Box: 25–75%; Middle line: Median; Whiskers: Min and Max.

driving this reduction observed had temperatures of 54.6 °C, very close to the 55 °C cutover temperature. A lower positivity for *Legionella* (72% vs 100%) was also observed at temperatures above 55 °C, as reported in prior studies [27,28]. Arvand et al. observed a drastic reduction from 87% to 11% in distal positivity for samples where temperature was below vs above 55 °C [27]. In their study, 309 samples collected after a 5 L flush were analyzed, of which 52 were below 55 °C. The lower positivity observed by Arvand et al. could be attributed to the fact that samples above 55 °C included water temperatures up to 70 °C, which would decrease further the positivity. In the present study, the highest temperature measured at the point of use was 60.8 °C. Positivity results obtained in our study are closer to those reported by Marchesi et al., who also observed a reduction in *Legionella* positivity when hot water temperature was above 55 °C, but to a lesser degree [28]. A total of 66 samples were collected after 1-min flush, with 90.5% positive for temperatures between 50 °C and 55 °C, 63% for temperatures between 55 °C and 60 °C and no positives for temperatures above 60 °C. Our observations and those previously reported show that thermal control can be an effective barrier to control *L. pneumophila*, but needs to be maintained over time in order to observe positivity decrease below 30% [29].

Fig. 3a presents *L. pneumophila* results as a function of the type of device sampled. No significant difference was noted in *L. pneumophila* concentrations when considering shower heads (9) and faucets (12 manuals and 8 pedal activated). Ten out of 12 manual faucets, all shower heads and all foot-operated taps were contaminated. The median concentrations were respectively 5200 CFU/L, 5675 CFU/L and 4250 CFU/L. Our results do not indicate an impact of the type of device on *L. pneumophila* contamination. However, the system wide contamination and the recirculation issues present at the time of sampling combined to the reduced sample size for each type of device make it difficult to conclude.

Elevated water residence times and stagnation have also been identified as contributing factors for *Legionella* growth in plumbing systems [30]. Most *Legionella* control guidance and regulations specify that dead-end and stagnation zones should be avoided [11,12,14,31,32]. Areas with low flow and stagnation are favorable to the development of biofilm which can detach during intermittent periods of higher velocity and turbulent flow occurring during water usage. In health-care facilities, a peak factor of 6 or more can be encountered for water usage during high demand periods such as bathing time [33], increasing further the variation between low and high usage periods. Several guidelines suggest to include sampling points furthest located from the water heater as representative of the risk for *Legionella* proliferation, based on the assumption that furthest points correspond to higher water residence time [12,31]. Results from this study suggested a general increasing trend between the *L. pneumophila* load and the linear distance from the manifold, but considerable scatter and weak correlation were observed (Fig. S2). As shown on Fig. 2, temperatures at the point of use are clearly a better risk indicator. In this case, the selection of the high risk indicator sites based on their distance from the water heater outlet may not be justified since the distance was not a good indicator of *Legionella* contamination levels. The selection of sampling points located furthest away from the water heater to monitor *L. pneumophila* risk may be representative in a balanced system [31,34]. Results from the current study suggest that selection of sampling points in an unbalanced system should be based on temperature rather than on the distance from the water heater in order to be better representative of the *Legionella* risk.

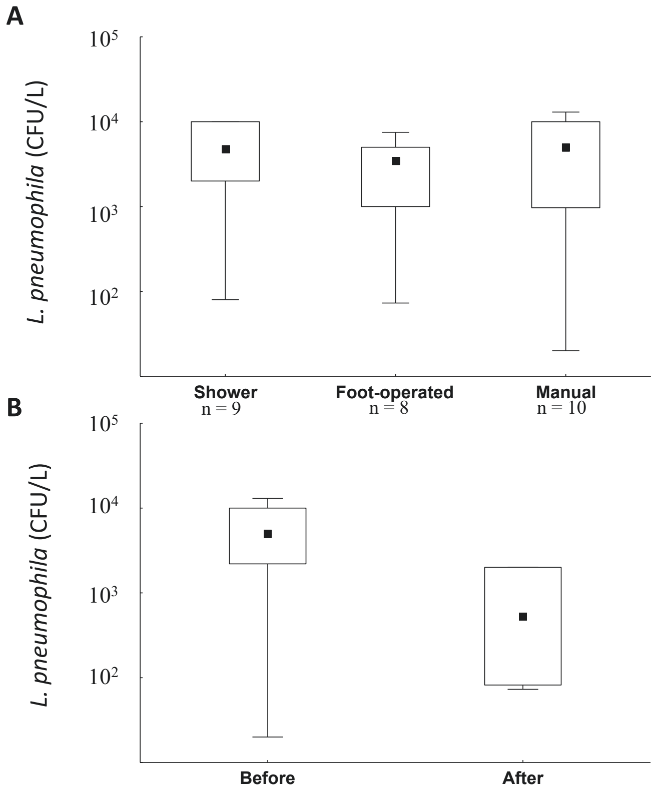

Fig. 3. *L. pneumophila* counts (CFU/L) measured by type of point-of-use before corrective measures (A), and for all positive samples before (October 2015–April 2016, n = 27) and after (June 2016, n = 6) the hydraulic corrective measures were implemented (B). Box: 25%–75%; Median: ■; Whiskers: Min and Max.

As several factors may be involved in presence of *Legionella* contamination in the hot water system, a multivariate adaptive regression spline (MARSpline) statistical analysis was conducted to identify the most significant contributors to elevated observed concentrations. The dependent variable was *L. pneumophila* culture results and the following variables were included as independent variables: type of device, maximum water temperature range, distance from the manifold, dissolved oxygen, pH, and turbidity. The resulting equation indicated that temperature and turbidity were the dominant predictive variables, followed by the type of device and the distance from the manifold, with a resulting

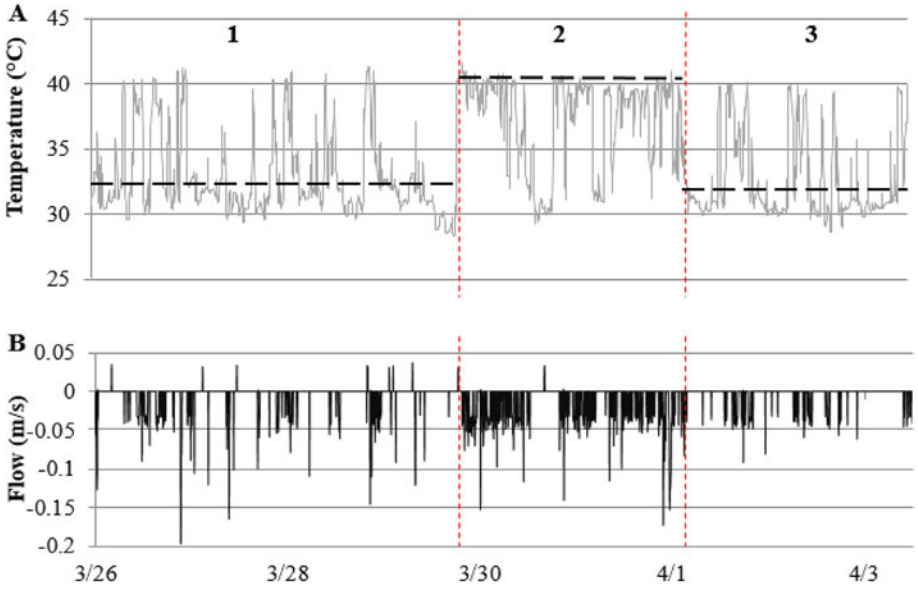

Fig. 4. Example of hot water temperature and flowrate measured at the bottom of a secondary vertical pipe (riser) in Wing 3 during the field investigation. The mixing valve of the shower was kept open during period 1 and 3 and closed during period 2. The median temperature for each period is represented by a horizontal dashed line.

correlation of $R^2 = 0.68$. Dissolved oxygen and pH were not predictive variables. These results also point toward temperature as an important factor to predict the risk of *Legionella* within HWDS, and suggest that turbidity should be investigated further. Based on these results, we hypothesize that overall hydraulic balancing issues of the HWDS and poor local water recirculation patterns were the main source of the temperature deficiencies that were observed, leading to high bacterial loads of *Legionella* contamination.

3.3. Effect of hot and cold water mixing at the point of use on the hot water system temperature

The presence of unfit equipment was investigated in Wing 3 where hot water temperature in showers was not meeting user expectations. As described in section 2.4, certain types of shower mixing valves enabled a connection between hot and cold water systems when improperly closed (Fig. S1). It should be noted that such connections may also occur if the faucet return valves are blocked or defective, which is a commonly reported problem in large buildings. A field investigation was conducted to measure the extent and impact of a connection between the hot and cold water at the point of use. Temperatures at the bottom of risers of each targeted shower were monitored over a period of 2 weeks. Fig. 4 shows temperatures and flow rates observed at the bottom of a riser when the shower mitigating valve was improperly closed (03/26 to 03/30 and 04/01 to 04/03) or closed (03/30 to 04/01). When the shower mitigating valve was left open (shower improperly closed), the median hot water temperature was 31.5 °C, with punctual increases when hot water was used. When the shower mitigating valve was closed, the median temperature was higher at 39.0 °C. Temperature decrease observed at night was not related to the closing of the shower valve, but rather to the lack of recirculation that was present in this wing before the hydraulic balancing of the system. In case of integrity breech between hot and cold water systems, cold water can flow into the hot water system if pressure differential is favorable, causing a decrease of hot water temperature. In this case, cold water pressure measured at the bottom of the risers was slightly superior to that of hot water (111 PSI vs 109 PSI), thus increasing the risk of mixing. The effect of flow rate on temperatures can also be observed on Fig. 4: in periods of stagnation (at zero flow), hot water temperature decreases, whereas in periods of use, hot water temperature increases. Moreover, negative flow rate values indicate reversed water circulation in the recirculation loop and suggest that recirculation water is being fed to the faucet. Results from this local detailed investigation show the large impact a single device can have on the distribution and maintenance of hot water temperatures in a large section of the HWDS. A single defective device was sufficient to increase the volume of water at risk for *Legionella* proliferation, as temperature could not be maintained in the vertical risers. Although the estimated water volume associated to a faucet or a shower is relatively small (10–500 mL), the impact is observed on a much larger volume contained within the connecting pipes and the secondary pipes. In the present case, the impact on temperatures was observed at the lower level of the risers, located 7 floors below the showers and corresponding to a volume of 6.5 L. These results highlight the importance of maintaining systems integrity between hot and cold water, even at local points of use such as showers or mitigated taps. Not only is the hot water distribution system more at risk for *Legionella* due to lower temperatures, but the intrusion of hot water into the cold water can also increase the risk of bacterial contamination and of *Legionella* proliferation in the cold water distribution system [27]. Thermostatic faucets have integrated check valves that are high-maintenance and are vulnerable due to poor quality material. The installation of additional single check valves on the hot and cold water feed pipes are recommended to prevent mixing of cold and hot water [16].

3.4. Impact of the addition of local secondary recirculation pumps

As a first attempt to force recirculation, the hospital staff installed local secondary recirculation pumps to force circulation in the sectors with documented insufficient water temperatures. These pumps were located on the recirculation loops of Wings 3, 4, 5 et 6. Temperature and flow rate monitoring results showed that the secondary local recirculation pumps induced a local water flow inversion within the horizontal and vertical secondary recirculation

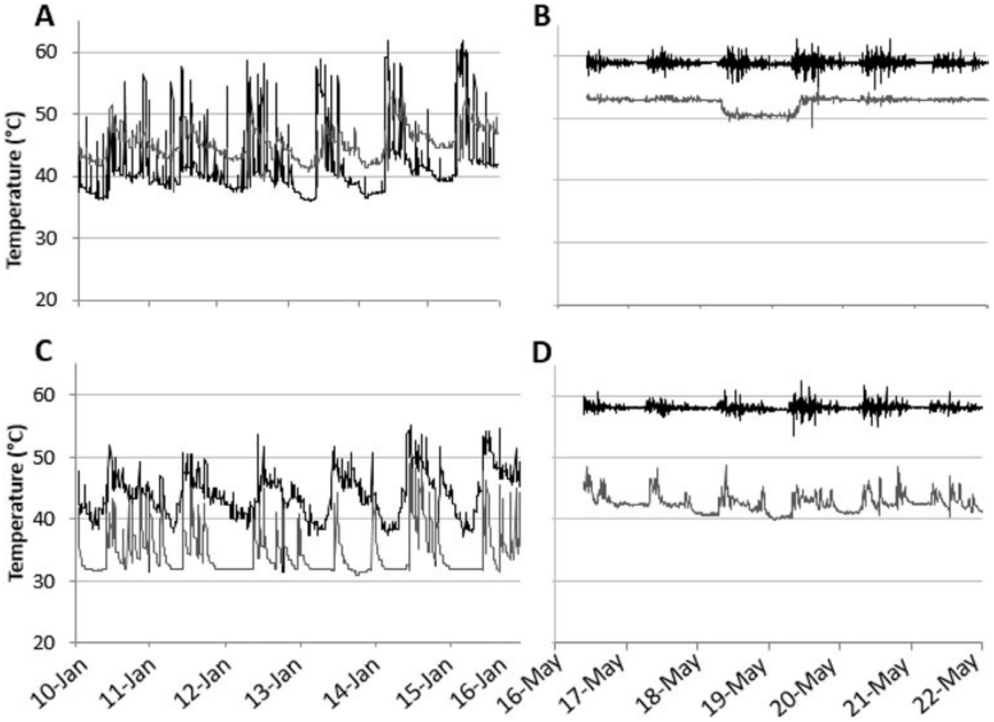

Fig. 5. Temperatures at the entrance (A & B) and end (C & D) of wing 3, before (A & C) and after (B & D) the modifications of the hydraulic system. Temperatures of hot water (black) and recirculated water (grey) were taken on vertical risers in January and May 2016.

loops (Fig. 5a). Temperatures were higher for the recirculating water (45.4 ± 0.9 °C) compared to the hot water (41.7 ± 5.3 °C). A high level of temperature variation between usages was also observed (Fig. 5 a, b). As a result and in order to work toward balancing the hot water system as a whole, all secondary recirculation pumps were removed. The resulting effects on water temperatures and flow rates in Wing 3 are presented in Fig. 6. Although the problems of poor temperatures remained in the furthest risers, circulation was improved at the inlet of the wing.

3.5. Hydraulic evaluation of the existing system and corrective measures

In order to determine which wing was hydraulically disadvantaged and to assess the level of balancing required between the different wings, temperature probes were placed on the surface of the horizontal secondary flow and return loop of each wing. These results revealed a mean hot water supply temperature of 58.1 ± 0.9 °C in the hospital kitchen whereas hot water was supplied to Wing 3 with a mean temperature of 49.6 ± 1.9 °C, a loss of 11.5 °C compared to the water heater outlet temperature. These results indicate uneven water distribution between the wings and suggest that certain loops offering minimal pressure losses (such as the kitchen) can act as a bypass for a large portion of the recirculated water volume. The lack of pressure differential between hot water and recirculated water observed points toward the same conclusion. Detailed investigation of temperatures and flow rates of the secondary horizontal flow and return loops led to the identification of 15 cm- diameter unused recirculation loop. The mean temperatures measured on the hot and recirculated water of that loop (52.5 °C and 38 °C) suggest the presence of water circulation, offering another bypass for the recirculating water. The unused recirculation loop was therefore eliminated and the recirculation flow in the kitchen was minimized to force the recirculation in the other wings. Given that pressure losses are more important in recirculation loops of the other wings, the restriction in the kitchen helped to induce a differential of 2 psi between the hot water and the recirculated water. Despite the observed improvement in

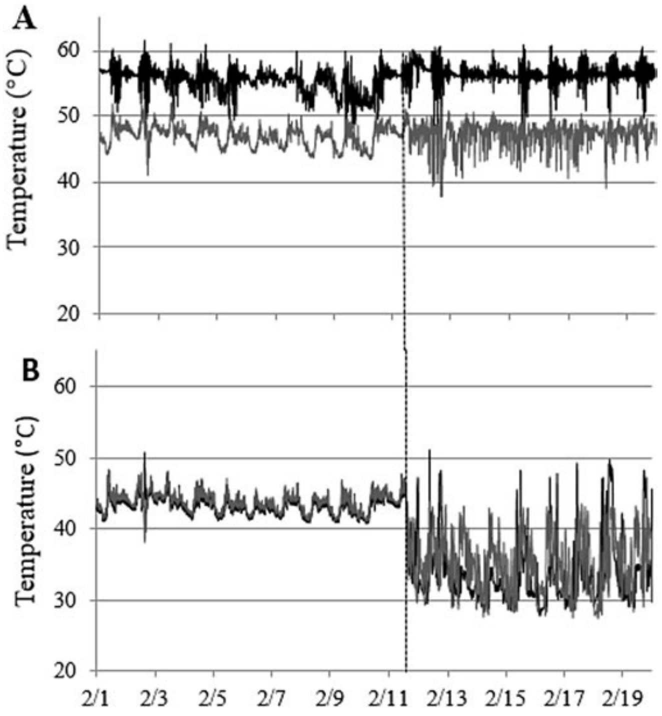

Fig. 6. Impact of secondary recirculation pump shutdown on temperatures in Wing 3 in February 2016. Hot water (black) and recirculated water (grey) temperatures were taken on main horizontal pipes. A) At the entrance of Wing 3; B) At the end of Wing 3.

Table 2
Mean temperature and standard deviation of the recirculated water at the entrance of Wings 1 to 8 in March and May 2016. ΔT represents the difference between May and March for each Wing. The changes made in the hot water and recirculation systems have led to an average of +5.9 °C in the whole recirculation system.

Wing	1	2	3	4	5	6	7	8
18–22 March	45.5 ± 1.6	49.7 ± 0.8	48.3 ± 1.2	44.6 ± 0.6	38.0 ± 1.4	38.0 ± 2.2	52.0 ± 0.5	50.4 ± 0.4
10–16 May	51.9 ± 0.7	53.1 ± 1.2	52.9 ± 0.9	51.5 ± 1.1	51.8 ± 0.7	52.5 ± 1.0	50.7 ± 0.9	49.6 ± 0.5
ΔT (°C)	+6.4	+3.4	+3.2	+6.9	+13.8	+14.5	−1.3	−0.8

temperatures, this measure was not sufficient to reach recommended minimum recirculation velocities [16]. Additional corrective measures were therefore implemented in 2016/05. Efficiency improvements of the principal recirculating pump and restriction of the recirculation flow for hydraulically advantaged wings (7, 8 and 9) contributed to increase water recirculation velocity up to 0.3 m/s.

Following these improvements, hot water and recirculation temperatures were monitored for each wing (05/10 to 05/16) and compared to results obtained from 03/18 to 03/22. A gain of 7.6 °C in hot water temperatures was observed in Wing 3 after the first phase of corrective measures, which included the closing of local secondary recirculation pumps and the restriction of the kitchen recirculation (49.6 ± 1.9 °C vs 57.2 ± 0.8 °C). The second phase of corrective measures resulted in a higher gain on the recirculation temperatures, as presented in Table 2. A mean temperature increase of 5.9 °C was observed before and after the 2nd phase, and the highest gain was observed in wings that had the lowest recirculation temperatures initially, suggesting generalized marked improvement on hot water temperature distribution within the system. Hydraulic balancing is key to ensure proper functioning of the water distribution system and to obtain required temperatures to control *L. pneumophila* at all points-of-use.

3.6. *Impact of hydraulic system improvements on temperature up to the point of use*

Following the observed gain in water temperatures in the horizontal secondary flow and return loops feeding each wings, temperatures at the bottom of the risers were monitored in Wing 3 (05/16 to 05/22) and compared to temperatures obtained prior to the implementation of corrective measures (Fig. 5). Temperatures results are presented for the first riser into the wing (Fig. 5a and b) and the riser next to the end of the wing (Fig. 5 c and d). The temperature drop observed on the recirculation water between 05/11 and 05/12 was attributed to a short event with the recirculation pump (Fig. 5b). As a result of the system hydraulic balancing, the mean hot water temperature in Wing 3 increased significantly (58.9 ± 0.7 °C) and better temperature distribution was observed throughout the wing. Increases of 14 °C in hot water and of 8.1 °C in recirculated water were observed in the riser next to the end of the wing (Fig. 5 c, d). Moreover, there were no more occurrences of flow inversions within the secondary vertical flow and return loop, with hot water temperature consistently higher than recirculated water temperatures (Fig. 5a, c).

Hot water temperature profiles were also conducted at points of use in Wing 3 to validate if the observed temperature increases at the bottom of the risers was also reflected at the points of use. Fig. 7 shows temperature profiles obtained before the beginning of corrective measures (2012–2015, Fig. 7a), after stopping all local secondary recirculating pumps (04/22 to 04/27, Fig. 7b) and after the implementation of all corrective measures (05/11, Fig. 7c). An important gain in hot water temperature at the point of use was achieved following hydraulic corrective measures. The proportion of taps achieving 55 °C within 2 min increased from 11% to 74% and *L. pneumophila* prevalence decreased from 93.1% to 46.1% four weeks after corrective measures were completed. In addition to the reduced positivity, Fig. 3b shows a significant bacterial load reduction in positive samples following system hydraulic improvements. However, more work is required to further reduce the percentage of positive points of use and to ensure that the observed reduction in culturable *L. pneumophila* is also reflected on the viable cell counts. Monitoring of culturable and non-culturable *L. pneumophila* over the next year together with continuous system improvement to reach 55 °C at all points of use after one minute will be the next steps to have a low risk system.

In light of the results obtained in this study, a step approach is proposed to rehabilitate an existing deficient large building hot water system and obtain recommended temperatures to improve *L. pneumophila* control:

- Ensure hot water temperature at the water heater outlet ≥60 °C through continuous monitoring.
- Eliminate local secondary pumps if present in the system.
- Evaluate the efficiency of the main recirculation pump to deliver water velocities ≥0.2 m/s.
- Measure pressure differential between the principal horizontal hot water feed and the principal recirculation return pipes; if no pressure differential is present, investigate for the presence of

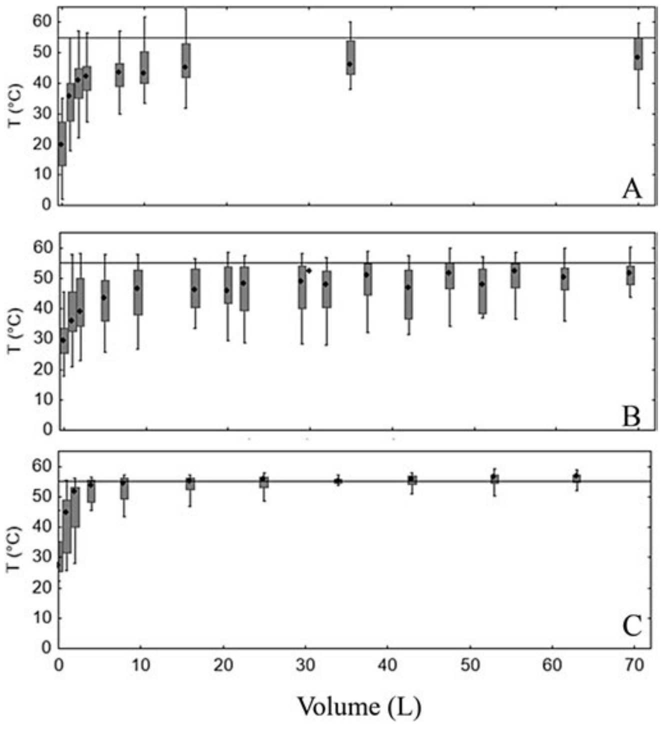

Fig. 7. Hot water temperature profiles at point of use as a function of flushed hot water volume prior to changes (A, n = 45), in April 2016, after the first phase of corrective measures (B, n = 39) and in May 2016, following the implementation of the corrective measures (C, n = 16). Boxes: 25%–75%; median ■; whiskers: min-max.

loops offering less resistance and offering a bypass for the recirculating water. This evaluation can be performed through temperature measurements of the hot water feeding the different parts of the building. Temperature results can be used to identify required hydraulic balancing between the different sectors of the hot water system.

- Perform balancing through flow restriction devices on the recirculation loops of the sectors with higher temperatures (hydraulically privileged) in order to force recirculation into wings with lower temperatures.
- Investigate for the presence of dead legs (stagnation areas) or unused loops in the principal and secondary flow and return loops.
- Investigate the presence of flow inversion in each sector of the building through temperature monitoring at each riser for a vertical architecture or by story for a horizontal architecture to ensure performance to design.
- Identify misfunctional equipment or local hydraulic deficiencies using temperature profiles at points of use. Water temperature at the faucet should reach 55 °C within 1–2 min of flow. If this criterion is not met, the required time to reach maximum temperature and the maximum temperature obtained can be used as indicators to locate the source of the problem.

Hot water distribution systems in large buildings are subject to numerous variations over the years, especially for healthcare facilities where numerous points of use are present and renovations/rehabilitation of building areas are frequent. The system that was designed and hydraulically balanced originally may become unbalanced overtime as wings are added (increased water usage and head loss), rooms are converted to offices (change in water usage pattern and removal of points of use, leaving dead legs), corrosion and biofilm build up and increase pressure loss overtime. Consequently, reduced water velocity and uneven distribution between the different sectors of the building will increase residence time and lead to suboptimal temperatures within areas of the system (below 55 °C) or at the point of use. As a result, the system becomes at risk of *Legionella* proliferation, leading to high levels of contamination and risk of infection for exposed individuals. This study documents an investigative step approach based on temperature monitoring that allowed the balancing of a 50-year-old hot water distribution system that had become unable to provide required hot water temperature for *Legionella* control and was faced with a widespread contamination. As a result of the investigation, minimal equipment changes were required (addition of flow restrictive devices on secondary horizontal return loops) and results could be observed within a month from the changes.

Finally, if temperature cannot be maintained throughout the HWDS up to the point of use because of improper circulation, thermal control cannot be efficient. Resolving hydraulic issues should therefore be the highest priority for any HWDS. It is also evident that disinfection in that situation would also fail, as improper distribution will hinder the effective distribution of disinfectant residuals across the HWDS.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.08.038.

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