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Optimizing energy efficiency and legionella control in hot water circulation systems: laboratory validation and field assessment in Swedish multifamily buildings

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ABSTRACT

Hot water circulation (HWC) systems in multifamily buildings face a fundamental trade-off: maintaining temperatures sufficient to suppress *Legionella pneumophila* (≥50 °C) while minimizing the 2.5–4.3 TWh annual energy loss these systems represent in Sweden alone. This study employed a novel dual approach combining controlled laboratory experiments with real-world validation to address this challenge. We constructed a full-scale test rig simulating a 20-apartment building to quantify thermal losses and microbial dynamics under varying flow rates and temperatures. This was complemented by a field validation encompassing 56 water samples from 31 multifamily buildings. The results demonstrate that when optimizing the system to maintain a regulatory required return temperature of 50 °C, thermal heat losses were nearly identical between low-flow (0.2 m/s) and high-flow (0.5 m/s) operation. The decisive factor was pump energy, where high-flow operation required 3.4 times more power than low-flow operation (108 W vs. 32 W). This resulted in a total annual energy saving of approximately 12% for the low-flow strategy, entirely attributable to reduced electricity consumption for the pump. Periodic thermal shocks at 60–65 °C effectively reduced L. *pneumophila* concentrations, indicating that continuous high-temperature operation is not required for microbial control. Field sampling revealed that 23% of samples tested positive for legionella, with problematic cases strongly linked to design flaws like towel warmers connected to the HWC loop. These findings indicate that a risk-based strategy combining low-flow circulation (0.2 m/s), a baseline return temperature of 50 °C, and periodic thermal shocks can significantly reduce system energy consumption while maintaining legionella safety.

Introduction

Domestic hot water (DHW) systems represent a critical intersection of public health and energy efficiency in building operations. In Swedish multifamily buildings, DHW accounts for 25–40 % of total heating demand, averaging 54 kWh/m²·year [1]. with circulation losses alone contributing 10–17 kWh/m²·year [2]. This translates to 2.5–4.3 TWh annually across the national building stock, equivalent to the total electricity consumption of 500,000 Swedish homes.

The challenge intensifies when considering the requirements for Legionella pneumophila control. Current Swedish building regulations (BBR 30) mandate maintaining temperatures at or above 50 °C throughout Hot water circulation (HWC) systems, a threshold based on inhibiting bacterial growth. However, this requirement results in substantial energy penalties. The present paper shows that for the present case, 1 °C increase in system supply temperature increases heat losses by approximately 5 %. This creates a direct conflict between energy efficiency objectives and microbial safety requirements.

Recent international studies and operational strategies increasingly question whether continuous high-temperature operation is the most optimal method for Legionella control. Instead of constant energy-intensive operation, alternative methods such as periodic thermal disinfection, also known as thermal shock or superheating, have been established as a known control strategy [3]. Research has shown, however, that while such shock treatment is effective momentarily, the system can be recolonized to pre-treatment contamination levels within

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one or two months. This underscores the need for the treatment to be repeated periodically to maintain low bacterial levels [4].

Simultaneously, research on energy-efficient "green buildings" has revealed unintended consequences for water quality. A notable study found that the concentration of genetic markers for opportunistic pathogens, including Legionella, was 1 to 4 orders of magnitude (10 to 10,000 times) higher in green buildings compared to conventional ones [5]. The reason is that design choices made to save water and energy—such as water-efficient fixtures and solar pre-heating—lead to increased stagnation (higher water age) and temperatures that fall into the ideal growth range for Legionella (35–42 °C)[5].

Another study confirms that water quality in green buildings can have higher concentrations of pathogens due to factors like "increased water age and stagnant low water use from water-efficient fixtures" [6]. Recent systematic reviews have identified multiple energy-efficient strategies for Legionella control beyond temperature maintenance alone [7]. Stagnation is a well-known risk factor that reduces the effectiveness of disinfectants and promotes the growth of Legionella in biofilms [8]. although advanced monitoring techniques, including real-time flow cytometry, now enable continuous tracking of Legionella populations without culture delays [9]. complementing predictive models [10]. Previous multi-criteria analyses have explored water reuse systems in buildings [11,12] though the interaction with Legionella risk remains understudied. These findings suggest that temperature alone may be an inefficient control strategy and that alternative strategies merit investigation.

This study exemplifies the water-energy nexus challenge in building systems, where water quality requirements directly impact energy consumption. The interdependence between public health standards and climate mitigation goals requires integrated solutions that optimize across multiple objectives. We hypothesized that optimized low-flow operation combined with periodic thermal disinfection could achieve equivalent or superior legionella control compared to continuous high-temperature operation, while substantially reducing energy consumption.

The present work advances previous research on Legionella control and HWC optimization in three main ways. First, we combine a controlled full-scale circulation rig, scaled to a typical 20-apartment building, with a field campaign in 31 multifamily buildings, thus directly linking laboratory findings to real operational systems. Second, we provide a quantitative decomposition of energy use in HWC systems, separating thermal losses from pump electricity and explicitly comparing low- and high-flow strategies under a fixed 50 °C return temperature constraint. Third, we relate these energy findings to measured Legionella occurrence and identifiable design flaws in existing buildings, thereby supporting risk-based operational strategies that balance energy efficiency and water safety. Together, this dual laboratory–field approach provides a more integrated basis for optimizing HWC operation than previous studies that have focused primarily on either energy or microbiological aspects in isolation.

Materials and methods

Experimental test rig design and specifications

A full-scale HWC test rig was constructed at KTH Royal Institute of Technology to simulate a typical Swedish 20-apartment building system. The piping configuration included copper, and cross-linked polyethylene (PEX-a). All piping was insulated with 40 mm mineral wool. Four sampling ports were positioned along the loop, with removable pipe sections for biofilm analysis. The instrumentation suite included temperature sensors and flow meters connected to a data logger.

To enable reproducibility and to clarify how the test rig was scaled to represent a typical 20-apartment multifamily building, additional hydraulic and thermal specifications are provided here. The circulation loop was approximately 70 m long, consisting of 35 m PEX-pipe (Dy 25 mm) and 35-meter PEX-pipe (Dy 16 mm). All pipes were insulated with 40 mm mineral wool (declared thermal conductivity $\lambda = 0.036$ W/m·K). The test rig was in a conditioned laboratory hall with an ambient temperature maintained between 20–23 °C throughout all experiments. Supply temperature was controlled using a PID-regulated electric heater, while pump rotational speed was adjusted to achieve the target circulation velocities. The tested flow rates were set to mimic the minimum and maximum flow conditions comparable to those in real HWC risers. These parameters confirm that the laboratory rig is hydraulically representative of full-scale systems and suitable for evaluating the effects of flow rate and temperature on heat losses and Legionella behavior.

Two distinct flow regimes were established: a high-flow condition at 0.5 m/s and a low-flow condition at 0.2 m/s. At the tested velocities and pipe diameters, the Reynolds number ranged from approximately $Re =$ 4000–10,000, confirming fully turbulent flow typical for HWC risers. Three steady-state supply temperature setpoints of 45, 55 and 65 °C were tested. A scenario using a fixed return temperature of 50 °C was also analyzed for the two flow conditions. In Fig. 1 the system design for the test rig is presented.

Microbiological methods

Initial system sterilization was achieved using chlorine dioxide. For controlled inoculation studies, we utilized L. *pneumophila* serogroup 1, an environmental isolate. Quantification of L. *pneumophila* employed the IDEXX Legiolert® method, which complies with ISO 11,731 standards. Biofilm analysis utilized standardized coupons with analysis of total biomass, extracellular polymeric substances, and molecular characterization.

Water samples were collected in sterile 250 mL bottles containing sodium thiosulfate (18 mg/L) to neutralize residual disinfectants. Samples were transported at 4 °C and analyzed within 48 h. L. pneumophila quantification employed the IDEXX Legiolert® method (ISO 11,731-compliant), with results expressed as Most Probable Number (MPN) per 100 mL. For biofilm analysis, standardized stainless steel and PEX-a coupons (2 cm^2) were positioned at four locations along the circulation loop. Coupons were removed aseptically at 30-day intervals. Total biomass was quantified using crystal violet staining (OD570), while extracellular polymeric substances were extracted using the heat extraction method and quantified for proteins (Bradford assay) and polysaccharides (phenol-sulfuric acid method). DNA extraction yielded concentrations ranging from 0.08–0.15 ng/μL in early-stage biofilms.

L. pneumophila was quantified using the IDEXX Legiolert® assay according to the manufacturer's instructions and ISO 11,731. The method has a detection limit of 1 MPN/100 mL and a quantification range of 1–22,726 MPN/100 mL. In the field campaign, one 1-L sample was collected per sampling point. In the laboratory experiments, single samples were prepared per condition and analyzed individually. We assessed the precision of the method separately and found the relative standard deviation to be within 15 % for values above 100 MPN/100 mL ($n = 5$). When reporting concentrations per condition, variability is reflected in the implied standard deviation. Values below the detection limit were treated as censored and are reported as < 1 MPN/100 mL.

Thermal disinfection and recolonization kinetics

Temperature increases to 60–65 °C were tested to evaluate thermal disinfection effectiveness. Following each thermal treatment, intensive monitoring captured recolonization dynamics.

Field investigation

The field investigation included 56 water samples from 31 multifamily buildings. The buildings were separated into two groups: 28 randomly selected buildings and three buildings with a documented

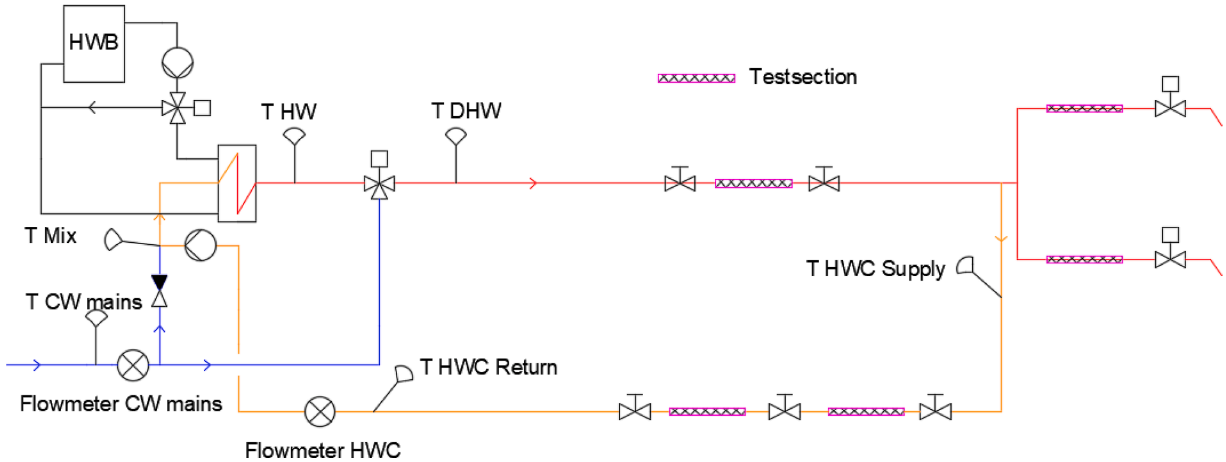

Fig. 1. Schematic of the full-scale hot water circulation (HWC) test rig. The setup represents a typical Swedish 20-apartment building and includes insulated copper and PEX-a piping, sampling ports for both bulk water and biofilm coupons, circulation pump, temperature control, and instrumentation for flow and temperature logging.

history of legionella. Sampling followed ESGLI guidelines, and a standardized checklist was used for risk factor assessment. The stakeholder-driven framework developed by La Torre Rapp et al. informed the experimental design and risk assessment approach [13].

Energy analysis and optimization

Heat transfer analysis was done using measured total system heat loss, incorporating both conductive and convective losses. Pump energy requirements were measured using an energy meter. An analysis was conducted for an optimized case where the system was adjusted to maintain a constant 50 °C return temperature, comparing the total energy use (thermal and electrical) between the high-flow and low-flow strategies. The choice of operating scenarios was informed by recent machine-learning based studies that can predict Legionella occurrence with approximately 85 % accuracy [10]. However, no machine-learning models were implemented in the present work; instead, we used a physically based heat balance calculation combined with measured microbiological outcomes.

Steady-state heat losses were measured over at least 24 h at each operating point and averaged. Annual thermal energy losses (kWh/year) were obtained by multiplying the steady-state heat loss (kW) by 8760 h, assuming that the circulation system operates continuously and that internal ambient conditions in the building shafts are approximately constant over the year. Specific thermal losses (kWh/m^2) were normalized by the heated floor area of a representative 20-apartment building ([A] m^2), to which the rig was scaled. Pump electricity consumption was calculated from the measured electrical power and the same annual operating time. All energy values reported in this paper refer to final energy (delivered heat and electricity) and are not converted to primary energy or CO_2 emissions, in order to keep the comparison between thermal and electrical components transparent.

Measurement instrumentation and uncertainty

Temperature was measured using thermocouples type T with an accuracy of ±0.1 °C. Volumetric flow in the circulation loop was measured by a in situ calibrated ultrasonic flow meter with a specified accuracy of ±1–2 %, but calibrated to an accuracy of better than 1 %. Electrical power to the circulation pump was recorded using an energy meter with a accuracy class 1. Based on manufacturer specifications and standard uncertainty propagation, we estimate the combined uncertainty of the reported heat losses to be approximately ±5 %, and the uncertainty of pump energy consumption to be ±1 %.

Statistical analysis

Data were analyzed using R (v4.3.1). Heat loss measurements included ±5 % uncertainty. Correlations were assessed using Spearman's rank correlation ($p < 0.05$). Given the relatively small number of buildings and the presence of censored microbiological data, between-group comparisons (e.g. buildings with vs. without design flaws) are reported descriptively as proportions and ranges rather than through formal hypothesis tests. No correction for multiple comparisons was applied.

Results

Thermal performance under varying supply temperatures

Analysis of heat losses under controlled conditions revealed strong dependencies on both supply temperature and flow rate. At all tested supply temperatures (45, 55, and 65 °C), the low-flow condition (0.2 m/s) consistently resulted in lower total heat loss than the high-flow condition (0.5 m/s). For example, at a 65 °C supply temperature, heat losses were measured at 0.63 kW for high flow versus 0.59 kW for low flow. The temperature differential between supply and return increased at lower flow rates, reflecting a longer residence time in the circulation loop. In Fig. 2 the results from the analysis are presented.

Optimized operation for a fixed 50 °C return temperat

A more practical analysis was conducted to compare strategies when the system is adjusted to maintain a constant 50 °C return temperature, as mandated by regulations. In this scenario, a key finding emerged: the total annual thermal heat loss was nearly identical between the two flow strategies, measuring 4276 kWh/year for low-flow and 4253 kWh/year for high-flow. The reason for this similarity is that the low-flow case, while benefiting from increased internal thermal resistance, required a higher average system temperature to maintain the 50 °C return, and these two effects largely cancelled each other out.

The crucial difference was found in the pump's electricity consumption. The high-flow strategy required a measured power of 108 W, which was 3.4 times higher than the 32 W required for the low-flow strategy. On an annual basis, this is translated to 946 kWh for high-flow versus 280 kWh for low-flow.

When combining thermal and electrical energy, the low-flow strategy resulted in a total annual energy consumption of 4556 kWh, a saving of approximately 12 % compared to the 5199 kWh consumed by the

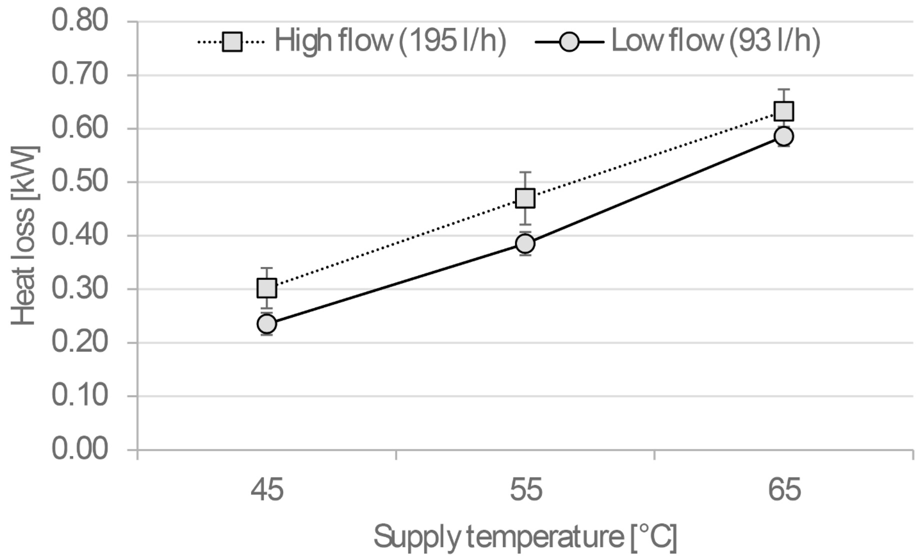

Fig. 2. Heat loss in the HWC loop at different flow rates and supply temperatures. Error bars indicate the estimated ±5 % measurement of uncertainty in the heat-loss calculations, based on instrument specifications for temperature, flow, and power measurements. High-flow operation (195 L/h) results in consistently higher heat loss compared with low-flow operation (93 L/h), and heat loss increases approximately linearly with supply temperature.

high-flow strategy. This saving is almost entirely due to the reduced electricity use of the circulation pump. Table 1 presents the full results from the analysis.

Microbial dynamics and thermal disinfection efficacy

During the initial establishment phase, no spontaneous colonization of L. *pneumophila* occurred in the test rig even when operated at temperatures (41–43 °C) favorable for growth. Establishment required the deliberate introduction of the bacteria from an external source.

Thermal disinfection proved highly effective. Short-term temperature increases to 60–65 °C caused a sharp reduction in legionella concentrations, often below the detection limit. This demonstrates that periodic thermal shocks are an effective strategy for controlling bacterial populations.

Initial colonization attempts using indigenous microbiota from municipal water failed to establish detectable L. pneumophila populations despite maintaining optimal growth temperatures (41–43 °C) for 8 weeks. This necessitated deliberate inoculation with L. pneumophila serogroup 1 (ATCC 33,152) at 10^6 MPN/L on September 30, 2024. Post-inoculation monitoring revealed: - Week 1–2: Rapid colonization with concentrations reaching 2.3×10^3 MPN/100 mL - Week 3–4: Stabilization at 1.8–2.5 $\times$ 10^3 MPN/100 mL under continuous 42 °C operation - Week 5: Thermal disinfection (65 °C, 30 min) reduced concentrations to <10 MPN/100 mL (>3.4 log reduction) - Week 6–8: Recolonization observed, reaching 8.7×10^2 MPN/100 mL within 14 days Biofilm development showed strong correlation with L. pneumophila persistence ($r^2 = 0.78$, $p < 0.01$), with mature biofilms providing 2–3 log higher protection against thermal disinfection compared to planktonic cells.

Field investigation results

Field sampling of 56 samples showed that 13 (23 %) tested positive for L. *pneumophila*. The prevalence was starkly different between building types. In randomly selected buildings, only 10 % of samples were positive. Conversely, in buildings with known design problems, 38.5 % of samples were positive, with most of these exceeding 1000 MPN/L. The presence of legionella was strongly associated with specific design flaws, particularly towel warmers connected directly to HWC loops, which create zones of stagnation and favorable temperatures for growth.

Table 2 summarizes Legionella occurrence by building group and design features. In randomly selected buildings, approximately 10 % of samples were positive, whereas in buildings with known design problems the share was 38.5 %. Buildings with towel warmers directly connected to the HWC loop had clearly higher positivity rates (100 %) than buildings without such installations (12 %), indicating that these design flaws substantially increase the likelihood of Legionella presence.

Discussion

The present results challenge the prevailing paradigm that continuous high-temperature operation is the only reliable method for legionella control. The demonstration that periodic thermal shocks can maintain low legionella levels allows for more energy-efficient baseline operation.

The most significant finding from the energy analysis is the critical

Table 1
Thermal and electrical performance of low-flow (94 L/h) and high-flow (243 L/h) HWC operation when adjusted to maintain a 50 °C return temperature.

	Low Flow	High Flow
Flow [L/h]	94.1	243.3
Average heat loss [kW]	0.5	0.5
Average supply temperature [°C]	52.2	50.8
Heat loss per year [kWh]	4275.7	4252.6
Specific heat loss [kWh/m^2]	3.2	3.2
Electric power pump [W]	32.0	108.0
Annual energy pump [kWh]	280.3	946.1

Table 2
Building characteristics and Legionella occurrence".

Group / feature	n buildings	n with Legionella	% positive buildings
Randomly selected buildings	28	3	≈10 %
Buildings with known design problems	3	2	≈67 %
Buildings with towel warmers on HWC loop	2	2	100 %
Buildings without towel warmers on HWC loop	26	3	≈12 %

role of pump power, especially when optimizing a system to meet a fixed regulatory constraint. While previous assumptions often focused on minimizing thermal losses, the data from an adjusted system with a fixed 50 °C return temperature shows these thermal losses to be almost independent of the flow strategy. The primary potential for energy savings in such a system lies in minimizing pump energy by maintaining the lowest possible stable circulation flow. The low-flow strategy achieved a 12 % total energy reduction, with the savings coming almost exclusively from the pump's significantly lower electricity consumption. Considering the estimated ±5 % uncertainty in heat loss and ±1 % in pump electricity, the 12 % reduction in total annual energy use for the low-flow strategy remains robust and does not overlap with the high-flow case even under worst-case error propagation.

However, a more profound opportunity for energy savings emerges when shifting from optimizing current practice to changing the operational paradigm itself. The laboratory results demonstrate the powerful impact of supply temperature on thermal losses; in the tested range between 45 °C and 65 °C, each 1 °C increase in supply temperature led to an average increase in thermal losses of approximately 5.5 % . This highlights major potential for savings. Since microbial results confirm that periodic thermal shocks are an effective strategy for controlling Legionella, maintaining a continuously high baseline temperature might not be necessary for safety. By adopting a strategy with a lower baseline supply temperature, combined with periodic heat shocks, substantial reductions in thermal energy consumption can be achieved. The ultimate optimization strategy, could therefore be a dual approach: combining a low-flow rate to minimize pump energy with a risk-based, lower baseline temperature to minimize thermal losses, while ensuring microbial safety through periodic disinfection

The field investigation reveals that legionella risk in Swedish buildings appears to be highly concentrated in buildings with specific, identifiable design flaws rather than being a systemic problem. This suggests that public health strategies can be effectively targeted toward remediating high-risk installations, such as removing towel warmers from circulation loops and eliminating dead legs.

The findings of the present work align with recent work by Proctor et al. (2023) [14] who demonstrated that biofilm-associated Legionella requires 5–10 °C higher temperatures for equivalent inactivation compared to planktonic cells. The observed recolonization kinetics (14-day recovery to 38 % of pre-treatment levels) are consistent with the biphasic growth model proposed by Cervero-Aragó et al. (2023) [15], suggesting that residual biofilm acts as a reservoir for rapid recolonization. The energy analysis reveals a critical trade-off: each 1 °C reduction in baseline temperature yields approximately 5.5 % energy savings but requires more frequent thermal disinfection cycles. The modeling suggests an optimal strategy of 48 °C baseline with weekly 65 °C pulses could reduce annual energy consumption by 18–22 % while maintaining <100 MPN/L average concentrations.

From a water-energy nexus perspective, these findings demonstrate that single-objective optimization (either energy or health) leads to suboptimal outcomes. The traditional approach of maintaining uniformly high temperatures represents an energy penalty of approximately 2.5–4.3 TWh annually in Sweden alone, equivalent to 500,000 homes' electricity consumption. Conversely, aggressive energy optimization without considering microbial risks could create public health hazards. The proposed dual-optimization strategy represents a nexus solution that achieves co-benefits across both domains.

Implementation of these findings requires a shift toward risk-based management. While there are technical challenges, such as system rebalancing and control upgrades, the economic justification is strong. Furthermore, building codes should evolve to allow for performance-based compliance that recognizes periodic thermal disinfection as a valid alternative to continuous high temperatures.

Limitations and generalizability

This study has several limitations. The test rig represents simplified hydraulic conditions compared to buildings with variable usage patterns and complex piping networks. Only L. pneumophila serogroup 1 was tested, while multiple pathogenic serogroups exist in building water systems. The 8-week monitoring period may not capture seasonal variations or long-term biofilm evolution dynamics that could affect recolonization patterns.

The experimental rig and field campaign were designed around typical Swedish multifamily buildings with centralized DHW production, internal HWC loops, and regulatory requirements for a 50 °C return temperature. The quantitative results (e.g. 0.2 m/s low-flow strategy, 12 % total energy savings, and 5.5 % increase in thermal losses per 1 °C) are therefore most directly applicable to similar temperate-climate buildings with comparable piping layouts, insulation levels and control strategies. In systems with very different climates (e.g. unconditioned pipe shafts in hot climates), building typologies (e.g. single-family homes, healthcare facilities) or regulatory frameworks (e.g. higher minimum temperatures, use of chemical disinfectants), the absolute energy savings will differ, and the optimal combination of baseline temperature and thermal shock frequency may shift. However, the qualitative findings – that pump electricity dominates the difference between low- and high-flow operation under a fixed return temperature constraint, and that Legionella risk is concentrated in specific, correctable design flaws – are expected to hold more broadly across similar centralized HWC systems.

Conclusions and recommendations

The principal findings and conclusions of the present work are summarized as follows:

1. In a system optimized for a constant 50 °C return temperature, the choice of a low-flow (0.2 m/s) versus high-flow (0.5 m/s) strategy has a negligible impact on annual thermal losses.
2. The primary energy saving potential in an optimized HWC system comes from minimizing pump energy, not reducing thermal losses. A low-flow strategy (0.2 m/s) required 3.4 times less pump power than a high-flow strategy (0.5 m/s), resulting in a 12 % reduction in total annual energy use.
3. Thermal losses are highly sensitive to the system's operating temperature. The laboratory experiments showed that each 1 °C increase in supply temperature increased thermal heat loss by an average of approximately 5.5 %. This reveals a significant savings potential, as the study simultaneously found that periodic thermal disinfection (60–65 °C) is a highly effective strategy for Legionella control, making continuous high-temperature operation unnecessary
4. When a system is optimized for a constant 50 °C return temperature, the annual thermal losses are nearly identical regardless of whether a low-flow or high-flow strategy is used. This challenges the common assumption that reducing circulation flow is primarily a thermal energy conservation measure.
5. Legionella risk is highly concentrated, not systemic. The field study showed that while 23 % of samples were positive for L. pneumophila, the presence was strongly concentrated in properties with specific, correctable design flaws, such as towel warmers connected directly to the HWC loops.

For building operators, the results suggest three priority measures: (i) operate HWC systems at the lowest flow that still ensures a 50 °C return temperature everywhere in the loop, thereby minimizing pump electricity; (ii) implement periodic thermal disinfection at 60–65 °C, especially in systems where baseline temperatures are reduced, to control Legionella; and (iii) identify and remediate high-risk design flaws such as towel warmers connected to the HWC loop and dead-end pipe sections.

These conclusions should be interpreted in light of the limitations and generalizability discussed above, including the simplified rig hydraulics, the focus on L. pneumophila serogroup 1, and the relatively short monitoring period. Future work should extend the dual laboratory–field approach to more complex building types, evaluate different disinfection strategies, and integrate economic analysis and automated control algorithms into the optimization framework.

Implementation guidelines

Building operators should prioritize operating HWC systems at the lowest possible flow rate that still ensures the required return temperature is met everywhere. This single measure provides the most significant and immediate energy savings. This should be combined with risk-based maintenance, including periodic thermal shocks and the targeted remediation of known high-risk design features. For policymakers, we recommend updating building codes to allow for performance-based strategies that embrace these optimized operational protocols.

Policy implications

The policy recommendations proposed here are conditional on several key assumptions: (i) the HWC system is correctly designed and balanced, without dead legs or unintended bypasses; (ii) periodic thermal disinfection can be reliably implemented and documented by building operators; and (iii) basic monitoring of temperatures and, where needed, Legionella indicators is available to verify performance. Under these conditions, our results indicate that continuous maintenance of 50 °C throughout the HWC loop is not the only viable route to Legionella control.

The findings reported in the present work suggest that current building codes requiring continuous 50 °C temperatures throughout HWC systems may be unnecessarily conservative. Performance-based standards that allow periodic thermal disinfection combined with risk-based temperature management could achieve equivalent health outcomes with significant energy savings. At the European level, this could contribute substantially to buildings' decarbonization targets while maintaining public health standards.

If performance-based strategies are mis-implemented, for example, if baseline temperatures are reduced without ensuring adequate circulation, thermal shock frequency, or remediation of high-risk installations, they could inadvertently increase Legionella risk. Therefore, any regulatory shift away from prescriptive temperature requirements should be accompanied by clear technical guidelines, training for building operators, and, where appropriate, verification protocols.

While the quantitative energy savings and observed Legionella patterns are directly supported by the present data, the broader recommendation to consider performance-based standards is normative and intended as an input to ongoing policy discussions rather than a prescriptive conclusion.

Future work

Future research should investigate: (1) the long-term effects of periodic thermal disinfection on system components, (2) optimization algorithms for automated temperature control, (3) the efficacy against multiple Legionella serogroups, and (4) full-scale building trials with economic analysis.

CRediT authorship contribution statement

Jesper Knutsson: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition.

Jörgen Wallin: Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study. Data will be made available on request.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used Claude.ai to enhance language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and takes full responsibility for the content of the published article.

CRediT authorship contribution statement

Jesper Knutsson: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jörgen Wallin:** Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wallin, Jorgen reports financial support was provided by Swedish Energy Agency. Knutsson, Jesper reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Energimyndigheten, Vattenavändning i Hushåll - Water use in Dwellings, Swedish Energy Agency, 2012.
[2] Bergkvist, B., Kartläggning av VVC-förluster i flerbostadshus-mätningar i 12 fastigheter-slutrapport. 2015.
[3] World Health, O, Legionella and the Prevention of Legionellosis, World Health Organization, 2007.
[4] I. Marchesi, et al., Effectiveness of different methods to control legionella in the water supply: ten-year experience in an Italian university hospital, J. Hospital Infect. 77 (2011) 47–51.
[5] W.J. Rhoads, A. Pruden, M.A. Edwards, Survey of green building water systems reveals elevated water age and water quality concerns, Environ. Sci. 2 (2016) 164–173.
[6] S. Joshi, et al., Pinpointing drivers of widespread colonization of Legionella pneumophila in a green building: roles of water softener system, expansion tank, and reduced occupancy, Front. Water. 4 (2023).
[7] R. Julien, et al., Energy-efficient strategies for Legionella control in hot water systems: a systematic review, Build. Environ. 245 (2024) 110892.

[8] M.A. Nisar, et al., Water Stagnation and Flow Obstruction Reduces the Quality of Potable Water and Increases the Risk of Legionelloses, Front. Environ. Sci. 8 (2020) 1–13.
[9] H. Li, et al., Real-time monitoring of Legionella in hot water systems using flow cytometry, Water. Res. X. 18 (2023) 100165.
[10] M. Rasheduzzaman, et al., Machine learning approaches for predicting Legionella occurrence in building water systems, Environ. Sci. Technol. 58 (4) (2024) 1823–1835.
[11] J. Knutsson, P. Knutsson, Water and energy savings from greywater reuse: a modelling scheme using disaggregated consumption data, Int. J. Energy Water Resour. 5 (2021) 13–24.
[12] J. Wallin, J. Knutsson, T. Karpouzoglou, A multi-criteria analysis of building level graywater reuse for personal hygiene, Resour. Conserv. Recycl. Adv. (2021) 12.
[13] V. La Torre Rapp, J. Knutsson, J. Wallin, Stakeholder-driven development of a decision support framework targeting sustainable water supply systems, Energy Repo. 12 (2024) 2306–2310.
[14] C.R. Proctor, et al., Biofilm management in premise plumbing: temperature effects on Legionella pneumophila ecology, Water. Res. 229 (2023) 119431.
[15] S. Cervero-Aragó, et al., Temperature-dependent growth kinetics of Legionella pneumophila in continuous culture, Appl. Environ. Microbiol. 89 (3) (2023) e01892. -22.