Experimental Study on Inhibition of Legionella Bacteria in Sealed Vessels for Higher Efficiency of DHW Heat Pumps

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Abstract

This study explores the feasibility of lowering the set temperature in domestic hot water heat pumps (DHW HP) systems to promote energy conservation. The current JIS standard requires a set temperature of 65°C to prevent Legionnaires' disease, based on guidelines from the Ministry of Health, Labor and Welfare. However, these guidelines were originally intended for open storage tanks and circulation heating systems, such as those in public bathhouses, where water is exposed to air and reused. A previous experimental study has reported that reducing the set temperature by 10°C can improve the COP of DHW HP by approximately 10%, contributing to substantial energy savings. In contrast, domestic DHW HP systems use sealed storage tanks and once-through heating. In sealed tanks, water is isolated from air, making it difficult for aerobic Legionella bacteria to enter or proliferate. Furthermore, once-through systems prevent used water from reentering the system. These structural differences significantly reduce infection risk.
Experimental results demonstrated that Legionella pneumophila is highly sensitive to combinations of high temperature, pressure, and chlorine. Specifically: (1) Under pressure above 0.17 MPaG and chlorine ≥ 0.1 mg/L, bacteria were inactivated by over three orders of magnitude within 10 minutes; (2) Between 46–55°C and chlorine 0.05–0.4 mg/L, synergistic effects of temperature and chlorine were observed. (3) These effects were further enhanced under high-pressure conditions. Importantly, such temperature reduction strategies can be implemented through software-based control modifications, without increasing equipment cost, while maintaining microbiological safety. This makes the approach both energy-efficient and economically accessible to consumers, which is especially relevant as the DHW HP top-runner standards continue to evolve.

Keywords: Legionella; Hot water temperature; Pressure; Residual Chlorine; Inactivation

1. Introduction

Enhancing the energy efficiency of heat pump water heaters can be achieved by operating the system during the daytime when the ambient temperature is higher and by lowering the set temperature. The lower limit of the set temperature plays a key role in reducing energy consumption.

According to the JIS C9220:2018 Residential Heat Pump Water Heater , the standard set temperature is specified as 65°C from the viewpoint of preventing legionellosis. [1]. The Ministry of Health, Labor and Welfare's technical guideline, which is the basis for setting the JIS standard set temperature at 65°C, states that "when hot water storage tanks or central circulating water heating systems are installed, the water temperature in the storage tanks must be at least 60°C." [2]. However in the case of Legionellosis that outbreaks at the time of the notice, this is thought to apply to "open storage tanks" and "circulating heating systems" used at hot spring facilities and public bathhouses.

Domestic Hot Water Heat Pump (DHW HP) uses a stratified hot-water storage tank with a non-circulation-type heating system. In a sealed storage tank, unlike an open storage tank where the hot-water surface is always

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exposed to air, the entire interior is filled with hot and cold water layers. In a non-circulation-type heating system, hot water that has come into contact with air or with the human body in the bathtub is not returned to heat pumps. In this system, it is very difficult for Legionella bacteria to enter the sealed tank. Even if Legionella bacteria are able to enter, their proliferation would be limited because the interior contains little or no air, and the bacteria are aerobic in nature.

Previous experimental studies have reported that lowering the set temperature of residential heat pump water heaters improves their efficiency; in particular, detailed performance tests have shown that the COP improves by approximately 10% per 10°C decrease in outlet water temperature [3], and similar temperature-dependent performance trends have also been confirmed in laboratory evaluations of residential heat pump water heaters [4], it is possible to improve system efficiency only by modifying the operation control software, without developing any elemental components and without increasing the dimensions or weight of the heat pumps.

This study aims to obtain evidence for lowering the lower limit of set temperature or JIS standard set temperature, which is currently 65°C, through various experiments using Legionella pneumophila.

Although thermal sterilization and chlorination are known to be effective inactivating Legionella bacteria, previous studies have been conducted[5]. The inactivation effect of Legionella bacteria under combined conditions of thermal sterilization and chlorination in a sealed, high-pressure environment, such as the storage tank of a DHW HP, has not yet been investigated.

The objective of this study is to experimentally clarify the effects of water temperature, chlorine concentration, and pressure on the inactivation of Legionella bacteria.

2. Methods

2.1. Evaluation apparatus

In this study, two types of evaluation apparatus were constructed to conduct the experiment.

The configuration of evaluation apparatus A is shown in Fig. 1. A sealed glass vessel with a volume of 130mL was used as the reaction container. To maintain the temperature of the sample water inside the reaction container at a constant temperature, the container was immersed in a thermostatic water bath, and the sample water inside the container was continuously stirred. Samples were injected into and withdrawn from the reaction container using a 5mL syringe. Another syringe of the same type was attached to reaction container and used as a buffer to maintain the internal pressure of the container at atmospheric conditions.

The configuration of evaluation apparatus B is shown in Fig. 2. An 18L stainless-steel reaction vessel was equipped with five valves that served as water sampling ports. The surface temperature of the reaction vessel was measured using thermocouples attached near each sampling port. A water supply line, which introduced tap water or deionized water, was connected to the reaction vessel through a pressure-reducing valve. A circulation line was provided to withdraw water from the upper part of the reaction vessel and return it to the lower part. The circulation line was equipped with a heater for water heating, a pump, a box for Legionella bacteria injection, a box for chlorine injection, a three-way valve, and a flow meter.

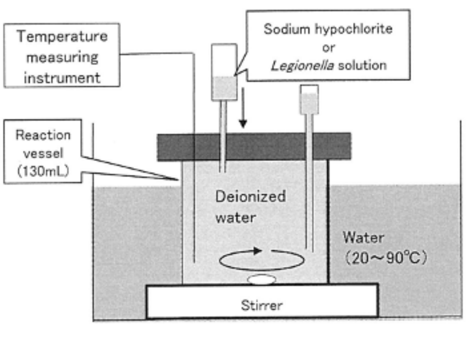

Figure 1 The diagram of evaluation Apparatus A

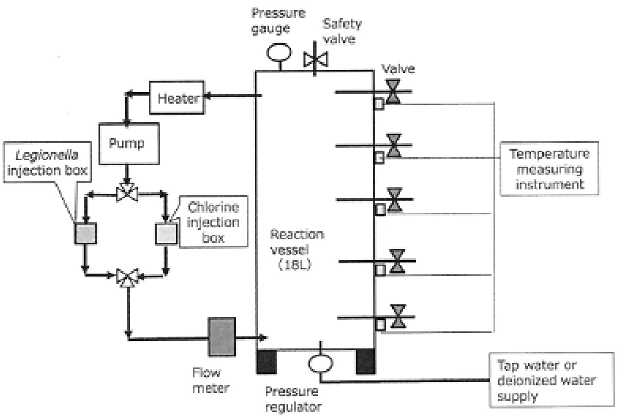

Figure 2 The diagram of evaluation Apparatus B

2.2. Materials

- Bacterial strain and preparation of test suspension

Legionella pneumophila was cultured on BCYEα agar medium. The resulting colonies were harvested and suspended in sterile distilled water to prepare a test bacterial suspension with a concentration of 10^8 to 10^9 CFU/ml.

- Chlorine solution

A chlorine solution with a residual chlorine concentration of 2000mg/L was prepared by adding 400mL of 0.5M phosphate buffer (pH 7) and 20mL of tenfold-diluted hydrochloric acid to sodium hypochlorite, whose residual chlorine concentration had been measured in advance, and then diluting the mixture with sterile distilled water.

2.3. Experimental procedures

- Evaluation Apparatus A

1) Deionized water obtained through an ion-exchange resin device was confirmed to have residual chlorine concentration below 0.02mg/L and was used to fill the reaction vessel shown in Fig. 1. The vessel was heated and stirred to maintain the water temperature within ± 1°C of the set value.
2) A chlorine solution and a test bacterial suspension were then added to achieve the target chlorine concentration and a Legionella density of approximately 10^6 CFU/mL.
3) The time of bacterial addition was defined as 0 min, and at specified intervals, 1mL samples were collected and mixed with 9mL of SCDLP medium to inactivate the disinfectant. Samples were serially diluted with autoclaved deionized water, plated on BCYEα agar, incubated at 35±1°C for six days, and the resulting colonies were counted.

- Evaluation Apparatus B

1) Deionized water from ion-exchange resin device was confirmed to have a residual chlorine concentration below 0.02 mg/L and was introduced into the reaction vessel. The vessel was pressurized with tap water to the specified pressure, and the pump and heater were operated to maintain a flow rate of 3.5L/min and the temperature within ±1°C of the set value.
2) A chlorine solution and test bacterial suspension were injected into the respective box to achieve the target chlorine concentration and approximately 10^5 CFU/mL of Legionella in the vessel, followed by 3 minutes of circulation for mixing.
3) The time of bacterial injection was defined as 0 min. At set intervals, 1mL samples were collected after draining 5mL of water, mixed with 9mL of SCDLP medium to inactivate the disinfectant, serially diluted with autoclaved deionized water, plated on BCYEα agar, incubated at 35±1°C for six days, and the resulting colonies were counted.

3. Results and Discussion

3.1. Experimental results using Evaluation Apparatus A

Fig. 3 shows the results of evaluating the effects of temperature and initial chlorine concentration on the inactivation of L. pneumophila under atmospheric pressure conditions (0 MPaG). At 30°C, no decrease in L. pneumophila was observed when the initial chlorine concentration was 0.10 mg/L or lower. When the initial chlorine concentration was 0.40mg/L or higher, a reduction of more than 3 log was achieved within 120 minutes. As the water temperature increased, the time required to achieve a 3 log reduction became shorter. At 60°C, a reduction of more than 3 log was observed within 2 minutes under all tested chlorine concentrations.

3.2. Experimental results using Evaluation Apparatus B

Fig. 4 shows the results of evaluating the effects of temperature and initial chlorine concentration on the inactivation of L. pneumophila under pressurized conditions of 0.17 MPaG and 0.28 MPaG. At both 0.17 MPaG and 0.28 MPaG, when the initial chlorine concentration was 0.10mg/L and the temperature was 30°C or higher, a reduction of more than 3 log was achieved within 10 minutes. When the initial chlorine concentration was 0.40mg/L and temperature was 30°C or higher, a reduction of more than 3 log was achieved in 5 minutes.

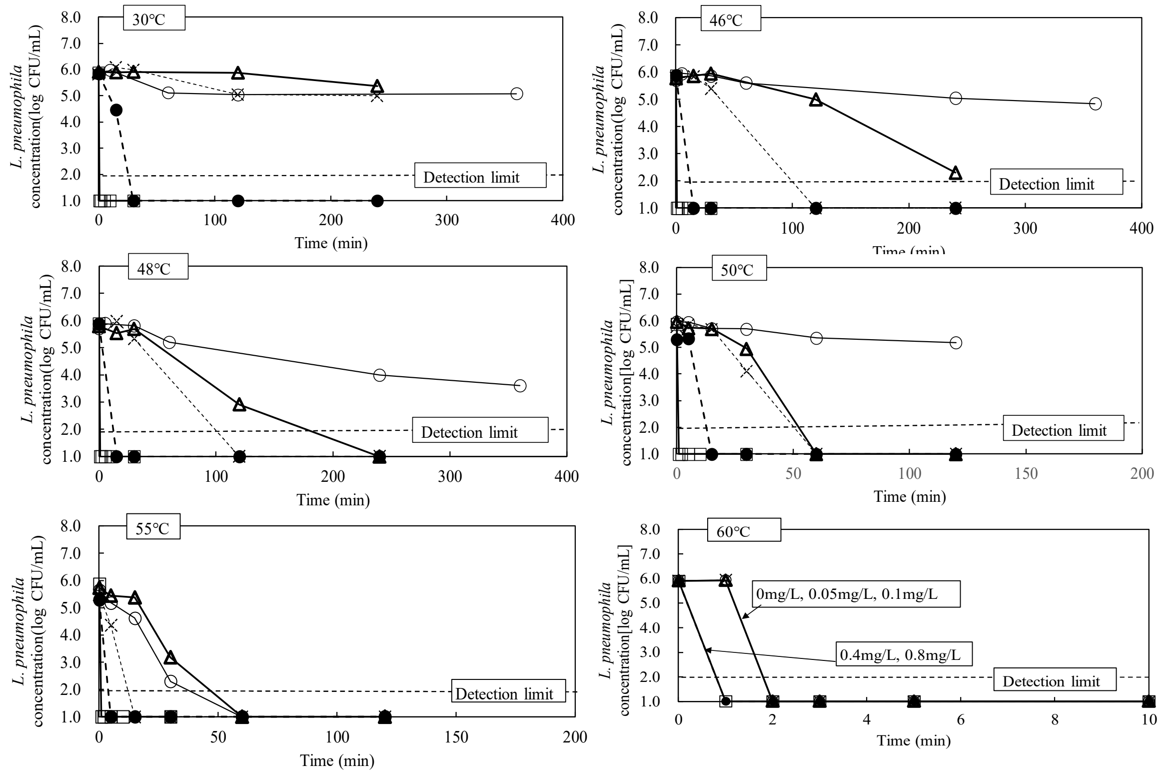

Figure 3 Inactivation of L. pneumophila by initial chlorine concentration 0, (○), 0.05 (△), 0.10 (×), 0.40 (●), and 0.80 (□) mg/L at 0 MPaG with evaluation apparatus A.

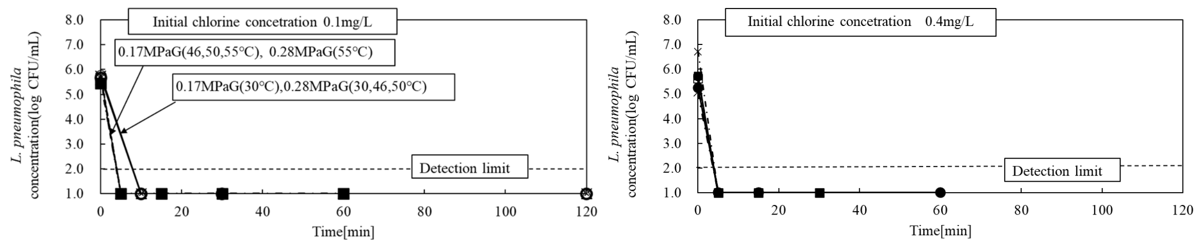

Figure 4 Inactivation of L. pneumophila at 0.17MPaG, 30°C (●) , 0.17MPaG, 46°C (▲), 0.17MPaG, 50°C (■), 0.17MPaG, 55°C (*), 0.28MPaG, 30°C (○), 0.28MPaG, 46°C (△), 0.28MPaG, 50°C (□), 0.28MPaG, 55°C (×) with evaluation apparatus B.

3.3. Discussion

Table 1 shows the inactivation rate of L. pneumophila at 0MPaG, 0.17MPaG and 0.28MPaG.

Table 1 Inactivation rate of L. pneumophila at 0MPaG, 0.17MPaG and 0.28MPaG

Unit: digit/min

Initial chlorine concentration (mg/L)	Pressure (MPaG) 0 (Apparatus A)				0.17 (Apparatus B)				0.28 (Apparatus B)			
	Temperature (°C)				Temperature (°C)				Temperature (°C)			
	30	46	50	55	30	46	50	55	30	46	50	55
0	0.0016	0.0030	0.0066	0.0810	—	—	—	—	—	—	—	—
0.10	0.0081	0.0428	0.0365	0.3040	0.466	0.950	0.889	0.933	0.476	0.920	0.950	0.946
0.40	0.1620	0.3250	0.3080	0.8600	0.851	N.D	0.946	0.816	0.943	N.D	0.925	1.143

- Synergistic inactivation effect of high temperature and chlorine under atmospheric pressure conditions

As shown in Table 1, under atmospheric pressure conditions at 30 °C with an initial chlorine concentration of 0.10 mg/L, the inactivation rate is 0.0081 digit/min. At 50 °C with an initial chlorine concentration of 0 mg/L, the inactivation rate is 0.0066 digit/min, whereas at 50 °C with an initial chlorine concentration of 0.10 mg/L, the inactivation rate increases to 0.0365 digit/min. Here, 0.0365digit/min≈ 2.5× (0.0081 digit/min + 0.0066 digit/min), indicating that the inactivation rate under the combined condition of high temperature and chlorine exceeded the simple sum of the inactivation rates obtained under each single condition by approximately 2.5 times. Since this relationship was also observed 46-55°C and initial chlorine concentrations of 0.05-0.40mg/L, the result suggests a synergistic effect between high temperature and chlorine concentrations on the inactivation of L. pneumophila.

- Synergistic inactivation effect of high pressure, high temperature, and chlorine concentration

The inactivation rates obtained under atmospheric pressure using Evaluation Apparatus A were compared with those obtained under sealed high-pressure conditions using Evaluation Apparatus B. As shown in Table1, at initial chlorine concentrations of 0.10mg/L and 0.40mg/L, the ratios of the inactivation rates under high-pressure conditions (0.17 MPaG and 0.28MPaG) to those under atmospheric pressure were approximately the same. The difference in inactivation rate between 0.17 MPaG and 0.28 MPaG was smaller than the effect of temperature and chlorine concentration. The enhancement ratio (high-pressure / atmospheric) was larger at lower temperatures, particularly at 30°C. This trend was consistently observed at both 0.10 mg/L and 0.40 mg/L chlorine concentrations, indicating that pressure more effectively compensates for reduced inactivation at low temperatures. Similarly, at both pressure conditions, the ratio of the inactivation rate under high-pressure conditions to that under atmospheric pressure increased as the initial chlorine concentration decreased. This implies that the decrease in inactivation efficiency caused by lower chlorine concentration may have been compensated by the effect of high pressure. From these results, it is considered that the synergistic inactivation effect of high temperature and chlorine was enhanced under sealed high-pressure conditions.

Fig. 5 shows the benefit of lowering the lower limit temperature (LLT). Reducing the LLT decreases the required heating temperature, which improves the COP. As a result, the energy needed to heat the storage tank decreases, making it unnecessary to heat the entire tank volume to a high temperature. Consequently, the electricity required to supply the same usable amount of hot water is reduced, leading to further reductions in primary energy consumption and CO_2 emissions.

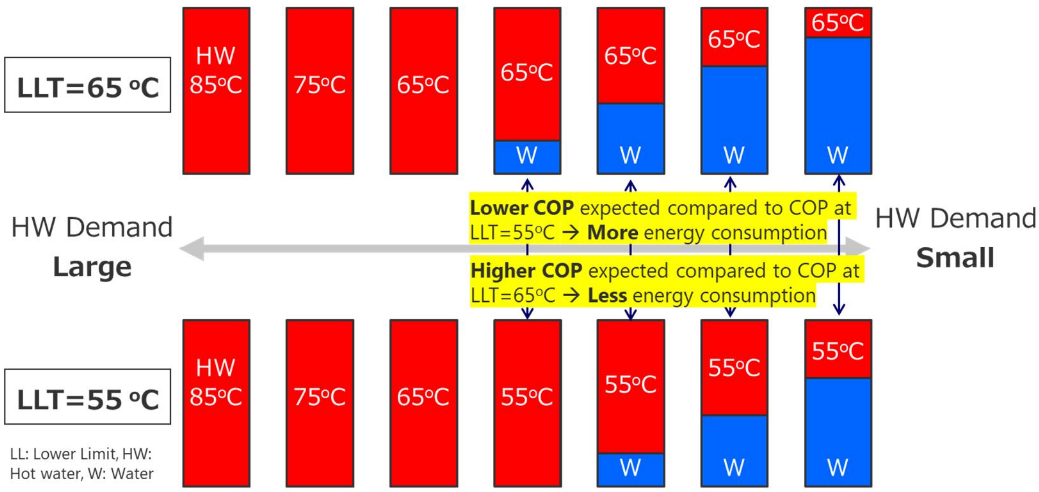

Figure 5 The benefit of lowering the set temperature

4. Conclusions

This study investigated the effects of high pressure under sealed conditions, elevated temperature, and chlorine on the inactivation of Legionella bacteria, and obtained the following remarks.

(1) Under pressure above 0.17 MPaG and chlorine $\geq$ 0.1 mg/L, bacteria were inactivated by over three orders of magnitude within 10 minutes; (2) Between 46–55°C and chlorine 0.05–0.4 mg/L, synergistic effects of temperature and chlorine were observed; (3) These effects were further enhanced under high-pressure conditions. Importantly, such temperature reduction strategies can be implemented through software-based control modifications, without increasing equipment cost, while maintaining microbiological safety. This makes the approach both energy-efficient and economically accessible to consumers, which is especially relevant as the DHW HP top-runner standards continue to evolve.

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