Journal of Building Engineering 43 (2021) 103147

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

The impact of using portable humidifiers on airborne particles dispersion in indoor environment

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ARTICLE INFO

Keywords:
Ultrasonic humidifier
Evaporative humidifier
$PM_{2.5}$
Water quality
DALY

ABSTRACT

Portable humidifiers are extensively employed to increase indoor humidity; however, the generated particles could affect people indoors and cause a heavy disease burden. This study aims to compare the potential for an ultrasonic humidifier and an evaporative humidifier to release suspended materials contained in the charging water in a room-sized chamber and estimate the disease burden attributed to $PM_{2.5}$ released by humidifiers. Size distributions and concentrations of indoor particles were measured when humidifiers were filled with five types of water with varying total dissolved solids (TDS). Results showed a linear association (R^2=0.980) between particles produced by the ultrasonic humidifier and the TDS in water. Evaporative humidifiers could produce a small number of particles when tap water was used, but the linear relationship between the released particles and TDS in water was weak (R^2=0.028). The disability-adjusted life years (DALY) attributed to $PM_{2.5}$ generated by the ultrasonic humidifier was 22.4 times that of the evaporative humidifier when using tap water. This study provides valuable data on characteristics of particles released by two different humidifiers and highlights the potential disease burden of exposure to $PM_{2.5}$ generated by humidifiers, which may help exclude any adverse effects of using portable humidifiers.

1. Introduction

The indoor air environment is crucial for human health because people spend about 80% of their time indoors. Dry air could be a reason for respiratory irritation and cause pharyngeal dryness, deterioration of the allergic disease, and increase the likelihood of respiratory infections [1–3]. Controlling indoor relative humidity (RH) to a reasonable level (RH=30%–60%) can relieve symptoms of stress response, skin and nasal dryness [4,5]. However, a study found that the indoor RH could be 20% in cities with central heating systems in winter [6]. Portable humidifiers are the most prevalent device to prevent excessive drying and maintain comfortable indoor humidity due to their convenience and flexibility in indoor spaces, such as offices, hospitals and residences.

According to the Association of Home Appliance Manufacturers [7], portable household humidifiers can be divided into five types: (i)ultrasonic humidifier; (ii)evaporative humidifier; (iii)cold mist impeller humidifier; (iv)steam vaporizer; and (v)warm mist humidifier. Different types of humidifiers have different impacts on airborne particles. Previous studies compared the performance of various humidifiers and found that ultrasonic humidifiers and impeller humidifiers could release a great number of particles, while steam humidifiers and evaporative humidifiers did not cause a particle increase [8–10]. However, these studies only used one type of water. There is an information gap regarding the impact of water quality on humidifiers, especially the evaporative humidifier. Recently, steam vaporizers and warm mist humidifiers are rarely used in the household due to the scalding and electrocution risk [11,12]. Impeller humidifiers are mainly used in industrial plants. Ultrasonic humidifiers and evaporative humidifiers are the most commonly used by consumers in homes [13] and are also the target humidifiers in this study.

Ultrasonic humidifiers have been found as a source of indoor particles, and the charging water can influence the particle characteristics. Umezawa et al. [14] compared the particles released by an ultrasonic humidifier filled with water containing serial concentrations of calcium

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https://doi.org/10.1016/j.jobe.2021.103147
Received 29 March 2021; Received in revised form 12 August 2021; Accepted 14 August 2021
Available online 17 August 2021

chloride solution and found the mass concentration of released particles was linearly related to the concentration of dissolved minerals in the water. Sain and Dietrich [15] found that 85%–90% of the released aerosol constitution derived from the water in the ultrasonic humidifier. Sain et al. [16] found that lower mineral water produced fewer particles than higher mineral water. Yao et al. [17] investigated the emission of iron and aluminium oxide particles from ultrasonic humidifiers and found suspended metal oxide particles were emitted as aerosols from the humidifier. In previous studies, the tested water was generally adjusted and synthesized by adding soluble salts to water [14,16,17], which lacks the information about the commonly used water. Four common types of water in daily life (tap water, plain boiled water, mineral water, and pure water) are chosen to fill the humidifiers in this study, with the deionized water as a control. The effect of evaporative humidifiers on particulate matter in the air is less studied. The influence of water quality in evaporative humidifiers on airborne particles still needs experimental verification.

Particles released by portable humidifiers could affect occupants' health and cause a heavy burden of disease. It has been found that children's wheezing, lower respiratory symptoms and allergic diseases were associated with using portable humidifiers [18,19]. Besides, humidifier lung and humidifier fever were associated with domestic ultrasonic humidifiers [20]. Disability-adjusted life years (DALY) are widely used as a metric of harm to quantify the disease burden attributed to exposure to pollutants [21,22]. The Global Burden of Diseases (GBD) has estimated and compared the DALY attributed to 69 risk factors and found that ambient particulate matter ranked seventh among these factors [23]. Logue et al. [22] developed a method to estimate the DALY of several air pollutants and found the total annual health impact of pollutants in U.S. residences was about 1100 DALY losses per 100,000 persons. Park et al. [24] only compared the $PM_{2.5}$ concentration generated by two humidifiers but did not quantify the harm caused by $PM_{2.5}$. For the first time, this study estimates the burden of disease attributable to exposure to $PM_{2.5}$ generated by two popular humidifiers. The results intuitively show the potential harm caused by different humidifiers through a quantitative outcome (DALY).

This study aims to explore the impact of the water quality for the commonly used humidifiers on airborne particle characteristics and quantify the disease burden of using portable humidifiers. The discussion will be formed in terms of (i) comparing concentrations and size distributions of particles emitted by an evaporative humidifier and an ultrasonic humidifier; (ii) measuring water quality parameters and investigating the effect of TDS on the airborne particles; (iii) estimate the DALY losses attributed to $PM_{2.5}$ generated by two humidifiers. It is expected to provide useful information on preventing exposure to high-level particles and decrease the burden of disease attributed to portable humidifiers.

2. Materials and methods

2.1. Instrumentation

A portable ultrasonic humidifier with a water output capacity of 350 mL/h and an evaporative humidifier with 200 mL/h were selected. Two humidifiers were filled with tested water and operated for 120 min with maximum output setting. Five typical water types (i.e., commercial pure water, deionized water, commercial mineral water, tap water, and plain boiled water) were used to evaluate water's impact on aerosols generated by two humidifiers. Water qualities were measured with a Water Quality Meter (Macro 900, Palintest, UK), which was calibrated with a standard solution before use. Airborne particle (mass and number) concentration and size distribution were measured with an Aerodynamic Particle Sizer (APS 3321, TSI., USA). The APS 3321 can distinguish particles with different diameters in the range of 0.5–20 μm and give the total number and mass of particles less than 0.5 μm. Temperature and humidity sensors (Green Eye 7798, AZ Instrument, China) were calibrated and placed in the chamber. All instrument information is summarized in Table S1 (Supporting information).

2.2. Experimental chamber

All experiments were conducted in an enclosed chamber. Fig. 1 shows the layout of the chamber, which is 4 m (length) × 4 m (width) × 2.7 m (height). Humidifiers were placed in the center of the chamber at a height of about 0.8 m. The APS was situated about 1.2 m on the side of the humidifiers. The air conditioning system in the chamber was employed to control the indoor background particle level at a low concentration and control the initial temperature and RH to be the same for each case. The air conditioning system was turned off during the operation of humidifiers. Each experiment was repeated three times. The air change rate of the chamber was measured by the tracer decay test with CO_2 (see in the supporting information) because the air conditioning system was turned off during experiments.

2.3. Burden of disease

Exposure to $PM_{2.5}$ may cause mortality, chronic bronchitis and nonfatal stroke, and these endpoints can reduce healthy years of life for people [25]. As an indicator to quantify the reduction in healthy years of life, DALY losses include years of life lost due to premature mortality (YLL) and years lived with disability (YLD) [26].

$$DALY = YLL + YLD \quad [1]$$

Previous studies [22,26] have determined the DALYs lost per incidence of specific diseases:

$$DALYs = (\partial DALYs / \partial disease\ \ incidence) \times disease\ \ incidence \quad [2]$$

Logue et al. [22] built a method to quantify the disease incidence rates by concentration-response (C-R) relationships:

$$\triangle \mathrm{Incidence} = -\left\{ \mathrm{y}_0 \times \left[\exp\left(-\beta \triangle C_{exposure} \right) - 1 \right] \right\} \times population \quad [3]$$

Equation [3] is built based on epidemiology data, where y_0 is the baseline prevalence of illness per year, β is the coefficient of the concentration change, $C_{exposure}$ is the exposure-related concentration, and the population is the number of persons exposed.

$$\triangle C_{exposure} = 0.0833 C_{PM2.5} \quad [4]$$

The exposure time is 2 h in this study, and the concentration contributed from indoor $PM_{2.5}$ exposure was therefore set to 8.33% of the $PM_{2.5}$ concentration. The $PM_{2.5}$ concentration is the average value within 2 h.

Three endpoints of exposure to $PM_{2.5}$ were chosen: total mortality, chronic bronchitis and nonfatal stroke [22,25]. The total DALY losses of $PM_{2.5}$ are the sum of the three endpoints [22].

2.4. Statistical analysis

The particle size distribution was displayed with a normalized concentration format $dN/d \log Dp$, independent of the width of the diameter range [27]. One-way analysis of variance (ANOVA) was carried out to examine significant differences. A *P*-value of less than 0.05 was considered a statistically significant difference at a confidence level of 95%. IBM SPSS 23.0 software was employed for all the data analysis.

3. Results

3.1. Water quality

Water quality parameters for each water type are summarized in Table 1. It can be found that the pH values for the five kinds of water were similar and ranged from 7.23 to 7.80, while the electric

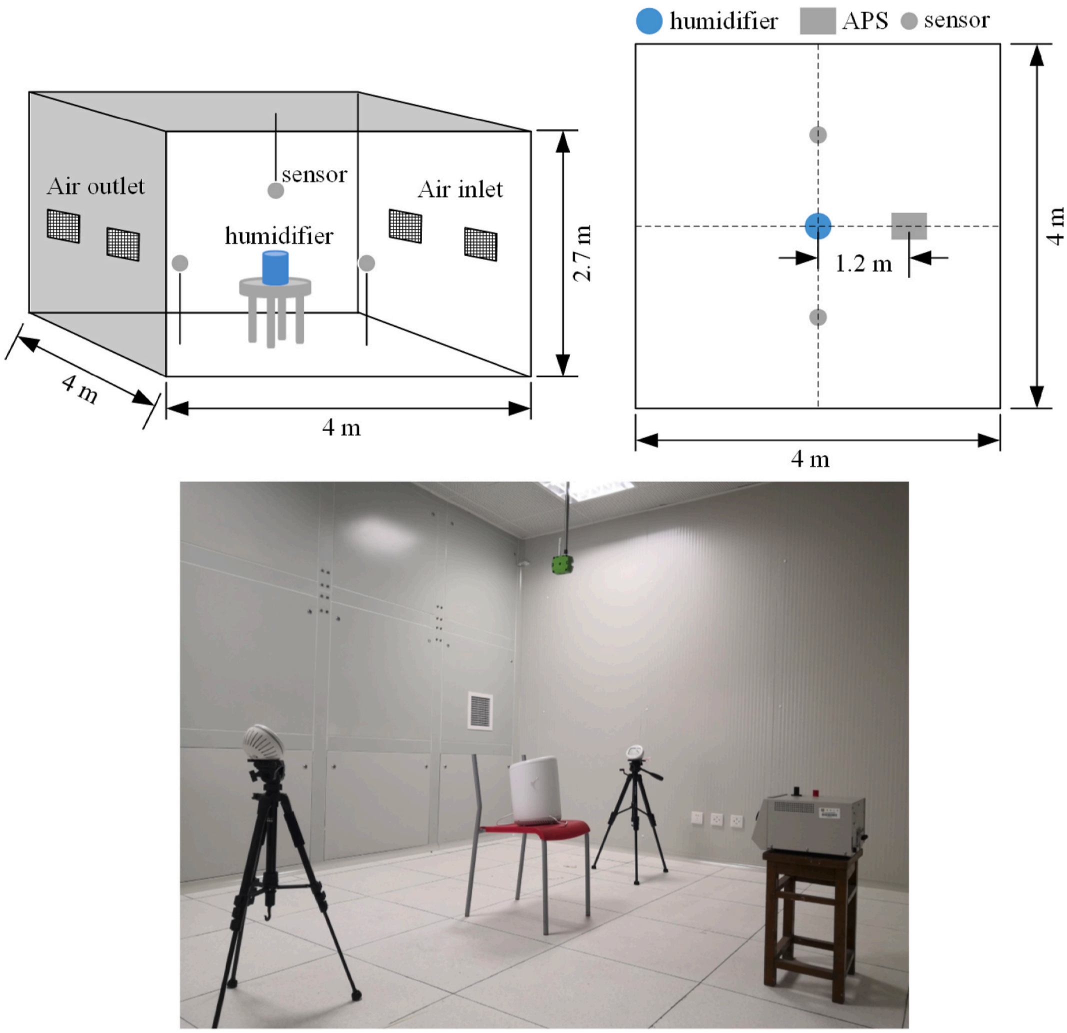

Fig. 1. Diagram of the experiment chamber.

Table 1
Average water quality data.

Parameter	Pure water	Mineral water	Plain boiled water	Tap water	Deionized water
TDS (mg/L)	2.67 ± 0.58	74.67 ± 7.02	239 ± 10.54	253.67 ± 6.03	0
EC (μS/cm)	6 ± 1.00	113 ± 7.55	372 ± 9.17	386.33 ± 8.62	1 ± 0.57
pH	7.37 ± 0.04	7.70 ± 0.04	7.80 ± 0.02	7.74 ± 0.04	7.23 ± 0.02

conductivity (EC) varied greatly from 1 to 386.33 μS/cm. The measured TDS was 0 mg/L of deionized water, 2.67 and 74.67 mg/L of pure water and mineral water. The TDS of plain boiled water (239 mg/L) and tap water (253.67 mg/L) were within the range of TDS value in the standard of WHO (600 mg/L) [28]. Tap water produced water scale when it was boiling, which cause the TDS in plain boiled water to be lower than tap water.

3.2. Particle concentrations

The initial indoor RH was 32.89 ± 5.03%, and the initial room temperature was 22.50 ± 2.33 °C. The air change rate of the chamber was 0.059 h^{-1}. After a 2-h humidifier operation, the final indoor RH increased to 56.5 ± 6.21% and 61.31 ± 4.53% for the evaporative humidifier and the ultrasonic humidifier, respectively. The indoor temperature was maintained at a relatively stable level during humidification. The indoor RH reached about 60% after 2 h of humidification, meeting the requirements of humidification and comfort [4]. Continue to humidify could cause excessive moisture and molds growth in the room [6,29]. The average background particle level was 24 particles/cm^3, with a coefficient of variation (COV) of 35.84%.

After the ultrasonic humidifier was operated, the particle number concentrations raised linearly for tap water, plain boiled water, and mineral water (Fig. 2a). However, the particle concentrations for deionized water and pure water changed little compared with the background level. The variation of particle levels indicated that the water type affected the number of particles produced by the ultrasonic humidifier. The ultrasonic humidifier charged with tap water generated the highest particle concentrations after humidification (2442 particles/cm^3, COV=18.3%, 76.3 times of background), followed by plain boiled water (2024 particles/cm^3, COV=2.3%, 92 times of background), and mineral water (589 particles/cm^3, COV=6.7%, 34.6 times of background). The pure water generated negligible particle concentration (33 particles/cm^3, COV=11.8%, 1.65 times of background). The deionized water produced the lowest average particle concentration (24 particles/cm^3, COV=25.7%, 1.05 times of background).

Fig. 2b illustrates that the particle number concentrations fluctuated after the evaporative humidifier was operated until they reached a steady state at about 80 min. In contrast to the ultrasonic humidifier,

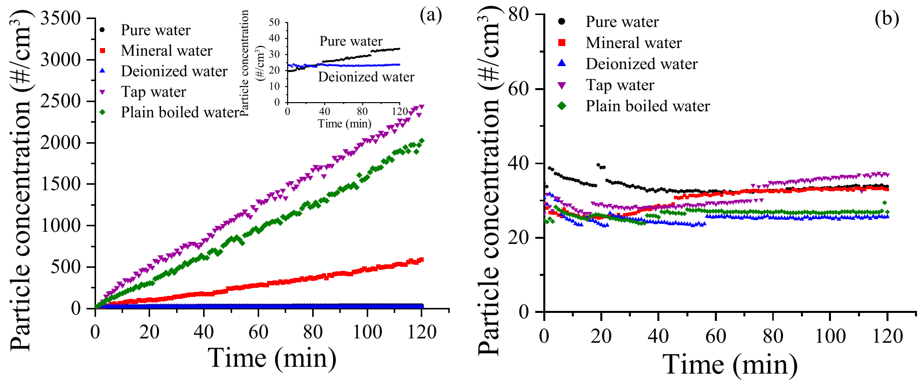

Fig. 2. Average particle concentrations (n=3) of using (a) ultrasonic humidifier, (b) evaporative humidifier.

particles emitted by the evaporative humidifier ranged from 25.7 to 36.9 particles/cm^3, without showing a significant difference between the five types of water (P>0.05, ANOVA). The average particle concentrations did not change much during the 120-min humidification process. The particle concentration of tap water increased slightly, reaching the highest of the five kinds of water (36.9 particles/cm^3, COV=17%, 1.4 times of background). The concentrations of plain boiled water and mineral water also showed slight rises, reaching 26.9 (COV=36.7%, 1.1 times of background) and 33 particles/cm^3 (COV=31.6%, 1.1 times of background), respectively. In contrast, pure water and deionized water generated slightly decreasing concentrations. The mass concentration of $PM_{2.5}$ is shown in Fig. S2 in the supporting information.

The ultrasonic humidifier and evaporative humidifier generate different levels of particles when charging the same water. Especially for tap water, particles emitted by the ultrasonic humidifier reached 66.2 times that of the evaporative humidifier. A linear relationship (R^2=0.980) was found between the particle number concentrations and the water TDS for the ultrasonic humidifier, as shown in the solid fitted line in Fig. 3. This strong correlation demonstrated that the higher TDS in water, the more particles produced by ultrasonic humidifiers. However, the particle concentration showed less dependence on TDS for the evaporative humidifier, causing a weak correlation (R^2=0.028), as shown in the dashed fitted line in Fig. 3. Evaporative humidifiers have little influence on air particle concentrations, no matter what water is used.

The different performance between the ultrasonic humidifier and the evaporative humidifier is determined by the humidifier process, as shown in Fig. 4. The ultrasonic humidifier atomizes the liquid film covering the atomizing sheet into fine droplets [30], and then blows these droplets into the air by a fan to increase the humidity. These tiny droplets consist of water and dissolved solids. Once the water evaporation is completed, the impurities remain suspended and can be carried by surrounding air, thus causing a particle surge [16]. The more TDS in water, the faster the particle concentration grows. The particle concentrations of using deionized water (1.05 times of background) and pure water (1.65 times of background) hardly increased because the TDS in these two kinds of water was almost zero (Table 1). Showering can also increase particle levels due to releasing droplets by shower sprayers [31]. However, the particle size of ultrasonic humidifiers is smaller than showering because of ultrasonic atomization.

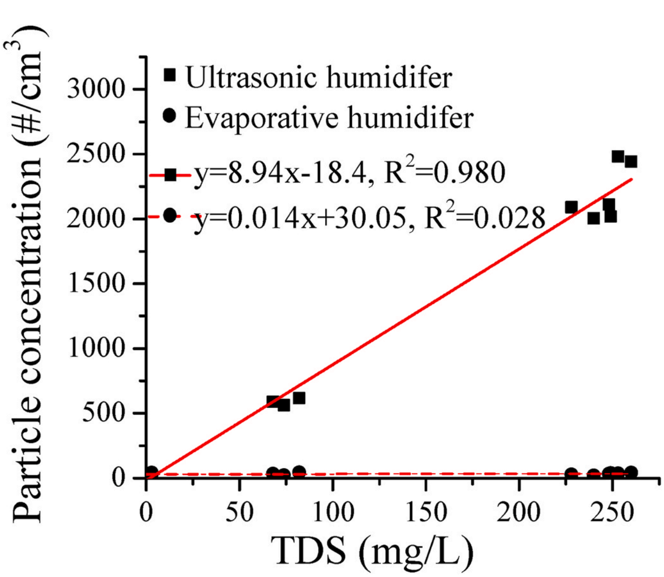

Fig. 3. Linear fits of particle number concentration and TDS in water.

It is generally believed that the evaporative humidifier has no obvious impact on indoor air particles because it only evaporates water into the air [16]. Evaporative humidifiers generate water vapor by fan-forcing air through a wringing sponge absorbing water from the reservoir [10]. Tyndall et al. [10] tested the particles produced by an evaporative humidifier using tap water and found that no detectable particles were observed 1 m away from the humidifier. However, in this study, a slight rise (from 26 to 36.9 particles/cm^3) in the particle concentrations of tap water was observed (Fig. 2b). Water scale appeared on the evaporative sponge after using tap water for a period, demonstrating that the sponge absorbed water and dissolved solids. Once the water evaporates, solids remain in the sponge and form limescale after a period. While air entering the wet sponge, it may carry some impurities, causing the particle concentration to rise slightly. However, the particle rise was limited, only 1.4 times that of the background concentration. The water scale on the sponge has a limited effect on airborne particle concentrations, but it significantly influences the humidification performance. It can reduce the water-absorbing capability of the sponge and prevent the water in the sponge from evaporating into the air. Therefore, spongs should be regularly replaced when using tap water. Besides, all types of humidifiers need to be regularly cleaned, and the water in the reservoir needs to be replaced frequently to reduce any growth of microorganisms [11].

3.3. Particle size distributions

Fig. 5 compares the size distributions of the particles (0.5–20 μm) generated by the ultrasonic humidifier and the evaporative humidifier. It shows similar decrease trends in particle number concentrations as the particle size increased from 0.5 μm to 20 μm for all cases. The particle size distributions showed few differences between the five types of water when using the evaporative humidifier (Fig. 5b). However, for the ultrasonic humidifier, the measured concentrations of particles less than 1 μm showed a large dependence on the water types (Fig. 5a), which indicated that the size of the airborne particles generated by the

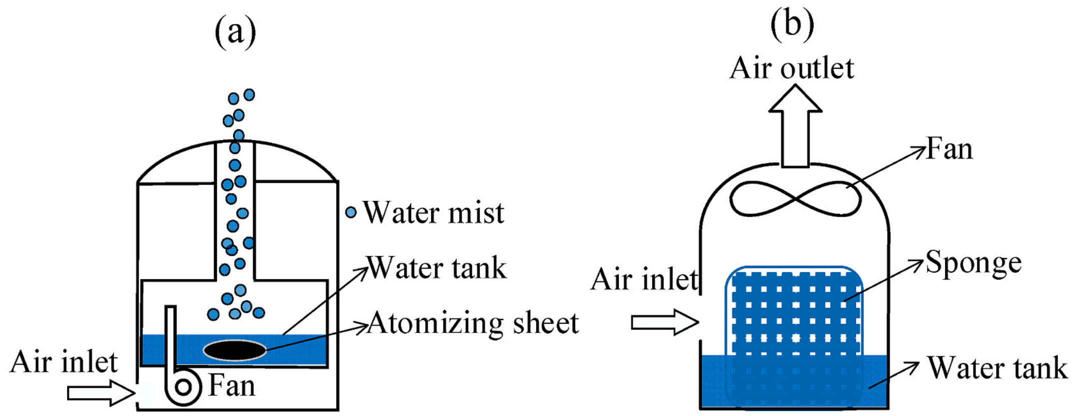

Fig. 4. Structure and operation process of the two humidifiers: (a) ultrasonic humidifier; (b) evaporative humidifier.

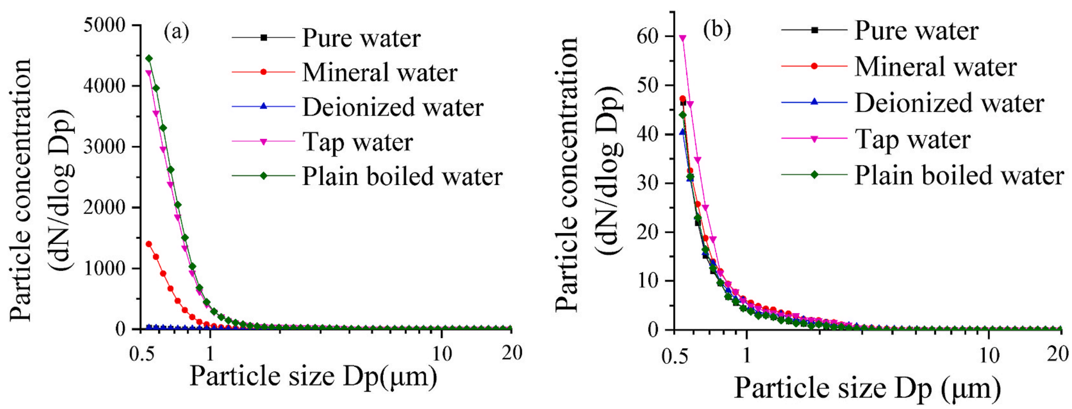

Fig. 5. Particle size distribution: (a) ultrasonic humidifier, (b) evaporative humidifier.

ultrasonic humidifier were mostly less than 1 μm. Tap water in the ultrasonic humidifier generated the highest particle concentrations, and it had higher particle concentrations in the size of <0.5 μm than plain boiled water. However, plain boiled water released slightly more particles in size range of 0.5–1.0 μm than tap water (Fig. 5a), which may be related to water components. The number of particles between 10 and 20 μm tended to be zero. That means almost all particles produced by the ultrasonic humidifier are in the inhalable range (<10 μm).

The proportion of particle numbers in each size range varied with the water and humidifier types (Fig. 6). For these two humidifiers, the percentages of particles <0.5 μm accounted for the largest (65.8%–86%), and the percentage of particles larger than 1 μm all decreased after humidification. Particle percentages of using high TDS water (tap water, plain boiled water, and mineral water) in the ultrasonic humidifier exhibited the same trend: particle number percentages decreased in the range of <0.5 μm but increased in the range of 0.5–1.0 μm. The two water types with low TDS (pure water and deionized water) showed the opposite results, which indicated that TDS impacted the percentage change of particles in various size ranges. However, all five water types showed the same trend in the evaporative humidifier. The proportions of particles <0.5 μm were found to increase to different values than the initial state. In contrast, the proportions of large particles in 0.5–1.0 μm presented a decline compared with the background level.

The number median diameter (NMD) of generated particles is

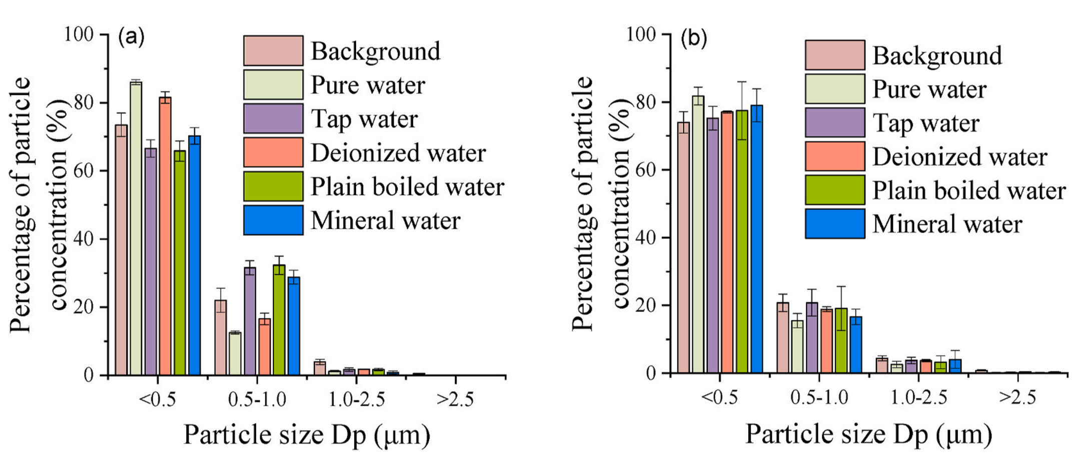

Fig. 6. The proportion of particle concentrations in different sizes: (a) ultrasonic humidifier, (b) evaporative humidifier.

presented in Fig. 7. It shows that the NMD resulting from humidification was ranged from 0.595 to 0.706 μm for particles of 0.5–20 μm. The particle number varied dramatically in different cases, while the NMDs were similar. The average NMD of the ultrasonic humidifier was 0.626 ± 0.017 μm, and the average NMD of the evaporative humidifier was 0.642 ± 0.025 μm. The evaporative humidifier produced negligible particles (Fig. 2b), so the particle size distribution was similar to the background. The background particle was larger than the particle emitted by the ultrasonic humidifier (Fig. 6a). After using an ultrasonic humidifier, the NMD becomes smaller due to the increase in fine particles. The characteristics of airborne particles are affected by indoor activities. Particles emitted by ultrasonic humidifiers can be smaller than cooking (NMD was 0.8 μm, in the range of 0.5–20 μm) [32]. The explanation could be that ultrasonic atomization cause particles smaller. The particle size decrease with the atomization frequency increase [30].

Rodes et al. [33] directly injected the output of an ultrasonic humidifier charged with tap water into the inlet of a particle measurement system and found that the count concentrations of particles in the range of 0.45–5 μm peaked around 2.5 μm and the NMD was 1.8 μm [33]. However, the particle size distribution can be different when particles are suspended in the air. This study found that the airborne particle concentrations in the range of 0.5–20 μm decreased with the increase of the particle diameters, and the concentrations in 2.5 μm were almost zero (Fig. 5a). The average NMD (0.626 μm) (Fig. 7) of the ultrasonic humidifier in this study was smaller than that of Rodes et al. A study found that small droplets (<40 μm) can evaporate totally within 0.4 s at a short distance of <0.5 m and the residual droplet nuclei continue to disperse in indoor environments [34]. The distance between the humidifier outlet and the APS instrument was about 1.2 m. What the APS measured was the particle nucleus after water evaporation in the surrounding environment. Their size was smaller than the particle directly from the outlet of the ultrasonic humidifier because of the evaporation of water. The same trend of particle size distribution are observed by previous studies [27,35]. Therefore, more attention should be paid to the suspended particles in indoor air.

The evaporative humidifier and the ultrasonic humidifier filled with low TDS water had no obvious effects on particle numbers. For these two occasions, particle percentages decreased in >0.5 μm but increased in the range of <0.5 μm when RH was rising (Fig. 6). One possible reason is that particles of >0.5 μm absorb water and deposit due to getting heavy, while particles <0.5 μm are easily suspended in the air. On the contrary, when ultrasonic humidifiers were charged with high TDS water, the particle number in all ranges increased. However, particles in the range of 0.5–1.0 μm had the highest increase ratio, resulting in a decrease in percentages in the rest ranges (Fig. 6a).

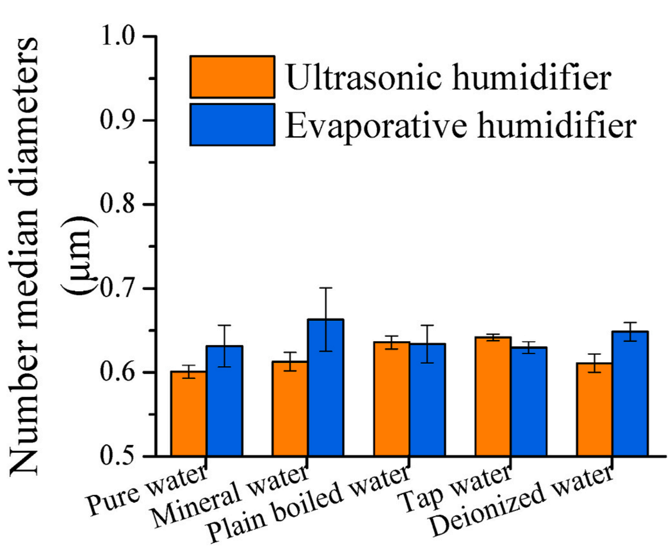

Fig. 7. Number median diameters of particles.

3.4. Disease burden

The trend of $PM_{2.5}$ mass concentrations (Fig. S2) was similar to the number concentration of particles. The mass concentration of $PM_{2.5}$ emitted by the ultrasonic humidifier using high TDS water was raised linearly. For the ultrasonic humidifier, the average $PM_{2.5}$ concentration for 2 h was 99.55 μg/m^3 and 82.7 μg/m^3 for tap water and plain boiled water, which exceeds the recommended value (25 μg/m^3) of WHO [36]. The average $PM_{2.5}$ mass concentrations within 2 h were used in the calculation of DALY. Coefficients in Equation [3] were based on the study of Logue et al. [22]. Fig. 8 indicates the average $PM_{2.5}$ mass concentration and the estimated DALY losses due to indoor $PM_{2.5}$ generated by humidifiers. Filling the ultrasonic humidifier with high TDS water leads to a high burden of disease. The use of tap water in the ultrasonic humidifier caused the highest burden of disease, an annual 463.8 DALY per 100000 persons, which was 22.4 times that of the evaporative humidifier using tap water.

Although the United States Environmental Protection Agency has recommended users to use pure water to fill humidifiers [11], tap water is still the most frequently used in the home due to its convenience and low cost [8]. The price of a cubic meter of tap water is about 3 CNY, while the same volume of pure water is about 1000 CNY in China. Assuming that the ultrasonic humidifier is turned on for 2 h a day, it consumes 700 mL of water a day, approximately 255.5 L of water a year. Tap water costs less than one CNY a year, while pure water costs about 250 CNY a year. Although tap water is economical and affordable, the DALY losses of tap water used in the ultrasonic humidifier were about 99.5 times that of pure water. Chan et al. [25] estimated the DALY losses of grocery workers exposure to $PM_{2.5}$ with the same method. The DALY loss attributed to using tap water in ultrasonic humidifiers is about 5 times that of workers in grocery [25]. The explanation could be that the average $PM_{2.5}$ concentration in grocery was lower than that of using tap water (17.7 vs. 99.55 μg/m^3). Aggarwal and Jain [37] estimated the burden of disease attributed to $PM_{2.5}$ generated by goods vehicles and found that it caused 1267 DALY per million people in Delhi. Due to the short exposure time, the average DALY loss in this study is lower than that of Aggarwal and Jain [37].

4. Implication and limitation

This study quantified and compared the health burden attributed to using different portable humidifiers and water. The findings imply that humidifier users need to consider potential health burdens when choosing portable humidifiers and water. Compared to ultrasonic humidifiers, evaporative humidifiers do not cause a sharp increase in airborne particle concentrations and high DALY losses. However, using water with high TDS can accelerate the calcification of the evaporative sponge. Ultrasonic humidifiers can release a great number of particles and cause a heavy disease burden when charged with high TDS water. More seriously, due to misusing disinfectants in the humidifier water tank, several lung injuries cases and death occurred in South Korea [38]. Therefore, it is better for ultrasonic humidifier users to charge the ultrasonic humidifier with pure water or deionized water to prevent heavy particle pollution and losses of healthy years of life. This study estimated the potential health burden of exposure to ultrasonic humidifiers and evaporative humidifiers, highlighting the importance of investigating particles released by humidifiers.

This study was limited by a single measuring point of particles in the chamber. Future research can set more measuring points to understand the distribution of particles in the whole chamber. This study is also limited by the experiment duration. Humidifiers were only operated for 2 h.

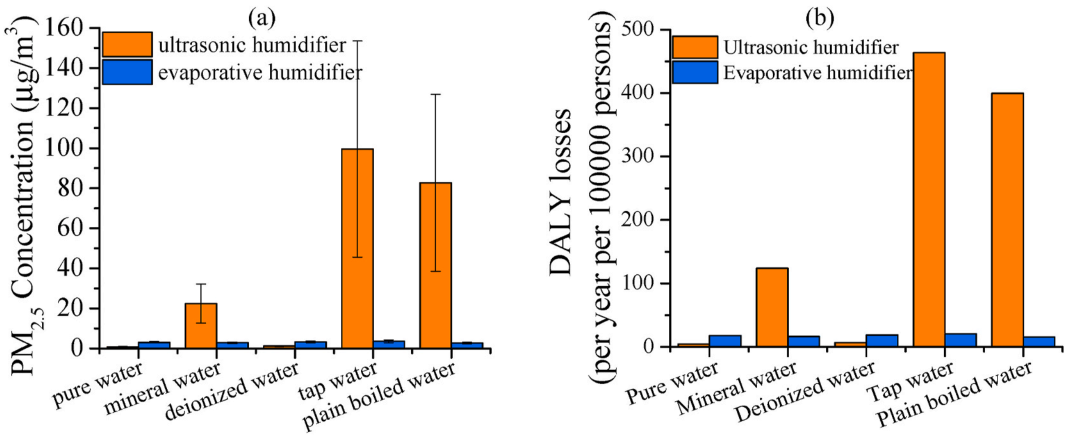

Fig. 8. Average $PM_{2.5}$ mass concentration within 2 h (a), average DALY losses due to $PM_{2.5}$ generated by humidifiers (b).

5. Conclusions

This study compared the characteristics of particles emitted from an ultrasonic humidifier and an evaporative humidifier filled with tap water, plain boiled water, mineral water, pure water, and deionized water. The water quality used in the ultrasonic humidifier had a significant influence on the characteristics of expelled particles, with a higher TDS of filling water inducing a greater number of particles. Almost all the generated particles are inhalable, increasing the DALY losses of occupants. The average NMD was 0.626 μm for particles released by the ultrasonic humidifier. The ultrasonic humidifier can produce 76.3 times more particles than the background when using tap water, so users should avoid using tap water in ultrasonic humidifiers. On the contrary, the water in the evaporative humidifier showed little impact on the particle concentration and size. Using tap water in the ultrasonic humidifier can cause about 22.4 times more DALY losses than that of the evaporative humidifier.

Author statement

Kangqi Guo: Writing - Original Draft, Conceptualization, Software, Methodology. Hua Qian: Supervision, Writing - Review & Editing, Funding acquisition, Conceptualization. Fan Liu: Writing - Review & Editing, Conceptualization, Software. Jin Ye: Writing - Review & Editing, Methodology, Visualization. Li Liu: Supervision, Writing - Review & Editing, Conceptualization. Xiaohong Zheng: Writing - Review & Editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported jointly by the National Natural Science Foundation of China [Grant No. 41977370], the National Key Research and Development of China [Grant No. 2017YFC0702800], and the Fundamental Research Funds for the Central Universities [Grant No. 2242019K41024].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2021.103147.

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