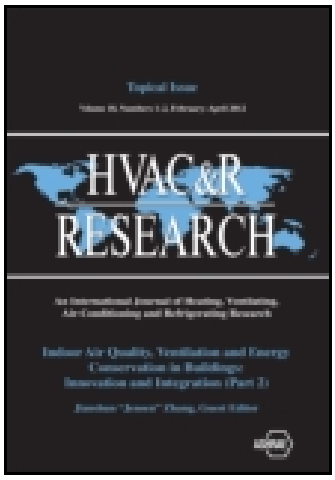

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The germicidal effects of microwave heating on microbes on evaporative humidifier elements

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To identify the germicidal effects of microwave radiation for evaporative humidifiers, we measured the germicidal effects of fungal spores of *Fusarium solani* and vegetative cells and spores of the bacterium *Bacillus subtilis* using a mock-up system. The germicidal effect was compared to the output powers, irradiation times, and water contents of the element to establish effective disinfection conditions of humidifier element surfaces. The results demonstrated that the fungal and bacterial strains were inhibited at 1200 W for 20 min, except for the *B. subtilis* spores under the nonoperation condition involving water spray and the blower. In general, the germicidal effects appear to be stronger on the upper portion of the elements than on the lower portion. The germicidal effect was stronger at higher output power and longer exposure time under wet conditions. To achieve a uniform disinfection on the element faces, it is necessary to consider variations of these methods to produce a uniform heating pattern.

Introduction

Evaporative humidifier elements are typically moist during operation. Therefore, microbial contamination of elements can occur when the air stream blows through a contaminated filter (Burge et al. 1980, Strindehag et al. 1991, Tyndall et al. 1995, Shimotsu et al. 2010). The microbes that grow on the humidifier element surfaces can become airborne and transported throughout the air conditioning system of a building (Marinkovich and Hill 1975, Katsui et al. 1996). To prevent this problem, this study sought a feasible method of microwave-mediated disinfection of evaporative humidifiers in air conditioning systems. Microwave disinfection is a suitable tool for the sterilization of evaporative humidifier elements in wet conditions. The germicidal effect of microwaves is a result of the dielectric heating of electrically insulating materials by dielectric loss. The threshold energy of ionization for water and DNA components of microorganisms is 4 to 5 eV (Fernando et al. 1998, Papadantonakis et al. 2002) and microwaves would be unable to damage DNA components of microorganisms, because the microwave energy would be too low at 1.02×10^{-5} eV. This method is capable of heating the inside of a material directly and rapidly due to its high degree of penetration.

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In our first study (Kang and Kato 2014a), the germicidal effects of microwave irradiation were confirmed on fungal spores (*Cladosporium herbarum* and *Fusarium solani*), vegetative bacteria, and bacterial spores (*Bacillus subtilis*) on a filter. The study also investigated whether the germicidal effect could be a direct result of the microwave irradiation or rather a result of the radiation-induced heat. The results of the study illustrated that the germicidal effect observed in the experiments could be attributed to the associated rise in temperature, particularly above 60°C, during the microwave irradiation of the fungal buffer solutions. Therefore, a second study (Kang and Kato 2014b) investigated the feasibility of microwave heating the element above 60°C using mock-up humidifier equipment. The results demonstrated that microwave heating can increase the temperatures on the element above 60°C at 1200 W for 3 min without the use of water spray or an air blower.

In this study, the germicidal effects on fungal spores of *F. solani* or vegetative cells and spores of *B. subtilis* were determined at element temperatures above 60°C using our mock-up system. Thus, the correlation between the exposure time, microwave power, and water contents of the element was determined to identify the effective disinfection mode using a two-fold approach. First, the germicidal effects on fungal spores of *F. solani* were investigated by (i) comparing the germicidal effect on the elements at different exposure times with different water contents of elements, (ii) comparing the germicidal effect at different microwave powers, and (iii) measuring the germicidal effect of microwaves with the operation of an air blower. Second, the germicidal effects on vegetative cells or spores of the bacterium *B. subtilis* were investigated under the conditions that led to a germicidal effect for fungal spores of *F. solani*.

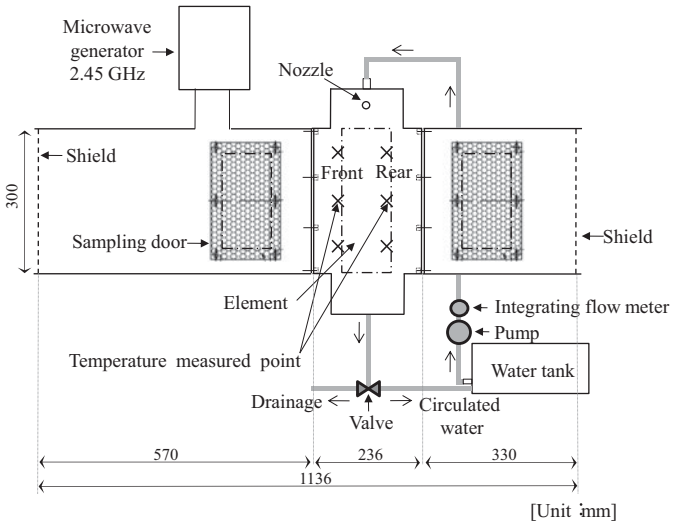

Fig. 1. Schematic of the evaporative humidifier.

Methods

A mock-up humidifier in air conditioning systems

To determine the feasibility of microwave irradiation in disinfecting humidifier elements, a mock-up humidifier unit was manufactured in a previous study (Kang and Kato 2014b). The experimental setup was composed of three parts: an air blower, evaporative humidifier, and microwave generator. The ventilation driven by the exhaust blower fan entered and exited the system through high-efficiency particulate air (HEPA) filters. The microwave frequency was 2455 ± 30 MHz. Microwave shields were installed between the duct and humidifier to prevent the leakage of microwave power (Figure 1). The microwave shields were perforated plates with a hole diameter and thickness of 1 mm. The humidifier and duct parts were composed of stainless steel. The cavity volume and surface area between the microwave shields of the humidifier was 0.112 m^3 and 1.692 m^2, respectively. The evaporative humidifier element had a honeycomb structure (Figure 2a) and was constructed using a noninflammable ceramic material with a composition of 86% Al_2O_3, 7% SiO_2, and 7% other materials. The element dimensions were 300 (W) × 300 (L) × 100 (D) mm^3.

Table 1. The experimental conditions for germicidal effects for *F. solani* spores as a function of microwave radiation exposure time at different water contents and power outputs.

Element condition		600 W	900 W	1200 W			
Dry	0 g of water	–	–	3 min	–	20 min	–
Wet	400 g of water	20 min	20 min	–	10 min	20 min	30 min
	800 g of water	20 min	20 min	3 min	10 min	20 min	30 min

Microorganisms

Many researchers have reported that aerobic mesophilic molds *Fusarium* sp. or *Cladosporium* sp. and the bacterium *Bacillus* sp. are frequently detected in humidifier elements (Burge 1980, Tyndall 1995). In our first study (Kang and Kato 2014a), the strains exhibited strong heat resistance in the following order: vegetative cells *B. subtilis* > spores *F. solani* > spores *C. herbarum*. Therefore, fungal spores from *Fusarium solani* NBRC30964 and vegetative cells and spores of *Bacillus subtilis* NBRC3215 were used in this study.

The density of fungal spores of *F. solani* in a solution was counted with a hemocytometer under a light microscope and then adjusted to a final concentration of 10^7 spores/mL. The vegetative bacteria *B. subtilis* density was adjusted to a final concentration of 10^7 cells/mL at 600 nm with a spectrophotometer (UV-mini-1240) using the optical density (OD) method described by Begot et al. (1996). The bacteria spores of *B. subtilis* were purchased from a commercial bio-company, and the spore density was adjusted to a final concentration of 10^7 CFUs/mL.

The germicidal effects on fungal spores of **F. solani** *on the element*

The germicidal effects on fungal spores of *F. solani* were confirmed on the humidifier element surfaces. To determine the optimum conditions for microwave disinfection, the following factors were considered: (i) a comparison of the germicidal effects on the elements at 4 exposure time levels of 3, 10, 20,

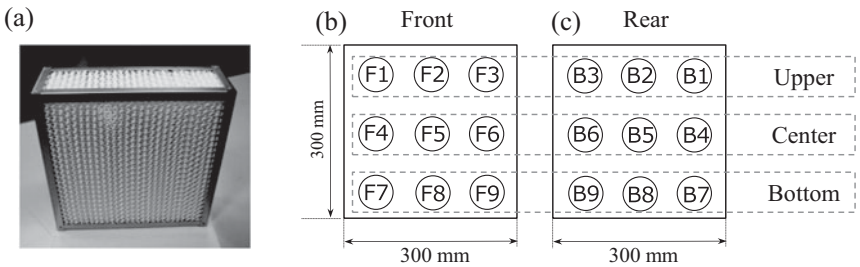

Fig. 2. Sampling points of a humidifier element for germicidal effects at the upper (F1–F3, B1–B3), center (F4–F6, B4–B6), and lower (F7–F9, B7–B9) parts. a An element. b. At the front face. c. at the rear face.

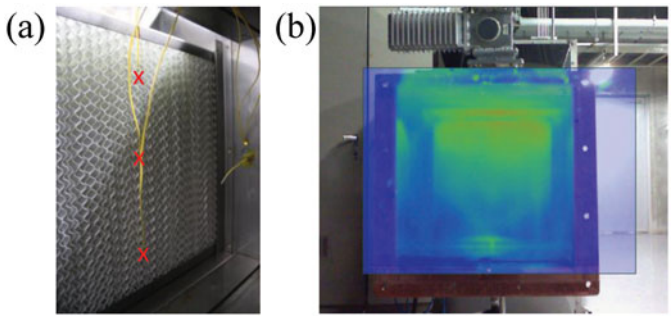

Fig. 3. Temperature measurement of the humidifier element. a. An optical fiber thermometer b. An infrared camera.

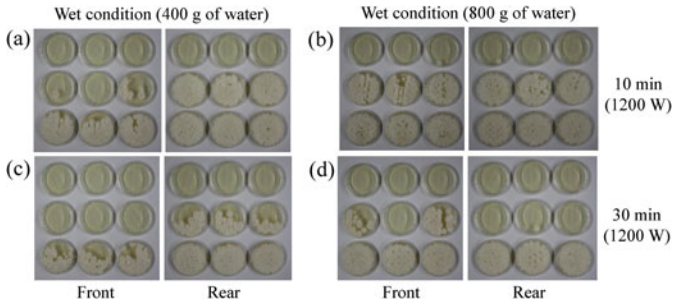

Fig. 4. Comparison of the germicidal effect on *F. solani* on the element surfaces at different irradiation times. a. 1200 W for 10 min with 400 g of water. b. 1200 W for 10 min with 800 g of water. c. 1200 W for 20 min with 400 g of water. d. 1200 W for 20 min with 800 g of water.

and 30 min with 3 water contents of the elements of dry, 400 g of water, and 800 g of water, (ii) a comparison of the germicidal effects at three microwave power levels of 600, 900, and 1200 W, and (iii) the germicidal effect of microwaves with the operation of the air blower (Table 1).

Comparison of the germicidal effects on the elements at four exposure time levels with three water contents of the elements

The germicidal effects on fungal spores of *F. solani* on the element surfaces were compared with 4 levels of exposure time, 3, 10, 20, and 30 min, at 1200 W on the dry element and wet elements containing 400 or 800 g of water. Distilled water was sprayed on the element using a water pump at a water flow rate of 0.48 to 0.52 L/min. Then, wet elements were dried using the air blower at an airflow rate of 29.1 m^3/min for 12 h as the dry element. The water weight of the wet elements was measured by the weight difference between the dry and wet elements. The wet elements with 800 g of water were in a sufficiently wetted condition, and elements with a water weight of 400 g were dried with the air blower for 15 min. Twenty milliliters of the suspended fungal spores of *F. solani* were sprayed on the surface of the prepared elements. Then, the elements were microwave irradiated at 1200 W for 20 min without the water spray or air blower. In the dry case, to vaporize the buffer of fungal spores, the element was irradiated after drying for 1 min with the air blower. A nonirradiated element was compared with the radiation-treated elements as a control. After irradiation, the element surface was touched on potato dextrose agar (PDA) media of stamp type. The surface area of the stamp media plates was 25 cm^2. Figure 2 presents sampling points at the upper (F1, F2, F3 and B1, B2, B3), center (F4, F5, F6 and B4, B5, B6), and lower (F7, F8, F9 and B7, B8, B9) parts of the front (facing the microwave generator) and back faces. The printed stamp media were cultured at 25°C in the dark for 5 days, and the colony forming units (CFUs) of the fungal spores were counted. The germicidal effects were determined by comparing the surviving colonies of the microwave-treated samples and control.

An optical fiber thermometer was used to take measurements at six points: at the middle of the upper (F2, B2), center (F5, B5), and lower (F8, B8) of both the front and rear faces of the element (Figure 3b). The temperature distribution of the element was measured from the outside of the microwave shield with an infrared camera (Figure 3c). The experiments were performed three times in all cases.

Comparison of the germicidal effects at three microwave power levels

The germicidal effect at different output powers was measured for exposures of 600, 900, and 1200 W for 20 min under wet conditions with a water content of 400 or 800 g. The germicidal effects and temperature on the element surface were determined as described previously.

Germicidal effect of microwaves while operating the air blower

In the previous study, Kang and Kato (2014a) reported that the microwave disinfection was due to a temperature increase

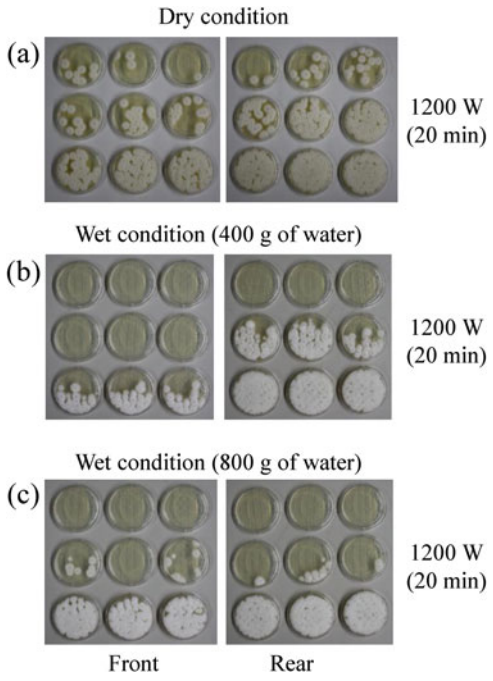

Fig. 5. Comparison of the germicidal effect on *F. solani* on the element surfaces at different water contents. a. In the dry condition. b. With 400 g of water. c. With 800 g of water.

arising from the heating effect. Thus, a study was performed to confirm whether the germicidal effect was caused directly by microwave irradiation or rather by the radiation-induced temperature increase of the element. The germicidal effects were measured when the temperature of the element did not increase. The microwave radiation was 1200 W for 30 min using the air blower at an airflow rate of 29.1 m^3/min with a wet element containing 800 g of water. To prevent the fungal spores of *F. solani* from draining, water was not sprayed on the element. The germicidal effects were determined as described previously.

Germicidal effect on vegetative cells or spores of B. subtilis *bacteria*

The germicidal effects on vegetative cells or spores of *B. subtilis* were measured at a 1200 W exposure for 20 or 30 min with the wet element containing 400 g of water. The element surface was printed using soybean casein digest (SCD) media, where the surface area of the stamp was 25 cm^2. The samples were cultured at 35°C in the dark for 2 days.

Results

The optimum conditions for efficient energy consumption and disinfection were determined by the following tests: (i) the germicidal effect on fungal spores of *F. solani* on element surfaces at four irradiation time levels, three water contents levels, and three microwave power levels and (ii) the germicidal effect on vegetative cells or spores of *B. subtilis* bacteria on the element.

Germicidal effects on fungal spores of F. solani *on the element surfaces*

Comparison of the germicidal effects on the elements at four exposure time levels

Figures 4 and 5b, c present the surviving colonies of the fungal spores of *F. solani* for different irradiation times with the wet element containing either 400 or 800 g of water. The germicidal effect of microwaves was not apparent after 3 min (data not shown). In the case of radiation exposure for more than 10 min, the germicidal effects appeared at the upper portion of the element on both the front and rear faces (Figures 4a and 4b). The temperature of the element was increased and the disinfected area widened with increased exposure time (Figure 4). However, the lower portion of the element did not exhibit a germicidal effect or an increase over 60°C when irradiated at 1200 W for 30 min.

Comparison of the germicidal effects on the elements at three water contents

Figures 5–8 present the surviving colonies of fungal spores of *F. solani* and the temperature distribution at 1200 W for 20 min with dry or wet elements containing 400 or 800 g of water. In general, the germicidal effects appear to be stronger at the upper part of the element than at the lower part, regardless of whether the element is dry or wet (Figure 5). The temperature difference between the front and rear faces was smaller than the temperature difference with height (in the vertical direction). The germicidal effect appears to be stronger for the wet elements. In contrast, the surface temperatures of the dry element were higher than those of the wet elements.

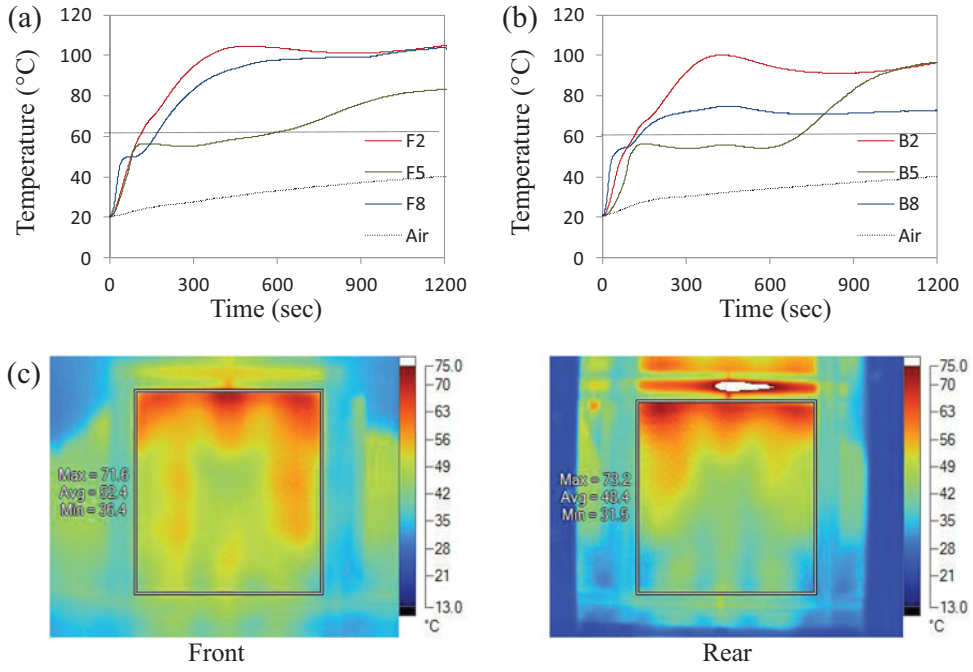

Fig. 6. Comparison of the temperature distribution on the element surfaces in the dry condition. a. Temperature change of the front surfaces measured at the upper, center, and lower parts. b. The rear surface. c. The front surface. d. The rear surface.

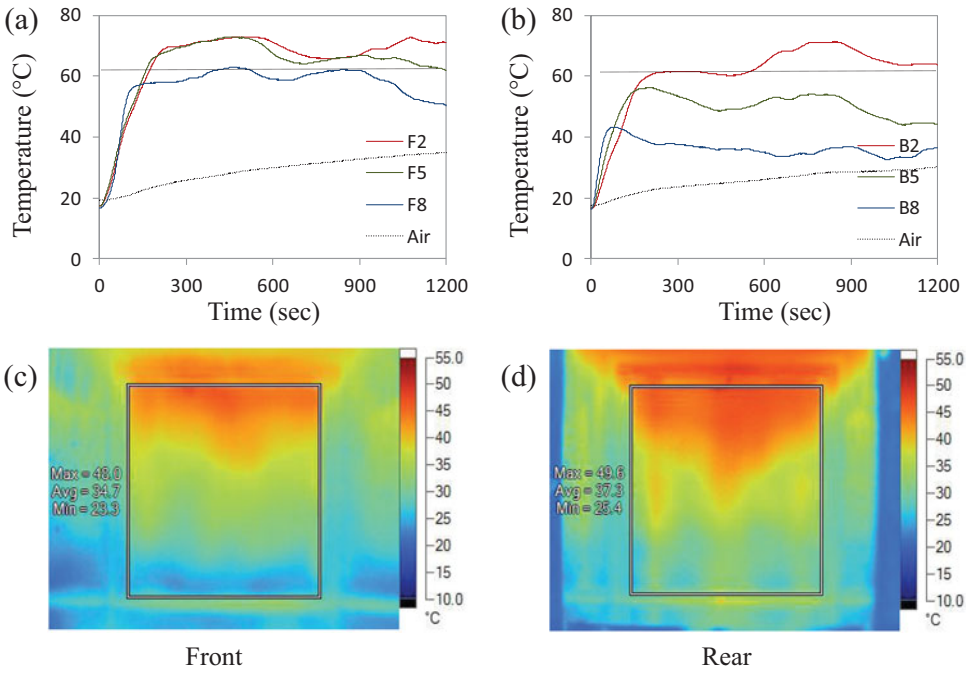

Fig. 7. Comparison of the temperature distribution on the element surfaces in the wet condition with 400 g of water. a. Temperature change of front surfaces measured at the upper, center, and lower parts. b. The back surface. c. The front surface. d. The rear surface.

Thus, we confirmed that both water content and temperature of the element affected the germicidal effects on *F. solani*.

In the dry condition, the element temperature increased above 60°C after 13 min of irradiation at 1200 W at all points, particularly the upper points (F2, B2) of the front and rear faces, which increased to 105.0 ± 1.1°C and 100.3 ± 1.9°C (Figures 6a and 6b), respectively. The temperature distribution is similar on both faces (Figures 6c and 6d). However, the surviving colonies appeared from 1 to 9 CFU/mL at the upper points (F2, B2; Figure 5a).

In the wet condition, with a water weight of 400 g, the germicidal effect on the front face was higher than that on the back face (Figure 5b). The upper and center parts of the front face (F1–F6) and the upper part of the rear face (B1–B3) of the element exhibited no detected colonies, although the temperature in the middle of the front upper point (F2), front center (F5), and rear upper point (B2) increased to 74.5 ± 0.1°C, 74.5 ± 0.6°C, and 72.9 ± 0.1°C (Figures 7a and 7b).

In the wet condition, with a water weight of 800 g, high germicidal effects were observed at the center, regardless of whether it was the front or rear face (Figure 5c). At the upper points (F2, B2), no colonies were detected when the temperature increased to 74.5 ± 1.1°C and 76.0 ± 0.7°C, respectively (Figures 8a and 8b). The center points (F5, B5) ranged from 1 to 9 CFU/mL when the temperature increased to 72.6 ± 1.9 and 68.2 ± 1.1°C, respectively.

Comparison of the germicidal effects at three microwave power levels

The viability of *F. solani* spores that were exposed to radiation of 600, 900, or 1200 W for 20 min is listed in Tables 2 and 3. In general, the germicidal effects on *F. solani* spores and the temperature of the element surfaces were high with an exposure of 1200 W.

In the case of exposure at 600 W, the germicidal effect on the element with 400 g of water was higher than that on the element with 800 g of water (Figures 9a and 9b). However, in the case of radiation exposure at 900 or 1200 W, there was no difference in the germicidal effects between the elements with 400 and 800 g of water. The germicidal effects on, and the temperature of, the element exposed to 1200 W for 10 min were higher than those for the element exposed to 600 W for 20 min with 800 g of water (Figures 4b and 9b).

The germicidal effects were investigated when the air blower was operated. There were no germicidal effects with the air blower, and the irradiation caused no heating (no data shown). These results confirmed that the disinfection due to microwaves is due to the increase in the temperature of the element.

Germicidal effects on vegetative cells and spores of B. subtilis *on the element surfaces*

The germicidal effects on vegetative cells or spores of *B. subtilis* are shown in Figure 10. The germicidal effect on *B. subtilis* vegetative cells was higher than that on *F. solani* spores when exposed to 1200 W for 30 min for an element with 400 g of water (Figures 4c and 10a), whereas *B. subtilis* spores were not suppressed (Figure 10b). These results suggest that if spores of *B. subtilis* germinate to vegetative cells, they are unable to form biofilms during microwave disinfection.

Table 2. The germicidal effects on *F. solani* spores and the temperature of elements at 1200 W for 10 or 20 min.

Output power		At 1200 W for 10 min					
		Front			Rear		
Contained water	Measured points	F2	F5	F8	B2	B5	B8
Water 400 g	Surviving cells	×	×	◎	×	◎	◎
	Max temperature,* °C	74.0 ± 0.7	74.6 ± 0.6	63.6 ± 1.1	65.1 ± 1.2	56.4 ± 2.9	44.0 ± 2.3
	Time,** s	437	449	206	405	0	0
	Increased temperature, °C	53.8 ± 2.3	50.1 ± 2.8	42.4 ± 1.9	47.9 ± 2.4	35.1 ± 1.3	18.5 ± 1.3
Water 800 g	Surviving cells	×	◎	◎	×	◎	◎
	Max temperature,* °C	69.1 ± 0.9	64.4 ± 1.5	54.2 ± 1.2	73.1 ± 0.6	64.7 ± 2.1	49.8 ± 1.3
	Time,** s	510	179	0	475	118	0
	Increased temperature, °C	48.6 ± 1.3	43.8 ± 1.6	33.2 ± 13	52.8 ± 0.8	44.1 ± 2.1	29.9 ±1.2
		At 1200 W for 20 min					
Output power		Front			Rear		
Contained water	Measured points	F2	F5	F8	B2	B5	B8
Water 400 g	Surviving cells	×	×	◎	×	◎	◎
	Max temperature,* °C	74.5 ± 0.1	74.6 ± 0.6	63.7 ± 1.1	72.9 ± 1.2	56.7 ± 2.8	44.0 ± 2.3
	Time,** s	1037	1049	446	1005	0	0
	Increased temperature, °C	53.7 ± 3.9	44.5 ±2.1	33.7 ± 2.7	47.2 ± 1.7	27.5 ± 1.6	20.0 ±1.2
Water 800 g	Surviving cells	×	×	◎	×	△	◎
	Max temperature,* °C	74.5 ± 1.1	72.6 ± 1.9	60.3 ± 2.8	76.0 ± 0.7	68.2 ± 1.1	54.5 ± 2.7
	Time,** s	1110	779	0	1075	675	0
	Increased temperature, °C	47.2 ± 0.3	39.6 ± 1.5	33.7 ± 3.8	49.5 ± 1.1	38 ± 2.8	20.4 ± 1.7

*The maximum temperature denotes the highest temperature with varying temperature after irradiation.
**Times denote the exposure times at 60°C.
Note. × = not detected; △ = 1–9 CFUs/mL; ○ = 10–99 CFUs/mL; ◎ = over 100 CFUs/mL.

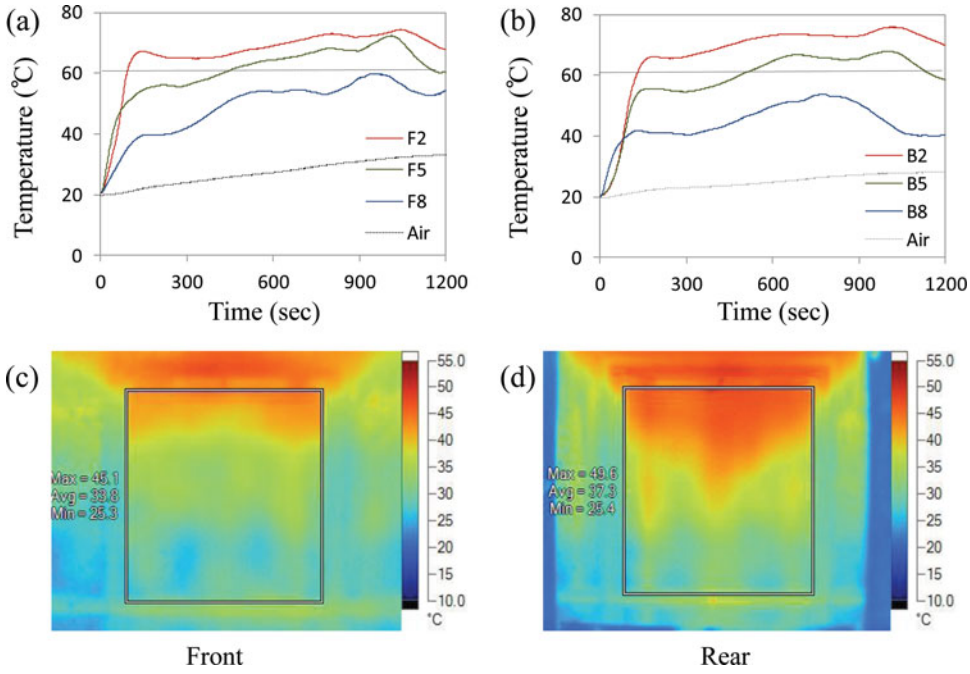

Fig. 8. Comparison of the temperature distribution on the element surfaces in the wet condition with 800 g of water. a. The temperature change of front surfaces measured at the upper, center, and lower parts. b. The back surface. c. The front surface. d. The rear surface Comparison of the temperature distribution on the element surfaces in the wet condition with 800 g of water: (a) the temperature change of front surfaces measured at the upper, center, and bottom parts and (b) the back surface, (c) the front surface, and (d) the rear surface.

Table 3. The germicidal effects on *F. solani* spores and temperature of elements at 600 W or 900 W for 20 min.

		At 600 W for 20 min					
Output power		Front			Rear		
Contained water	Measured points	F2	F5	F8	B2	B5	B8
Water 400 g	Surviving cells	×	×	○	△	◎	◎
	Max temperature,* °C	60.7 ± 2.6	62.1 ± 0.9	61.1 ± 0.9	62.8 ±3.3	55.7 ± 4.2	44.4 ± 3.1
	Time,** s	65	696	186	125	0	0
	Increased temperature, °C	42.1 ± 3.2	42.4 ± 2.6	38.8 ± 5.8	43.3 ± 2.8	33.4 ± 4.1	18.5 ± 3.5
Water 800 g	Surviving cells	○	○	◎	×	◎	◎
	Max temperature,* °C	58.8 ± 2.2	60.5 ± 3.0	50.7 ± 6.2	64.0 ± 2.6	54.3 ±3.2	43.6 ± 1.9
	Time,** s	0	38	0	426	0	0
	Increased temperature, °C	37.8 ± 2.6	39.4 ± 3.1	28.7 ± 7.5	43.2 ± 2.8	33.5 ± 3.3	22.9 ± 2.1
		At 900 W for 20 min					
Output power		Front			Rear		
Contained water	Measured points	F2	F5	F8	B2	B5	B8
Water 400 g	Surviving cells	×	○	△	◎	◎	◎
	Max temperature,* °C	67.4 ± 1.4	63.1 ± 3.3	69.5 ± 0.3	59.5 ± 3.2	46.6 ± 4.0	44.4 ± 3.1
	Time,** s	1052	296	880	0	0	0
	Increased temperature, °C	44.0 ± 0.2	37.2 ± 0.2	50.8 ± 3.3	35.2 ± 2.6	17.0 ± 1.8	18.5 ± 3.5
Water 800 g	Surviving cells	△	◎	×	○	◎	◎
	Max temperature,* °C	65.8 ± 3.7	56.7 ± 5.4	71.7 ± 1.1	64.8 ± 1.3	54.2 ± 0.6	43.6 ± 1.9
	Time,** s	569	0	1039	430	0	0
	Increased temperature, °C	43.8 ± 2.3	33.7 ± 2.9	51.0 ± 1.0	43.5 ± 2.0	29.7 ± 3.4	22.9 ± 2.1

*The maximum temperature denotes the highest temperature with varying temperature after irradiation.
**Times denote the exposure times at 60°C.
Note. × = not detected; △ = 1–9 CFUs/mL; ○ = 10–99 CFUs/mL; ◎ = over 100 CFUs/mL.

Discussion and conclusion

Kang and Kato (2014a) demonstrated that the germicidal effect of radiation is primarily due to the change in temperature to greater than 60°C in the liquid condition. The possibility of microwave heating the humidifier element above 60°C was investigated using a mock-up humidifier system (Kang and Kato 2014b). However, the liquid condition and surface of an element are different conditions. Therefore, the germicidal effects on strains on the humidifier element surface was confirmed when the temperature of the element surface exceeded 60°C.

In this study, the effective disinfection mode was investigated for different parameters, including the microwave output power, the exposure time, and whether the materials contained

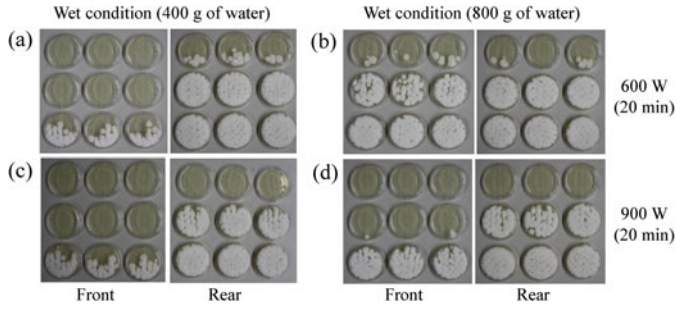

Fig. 9. Comparison of the germicidal effect on *F. solani* on the element surfaces at different output powers. a. 600 W for 20 min with 400 g of water. b. 600 W for 20 min with 800 g of water. c, 900 W for 20 min with 400 g of water. d. 900 W for 20 min with 800 g of water.

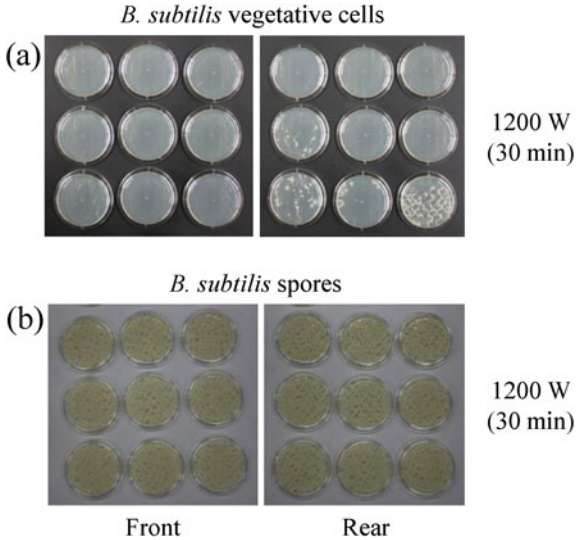

Fig. 10. The germicidal effect on *B. subtilis* at 1200 W for 30 min. a. Vegetative cells. b. Spores.

moisture, using the mock-up humidifier system. The results demonstrated that in general, the germicidal effects on the upper parts of the element were higher than those on the lower parts of the element regardless of whether the element is dry or wet. The minimum temperature of the element surfaces that led to no detection of surviving colonies was 60.7 ± 2.6°C when exposed for 65 s at over 60°C.

The germicidal effects on fungal spores of *F. solani* at different water contents of the element appear to be stronger for wet elements. These results indicate that microwave irradiation can be an effective method of disinfection in wet conditions. Therefore, we suggest that microwave disinfection for evaporative humidifiers does not require another dry process because an evaporative humidifier is wet.

The germicidal effects on fungal spores of *F. solani* at different output powers and water contents were high when the element was irradiated with a higher output power. The germicidal effects were higher on the upper portion when exposed to 900 W, and germicidal effects occurred on the upper and center portions when the element was exposed to 1200 W. The germicidal effects and temperature of the element after exposure at 1200 W for 10 min were higher than those after exposure at 600 W for 20 min with a wet element containing 800 g of water. These results indicate that the disinfection by microwaves is highly efficient for a high output power even if the element is exposed using the same energy in the wet condition.

The germicidal effects on vegetative cells of *B. subtilis* were higher than of those on fungal spores of *F. solani* when exposed to 1200 W for 20 min. However, the *B. subtilis* spores showed no degradation when exposed to 1200 W for 30 min. These results suggest that *B. subtilis* vegetative cells are unable to form biofilms during microwave disinfection.

In addition, the microwave disinfection experiment was performed with an air blower. The results indicated no germicidal effects and that the irradiation caused no heating. These results agree with those reported in Kang and Kato (2014a), where the germicidal effect of radiation was found to be due to the increasing temperature due to heating effects.

In this study, we assumed that the germicidal effects were high with exposure to a higher output power at a longer exposed time and under wet conditions. However, high-output microwave irradiation is not appropriate from the perspective of energy efficiency. This study demonstrates that there is a possibility that the temperature reaches the disinfection temperature with a small amount of water using less heat input. However, no disinfection effect was observed in the dry condition. Therefore, a suitable combination of output powers and water contents of the elements is expected to be capable of disinfection for efficient energy savings. In our mock-up system, the cavity volume between the microwave shields and their surface area and the element size were small compared to actual humidifiers in buildings. Thus, the electric power consumption should be considered for the practical use of microwave disinfection for humidifier elements in buildings.

Furthermore, the germicidal effects on the element were found to be nonuniform. In particular, the germicidal effect was not apparent on the lower portion of the elements. Variations of these methods should also be considered to produce a uniform heating pattern. In future studies, a method of heating the lower portion of the elements should be investigated, as well as a large-scale heating pattern by microwave simulation.

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