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# Ambient Temperature and Relative Humidity Remained Stable after Prolonged Application of Superheated Steam in Enclosed Spaces

## ABSTRACT

Superheated steam has been proposed as a novel tool for surface sanitation, yet its impact on the relative humidity (RH) and temperature within enclosed dry food processing environments for extended exposure is unknown. This study measured RH and temperature within 12 enclosed and semi-enclosed indoor spaces of varied size, air handling systems, and ventilation rates during prolonged (<5 h) superheated steam operation at 135°C. The RH and temperature were monitored at locations near (0.3 and 1.5 m) the steam nozzle, entrances, vents, and walls. Superheated steam application did not significantly ($P > 0.05$) increase the ambient temperature or RH among all spaces, except near the steam source (0.3 m). A significant increase in RH and temperature occurred near the steam source (0.3 m), where the maximum increase in RH (47%; small facilities, high ventilation rate) and temperature (9.3°C; large facilities, low ventilation rate) was observed, resulting in limited steam cooling and surface condensation. The results suggested that prolonged superheated steam exposure did not substantially increase the RH or temperature, except for small facilities with low ventilation rates and locations near the steam source. This indicates that the application of superheated steam could enhance sanitation efforts in dry processing environments.

## INTRODUCTION

Superheated steam, or "dry steam," has been proposed as a novel alternative for environmental surface sanitation in dry food processing and produce handling environments. Specifically, superheated steam can achieve high temperatures (125 to >300°C) above the saturation point at a given processing pressure (100°C at atmospheric pressure), which limits the introduction of water *(25, 48)*. In contrast to other conventional dry sanitation methods (e.g., product push through, alcohol-based sanitizers), superheated steam can effectively penetrate cavities, crevices, and follicles that may provide protection for microbial targets *(15, 35, 36)*. Previous studies reported the efficacy of superheated steam for microbial inactivation on various food processing surfaces, including stainless steel, polyvinyl chloride, and rubber; therefore, this

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emergent technology could be effectively implemented as a sanitization strategy for surfaces within dry food processing facilities, such as dry produce handling operations, which exclude the introduction of water during packing of produce and sanitation *(5, 21, 27, 28, 29, 31)*. However, several key knowledge gaps remain before superheated steam can be fully commercially realized by the industry as a manually operated sanitizer.

The ambient temperature and relative humidity (RH) of the handling or processing facility have important effects on sanitation outcomes *(11)*. These factors can influence the growth and dispersion of microbial cells, especially bacterial pathogens and spoilage fungi because the growth of these organisms are preferred at a temperature close to 35°C with RH exceeding 60% *(3, 18)*. In addition, implementation of different sanitation regimes also influences ambient RH and temperature *(19, 45)*. Similarly, changes to RH and temperature can influence cleaning outcomes by increasing the adhesion and cohesion of food and other organic residues on surfaces *(20)*. Chen et al. showed a decreased efficacy of dry cleaning was due to changes in RH *(9)*.

Although superheated steam inactivates microbial cells without introducing significant amounts of water onto treated surfaces, the effect of prolonged superheated steam use on ambient RH and temperature within enclosed or semi-enclosed spaces is not clear and may represent a limitation for some operations. Processors and produce handlers in different types of dry environments may differ in the relative tolerance to modest changes in RH and temperature. Therefore, the purpose of this study was to determine ambient RH and temperature changes that occurred as a consequence of prolonged use of superheated steam in varying indoor spaces.

## MATERIALS AND METHODS

### Characterization of tested facilities

In total, 12 indoor or semi-enclosed spaces were tested in this study. The room length, width, and ceiling height were measured to estimate volume in cubic meters. Qualitative information on the ventilation (central air, unit ventilation, or natural) and features disruptive to air flow (e.g., fans, density of equipment) was collected *(Table 1)*. The spaces were categorized into four types on the basis of size and ventilation rate: large facilities with high ventilation rates; large facilities with low ventilation rates; small facilities with high ventilation rates; and small facilities with low ventilation rates, where an air exchange per hour (ACH) >60 was defined as a high ventilation rate and <60 ACH was defined as a low ventilation rate. Large facilities were categorized as >110 $m^3$, and <110 $m^3$ was defined as a small facility in accordance with a study conducted by Huang et al. *(22)*.

**TABLE 1. Characterization of indoor and semi-enclosed sites**

| Name of space | Type of ventilation | Location | Size ($m^3$) | Category[a] | Ventilation rate (ACH[b]) | Initial RH (%RH) | Initial temperature (°C) |
|---|---|---|---|---|---|---|---|
| Fruit and Vegetable Processing Plant | Combination | Geneva, NY | 3,158.6 | A | >60 | 25 | 25.1 |
| Raw Products | Combination | Geneva, NY | 946.9 | B | 9.35 | 46 | 25.4 |
| Potting Shed | Natural | Geneva, NY | 299.6 | B | 22.99 | 61.5 | 22.9 |
| Medium Greenhouse | Mechanical | Geneva, NY | 72.8 | C | >60 | 39 | 27.9 |
| Growth Chamber | Mechanical | Geneva, NY | 11.7 | D | 2.7 | 82.3 | 21 |
| Large Greenhouse | Mechanical | Geneva, NY | 452.4 | A | >60 | 41.2 | 32.2 |
| Pilot Plant | Mechanical | Ithaca, NY | 1950.0 | A | >60 | 64.7 | 21.4 |
| Winery | Mechanical | Ithaca, NY | 288.4 | A | >60 | 49 | 20.4 |
| Conference Kitchen | Mechanical | Ithaca, NY | 51.8 | D | 16.8 | 60.6 | 20.9 |
| Break Room | Mechanical | Ithaca, NY | 32.2 | D | 1.25 | 59.2 | 22.9 |
| Cold Storage 1 | Mechanical | Geneva, NY | 33.3 | D | <4 | 60 | 12.8 |
| Cold Storage 2 | Mechanical | Geneva, NY | 33.3 | D | <4 | 60 | 12 |

[a]Facility category: A, large facilities with high ventilation rates; B, large facilities with low ventilation rates; C, small facilities high ventilation rates; D, small facilities with low ventilation rates.

[b]ACH, air exchange rate per hour.

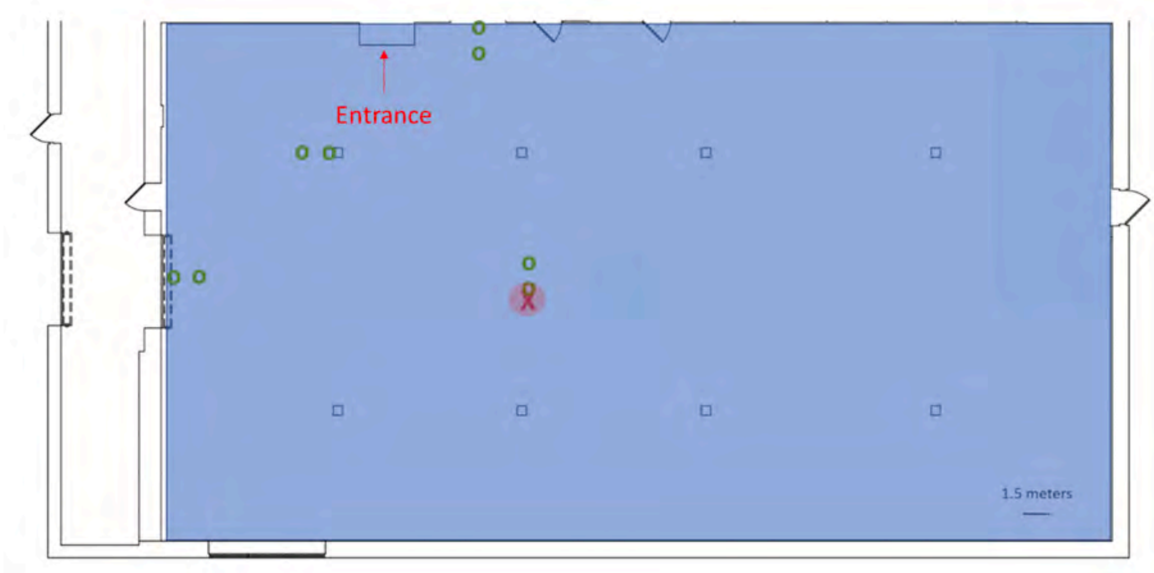


**FIGURE 1. Floor plan of fruit and vegetable processing plant. Red X shows the placement of the superheated steam source. Green circles show the placement of RH and temperature data loggers. In total, there were eight probes that were placed at 0.3 and 1.5 m away from four locations, including the superheated steam nozzle, vents, walls, and entrances, respectively. Black squares show the vent locations in the facility. The blue shade represents areas within the enclosed space of a facility.**

### Ambient RH and temperature measurement

Baseline RH levels and temperatures were measured by using data loggers (EL-WiFi-TH, EasyLog, Erie, PA) over 30 min. The data loggers were equilibrated for 1 h prior to the start of experimentation. A schematic floor plan of the fruit and vegetable processing plant and the placement of the eight data loggers recording RH and ambient temperature within the space are shown in *Fig. 1*. The superheated steam source was positioned in the approximate center of the space (red X), and the data loggers (green circles) were placed 0.3 m (1 ft) and 1.5 m (5 ft) away from the superheated steam nozzle, entrances, and vents. All loggers were placed at the same height that the superheated steam nozzle was positioned above the floor. Distances (0.3 and 1.5 m) between the superheated steam nozzle outlet and surfaces were selected in accordance with the operating guidelines for the superheated steam unit for sanitation efficacy. The RH at each location was recorded continuously, and the temperature was recorded every 15 min for up to 5 h. The superheated steam equipment remained stationary at the same position throughout the 5-h treatment time.

### Superheated steam system and setup

The temperature of the superheated steam unit (HGA-S, MHI Inc., Cincinnati, OH) was set to 135 ± 1°C, a typical temperature for superheated steam application. The superheated steam outlet temperature was equilibrated for 15 min and measured to be 135 ± 1°C between replications. Approximately 1 liter of water was used over 5 h. Coupons (30.5 by 30.5 cm and 0.15 cm thick) composed of stainless steel (grade 304 2B; Rose Metal Products, Springfield, MO) were placed vertically with the flat side facing the superheated steam outlet and at a distance 0.3 m from the superheated steam outlet to detect any condensation formation *(Fig. 2)*. Images showing surface condensation on stainless steel coupons were captured every 5 min for up to 15 min to qualitatively assess saturated steam formation during the superheated steam application.

### Ventilation rate assessment using a $CO_2$ decay method

ACH was calculated for each space as previously described *(6)*. The $CO_2$ level of the air outside of the test space was first measured for 5 min near the air intake of the ventilation system outside the building before each experiment. Then, $CO_2$ decay levels were determined inside the test spaces. To raise the peak $CO_2$ levels inside the facility spaces to at least 2,000 ppm, approximately 250 g of dry ice was placed in a cardboard box and left in the room for 2 min. A small oscillating fan was used to keep the $CO_2$ well mixed in the room. The $CO_2$ level was then measured at 1-min intervals by using a $CO_2$ handheld gas detector (range 0 to 9,999 ppm, accuracy ± 50 ppm; GasLab Plus, Ormond Beach, FL) for up to 2 h. The ventilation rate was determined by $CO_2$ clearance with dry ice (ACHDI) by using the $CO_2$ concentration decays *(1, 22)*

$$ACH_{DI} = 1\ \Delta t \ln\left[(C_1 - C_R) / (C_0 - C_R)\right] \quad (1)$$

where $\Delta t$ is the period between measurements, $C_0$ and $C_1$ are $CO_2$ levels measured at the beginning and the end of the decay period (ppm), and $C_R$ is the $CO_2$ level in outdoor air (ppm).

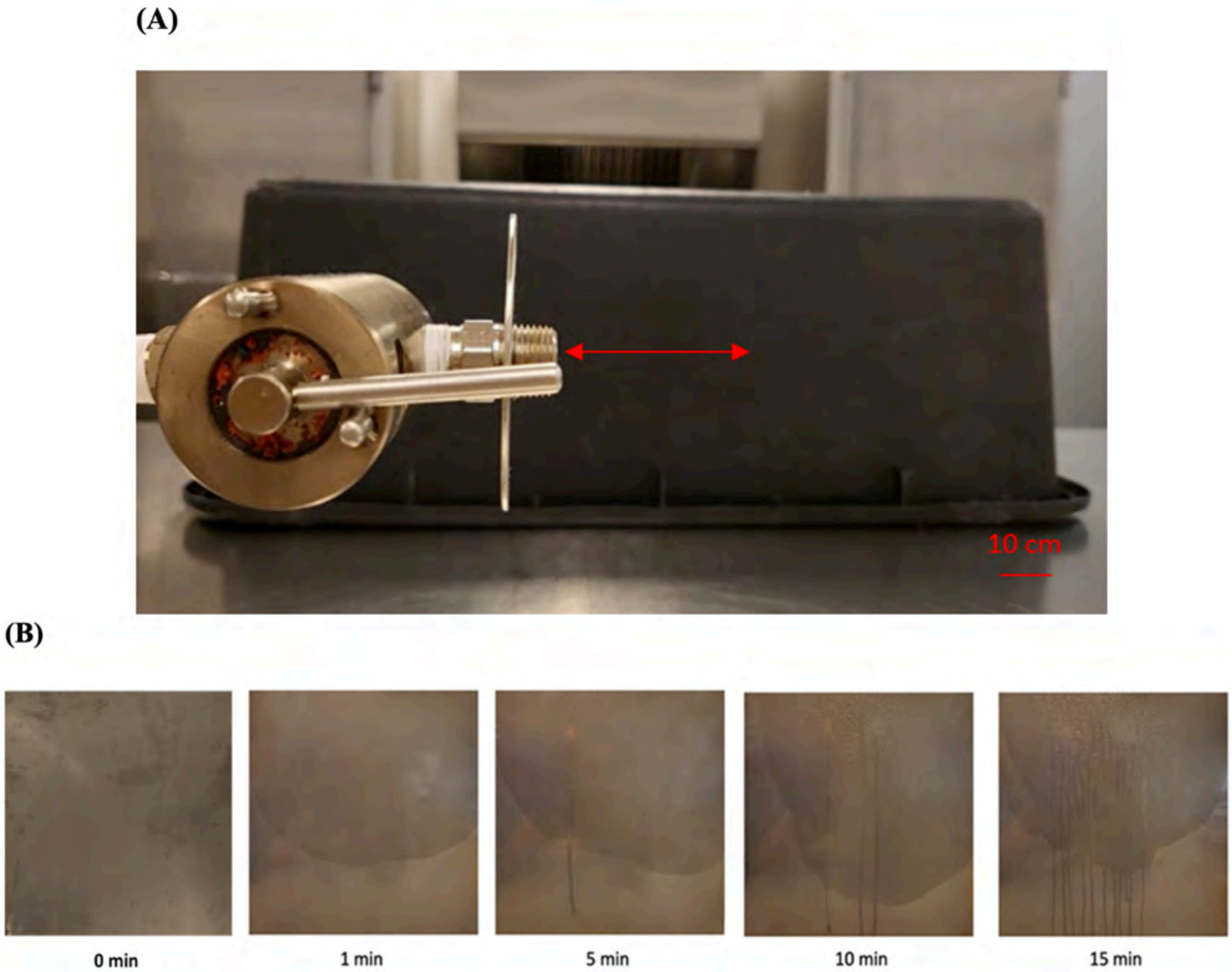


FIGURE 2. A, Visible saturated steam was observed within the distance between the superheated steam source and stainless steel coupon when placing the coupon 0.3 m away (red arrow) from the superheated steam source B, resulting in a small amount of stainless steel surface condensation during extended exposure.

**Statistical analysis**

All statistical analyses were conducted in R (version 3.3.1, RStudio, Boston, MA). The percent change in ambient RH and temperature was analyzed in separate linear regression models *(42)*. The data were analyzed by using the following two-way interaction model:

Change in ambient RH or temperature = location x duration (2)

where $P < 0.05$ was considered significant. Separate models were used for each facility type. Analysis of variance (ANOVA) tests were performed to evaluate statistically significant parameters of the two-way interaction model by using the ANOVA() function in R (version 4.3.1) *(42)*.

## RESULTS AND DISCUSSION

**Change in RH and temperature was significant at 0.3 m from nozzle but not other locations**

Sensor location was a significant factor for both change in RH ($P < 0.001$) and temperature ($P < 0.001$). Specifically, the change in RH and temperature that occurred at the location 0.3 m directly in front of the superheated steam nozzle was significantly higher than those at any other location *(Fig. 3)*. Following 1 h of treatment, the RH level at 0.3 m in front of the nozzle location increased by 29% in the fruit and vegetable processing plant *(Fig. 3A)*. However, the ambient RH remained relatively constant at all other locations in the fruit and vegetable processing plant. Similar trends were observed in the greenhouse test space (small space, high ACH; *Fig. 3C*). Thus, sensors at locations at <0.3

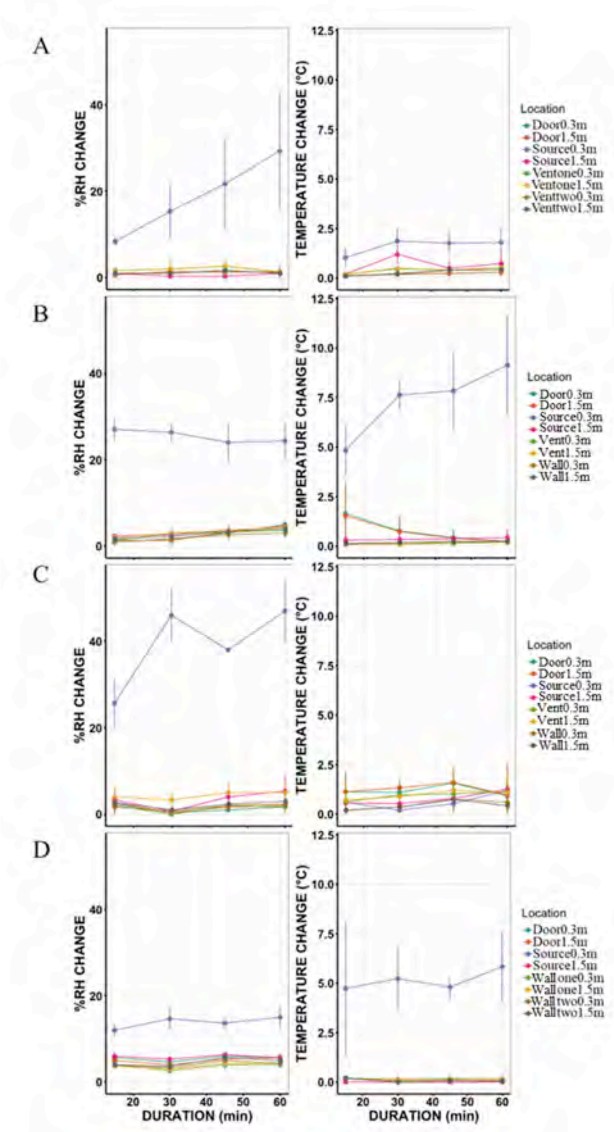


**FIGURE 3. RH and temperature during use of superheated steam for 1 h in the following: A, fruit and vegetable processing plant, a large facility with high ventilation rate; B, potting house, a large-sized facility with low ventilation rate; C, medium greenhouse, a small-sized facility with high ventilation rate; and D, growth chamber, a small-sized facility with low ventilation rate.**

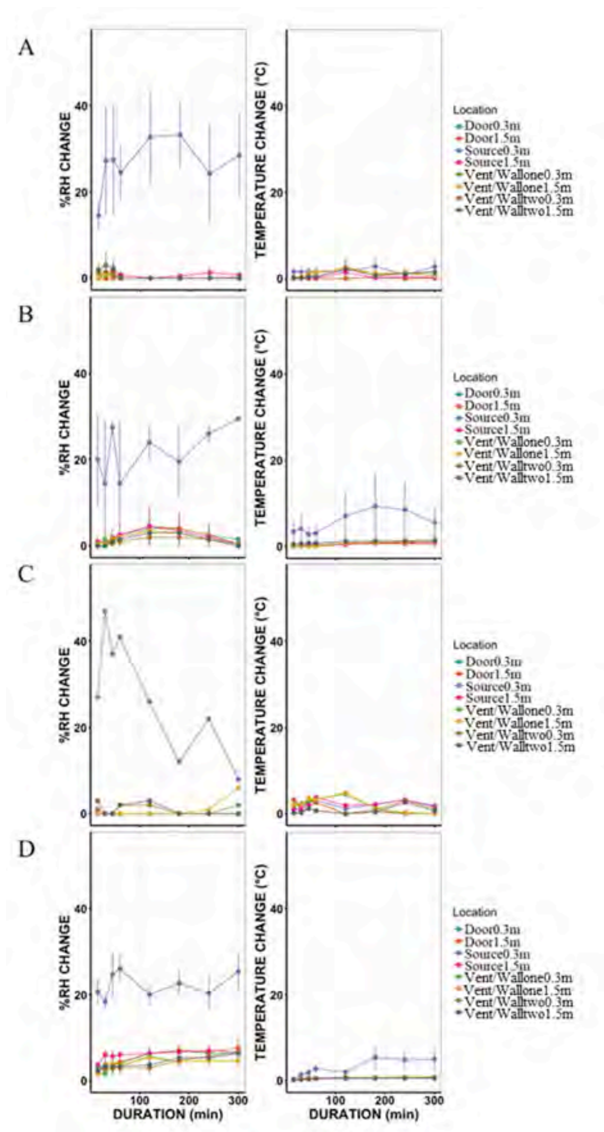


**FIGURE 4. Average RH (left) and temperature (right) during superheated steam use for 5 h in the following: A, large facilities with high ventilation rate ($n = 4$); B, large facilities with low ventilation rate ($n = 2$); C, small facilities with high ventilation rate ($n = 1$); and D, small facilities with low ventilation rate ($n = 3$).**

m of the steam source may represent worst-case scenarios for changes to RH and temperature, as a result of the close vicinity to the localized superheated steam stream. The sensors at more distal locations and near areas of high air exchange (e.g., vents, entrances) are subject to greater air flow, and the temperature difference of the ambient air could influence the effect of the superheated steam treatment on the change of RH and temperature. Interestingly, an increase in RH was observed at locations near the superheated steam source (0.3 m) from the two facilities with high ventilation rates after exposure to superheated steam for 1 h. The increase of RH within these spaces was mainly due to steam fluctuations near the nozzle. Therefore, the results did not suggest that the high ventilation rate was contributing to the increase in RH. In fact, in small facilities with high ventilation rates, the RH decreased after 5 h of superheated steam exposure, indicating that a high ventilation rate eventually removed moisture produced from the superheated steam source *(Fig. 4C)*.

Facilities with lower ventilation rates, such as the potting house *(Fig. 3B)* and growth chamber *(Fig. 3D)*, also had significantly higher RH levels when 0.3 m in front of the superheated steam unit. However, the RH at other locations within these sites also increased by an average of 4%. Therefore, in spaces with a low ventilation rate, a small percentage of change, but statistically insignificant increase of indoor RH, was observed. Although the increase of indoor RH was minimal, recurrent superheated steam exposure during dry sanitation of the space could introduce water vapor to the ambient environment and gradually increase the overall indoor RH as it mixes with the surrounding air. This increase in RH could affect the sanitation efficacy of superheated steam and comfort of the personnel within the facility *(29, 38, 39, 50, 51)*. Specifically, the excessive moisture could promote microbial growth and increase the difficulty of removing organic food soil in the food processing environment *(9)*. Thus, dry food and produce handling facilities with small spaces and low ventilation should consider alternative dry sanitization methods or decrease the indoor RH (e.g., venting out water vapor content or elevating the ambient temperature) prior to superheated steam sanitation treatments.

Similarly, visible saturated steam and surface condensation formed at a distance of 0.3 m between the steam nozzle and the surface (23.2°C) after several minutes *(Fig. 2)*. Thus, the formation of condensation may be attributed to the distance between the steam nozzle and the surface. Previous studies report that as the superheated steam moves away from the steam source (nozzle), it interacts with the surrounding air and rapidly cools down *(38)*. Various factors contribute to this: decrease in fluid flow velocity; formation of a boundary layer; and temperature gradient between ambient air (or surface) and the gaseous superheated steam *(2, 10, 14, 24, 32, 34, 43, 44)*. Steam condensation could result as these factors decrease the superheated steam temperature below 100°C and condense the water vapor. As a result of condensation, extended superheated steam exposure with a large distance between the source and the surface could represent a worst-case condition for accumulation of surface condensation. Prior studies confirmed our qualitative observations, suggesting that the temperature difference between the superheated steam and the surface (or ambient air), as well as the nozzle-surface distance, may be attributed to phase change (condensation) and the transfer of latent heat to surfaces *(4, 8, 23, 53)*.

Depending on the facility, introduction of moisture could be a drawback. For wet zones in low-moisture food processing facilities, such as areas that are distant from the final products, a limited amount of moisture would not substantially affect dry food processing when moisture is removed (e.g., wiping with dry rag) or air dried immediately. However, dry food processing and produce handling environments typically exclude wet sanitation and limit the introduction of moisture because increases in RH and surface condensation could facilitate microbial and fungal growth within harborage sites or contamination of food products and equipment (e.g., conveyor belts or harvester equipment) *(7, 15, 26, 33, 39–41, 47, 49, 52)*. Similarly, significant increases in RH and temperature could decrease the ease of removal of food and organic food soils, as well as increase deterioration of cardboard, fiber-based products, and other dry materials. Thus, dry food processing facilities implementing superheated steam for surface sanitization should examine the practical environmental considerations within industrial food processing settings, including changes of indoor RH and temperature, as well as manual operation of handheld superheated steam units at close distances from target surfaces.

**Change in RH not time dependent through 5 h of continuous superheated steam under test conditions**

Twelve spaces with sizes ranging from approximately 11.7 m$^3$ (413 ft$^3$) to 3,437.3 m$^3$ (12,1387 ft$^3$) were analyzed in this study to capture a range of diverse environmental settings *(Table 1)*. The following three types of ventilation were included: natural, mechanical, and combination. The ventilation rates ranged from 1.25 to >60 ACH. Within commercial processing facilities, high ACH and positive air pressure are commonly used as a good manufacturing practice. Prior research has shown that low ACH and high RH contribute to the spread of airborne infectious agents *(13, 16, 31, 54)*. Therefore, most manufacturing facilities have already implemented 2 to 6 ACH as part of standard operating procedures *(46)*. In addition, the semi-enclosed, naturally ventilated space also had very high ACH (>22 ACH). By contrast, the lowest ACH was observed in the break room (1.25 ACH).

The two-way ANOVA test showed that exposure time did not significantly affect ambient RH or temperature ($P > 0.05$) among all spaces 1.5 m or greater from the source. However, the average change in RH and temperature fluctuated over time and were localized *(Fig. 4)*. The largest increase for RH and temperature was 47% and 9.3°C, respectively, and occurred 0.3 m from the source, when examining all facility spaces during a 5-h superheated steam operation *(Fig. 4)*. The greatest variation in temperature change ranged from 2.85 to 9.3°C (large-sized facility with a low ventilation rate, 0.3-m distance between the sensor and the superheated steam source; *Fig. 4B*). The greatest variation in RH change ranged from 8 to 47% (small-sized facility with high ventilation rate, 0.3-m distance between the sensor and superheated steam source).

The minimum change in RH and ambient temperature may be attributed to two variables: the high efficiency of both mechanical and natural air handling systems; and the relatively low volume (1 liter) of water used to generate superheated steam during the 5-h treatment. In practice, a sanitation shift within a dry produce handling operation may last for 5 to 8 h; the application of a sanitizer, such as superheated steam, would likely constitute only a fraction of the total time during a shift. By comparison, an indoor portable ultrasonic humidification system can increase RH from 34 to 90% over a 4-h interval within an enclosed chamber (length by width by height: 4 by 3 by 3 m), according to a study conducted by Feng et al. *(12)*. Similarly, Guo et al. reported that the indoor RH increased from approximately 32.89 to 56.6% and 61.31% for an evaporative humidifier and ultrasonic humidifier, respectively, within an enclosed treatment chamber (4 by 4 by 2.7 m) over a 2-h duration (ambient temperature of 22.5°C and an air exchange rate of 0.059 $h^{-1}$) *(17)*. Note that the location 0.3 m in front of the superheated steam unit experienced the greatest increase in RH and temperature among all sites (as discussed in detail in the following). However, the changes to RH and temperature at that location were not significantly influenced by time over 5 h.

## CONCLUSIONS

This study examined the effects of extended superheated steam exposure on the change in ambient RH and temperature within enclosed and semi-enclosed spaces of dry food processing and produce handling facilities. Results indicated that 5 h of superheated steam exposure did not result in statistically significant ($P > 0.05$) or practically relevant increases in ambient RH and temperature among all spaces. However, significant increases in change of RH ($P < 0.001$) and temperature ($P < 0.001$) were observed in proximity (0.3 m) to the superheated steam nozzle. Although a small volume of surface condensation was generated, a static and relatively long exposure (0.3-m distance for 15 min) was required. Similarly, results suggest facilities with lower ventilation rates (<60 ACH) could be more susceptible to changes in RH throughout the space during superheated steam treatments. Manually operated tools, such as the superheated steam unit, are unlikely to remain stationary within the facility space (i.e., centered in the facility) or treat a target surface at a static distance for an extended time during sanitation. Thus, future studies should assess the variation in RH, temperature, and surface condensation during manual operation of pilot-scale superheated steam units (e.g., mobile treatment across a surface or throughout the space) at close distances from surfaces within semi-enclosed and enclosed indoor spaces, as well as varying ambient temperatures (e.g., refrigeration). Similarly, additional research on the mediating effects of varying RH and temperature during superheated steam exposures on microbial inactivation could complement previous studies that investigate the efficacy of superheated steam as a novel dry sanitization technology. Despite these limitations, the study demonstrated the impacts on the processing environment when using superheated steam and provided insights on the efficacy of applying superheated steam as a method for dry sanitation.

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