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Key Words

Filtration · Indoor environment · Aerosol particles · Control technology · Particle counter

Abstract

Two independent modifications were made to one of two identical side-by-side filter banks for a large air-handler: (1) new filter holders, intended to provide a better seal and (2) ultraviolet germicidal irradiation (UVGI) lamps, intended to control microbiological growth. Total system efficiency testing with optical particle counters was performed to determine the effectiveness of the new filter holders. The efficacy of the UVGI lamps was determined through biological surface and air sampling. Results indicated that the side with the new filter holders was about 3.4% more efficient per year during the 22-month sampling period, whereas the coil chamber with the UVGI lamps had less biological contamination than the corresponding control chamber for over 75% of the sampling days.

Introduction

The testing of real-time total system efficiency (including filter efficiency, filter frame-holder leaks, faulty seals, etc.) is a significant challenge. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, as well as other standard-setting bodies, have established well-defined standards and procedures for testing the efficiency of "air-cleaning devices" (i.e., filters) [1,2], but there are no available standards for *in situ* testing

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of total filtration unit efficiency. Therefore, investigators at the National Institute for Occupational Safety and Health (NIOSH) have adapted the procedure from the American Society of Agricultural Engineers (ASAE) Standard S525 for testing the total enclosure filtration efficiency of agricultural tractor cabs for use in ventilation systems [3]. Simple inlet modifications (isokinetic sampling inlets) to the optical particle counters (OPCs) used for the ASAE procedure have allowed for successful *in situ* comparison and testing of the filter efficiency [4].

Research has demonstrated that ultraviolet germicidal irradiation (UVGI) is effective in killing or inactivating *Mycobacterium tuberculosis* under experimental conditions [5–8] and in reducing transmission of other infectious agents in various settings [9–12]. Although UVGI has seen limited use in air-handling unit applications, two previous studies [13,14] have shown that UVGI lamps reduce the surface levels of bacteria and fungi within air handling units (AHUs).

A recent study by a NIOSH facility of its large walk-in AHU number 8 (NIOSH AHU 8) revealed several areas needing improvement [15]. The factory-supplied spring-style filter holders for securing a filter to the frame tended to jam the filter. This caused the spring-loaded filter holder to dislodge from the filter rack-frame and increased the time needed to replace the filters. In addition, vibrations from the AHU fan motors appeared to cause the filter holders to come loose, creating a leak path around the filter and reducing the total system efficiency of the AHU. In response, a new filter holder was designed to prevent these problems. A second issue was controlling microbiological growth using UV lamps, which could lead to a reduction in maintenance costs and to an improvement of air quality in the building.

In order to assess these changes, a 22-month study was undertaken to (1) evaluate the effect that the new filter holders would have on the total system efficiency and (2) determine the efficacy of installing an UVGI system to control the bacterial and yeast-and-mold growth within NIOSH AHU 8.

Materials and Methods

AHU 8 Description

NIOSH AHU 8 is a walk-in constant-volume system with a heat-recovery and preheated/chilled water coil (Figure 1). The AHU holds 64 filter assemblies ($61 \times 61\,cm^2$) in two separate and equivalent banks of filters containing eight filters in each of four rows. The two fan-banks, which are identical and parallel, each contain two fans where each fan operates at $28.3\,m^3 \cdot s^{-1}$. Fan-bank 1 was fitted with the new filter holders and the UVGI system, whereas fan-bank 2 acted as the control. During the study the system operated 24 h a day, 7 days a week, and was a 100% outside-air intake unit (i.e., all air being exhausted). An automated humidification system was located in the chamber just before the final filters. This system automatically activated whenever an exhaust air sensor indicated that the humidity had dropped below 40%, thus maintaining a relative humidity in the building environment within the range of 38–52%. All the filters were a pleated V-panel design (Filtration Group FP Mini-Pleat 4E412, Joliet, IL). The air handler with these filters had a measured air-flow velocity (TSI Model 8324 VelociCalc Plus, St Paul, MN) of $2.6\,m \cdot s^{-1}$.

For this study, an ExStream Series EXTV-60-16-83X198 air disinfector system (Lumalier, Memphis, TN), designed to handle $38\,m^3 \cdot s^{-1}$ of air throughput, was installed in the coil area chamber of fan-bank 1. The air disinfector system was wired for four 60 W (nominal) biaxial high-output windchill-corrected lamps, which produce 17 W of ultraviolet energy with a wavelength of 253.7 nm, arranged to provide for a 360° disinfection zone. In the AHU, at velocity of $2.0\,m \cdot s^{-1}$ and 28°C, the output at one meter from the lamps was $175\,\mu W \cdot cm^{-2}$. No UVGI system was installed in the coil area chamber of fan-bank 2 (i.e., the control side). The manufacturer-suggested cleaning schedule was every 6 months, with lamps to be replaced yearly. Prior to installation of the UVGI system, both coil areas were cleaned by the maintenance department in accordance with their yearly standard operating procedure.

New mechanical filter holders (Figure 2) were also installed with the filters in fan-bank 1 in order to secure the new filters tightly to the support rack. When properly installed, all four corners of the filter were supported. The new aluminum support clip (1.91 cm thick × 5.04 cm wide × 7.62 cm long, with a U slot 1.27 cm wide × 5.08 cm long) was manufactured by NIOSH. A plated thumb screw was used to secure the support clip against the filter frame and a soft neoprene gasket was glued to the contact surface to cushion this area. Factory-supplied clips were installed with the filters in fan-bank 2. The seals were verified in all cases.

Aerosol Total System Efficiency Testing

Testing of AHU 8 with OPCs was performed to determine if there was a difference in total system efficiency due to the modifications made to fan-bank 1. The OPCs were Grimm

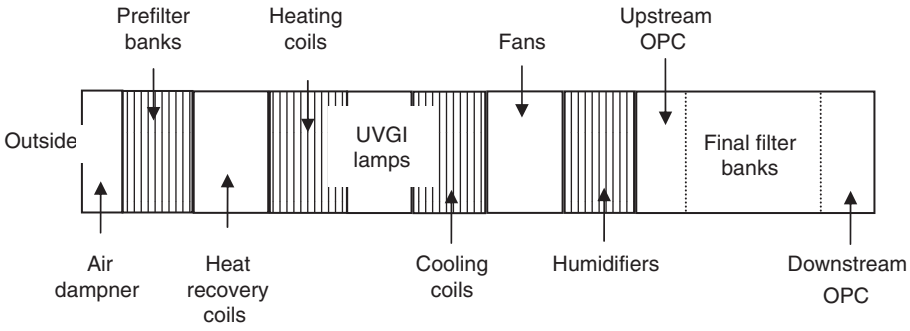

Fig. 1. Schematic of the treatment side of the NIOSH Air Handler #8 (fan-bank 1). The control side was identical except for the UVGI lamps and new filter holders. Both the prefilter and final filter banks on each side of the air handler were comprised of 32 individual filters.

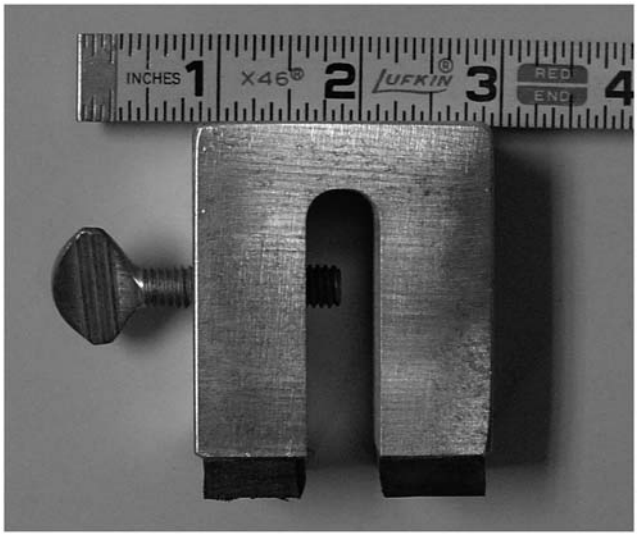

Fig. 2. New filter holder.

Model 1.108 portable dust monitors (Grimm Technologies, Douglasville, GA), which measured the particle number concentration in fifteen different size channels: 0.30–0.40 μm, 0.40–0.50 μm, 0.50–0.65 μm, 0.65–0.80 μm, 0.80–1.0 μm, 1.0–1.6 μm, 1.6–2.0 μm, 2.0–3.0 μm, 3.0–4.0 μm, 4.0–5.0 μm, 5.0–7.5 μm, 7.5–10 μm, 10–15 μm, 15–20 μm, and >20 μm. The conditions of the study were within the operational parameters of the Grimm OPC [16]. In addition, the Grimm OPCs were calibrated by the manufacturer as matching units, to reduce instrument-to-instrument variability from the standard 10% to 5%. In other words, each matched pair of OPCs consisted of two instruments with total particle counts within ±2.5% in the 0.3–3.0 μm size ranges, in order to limit the effect of potential bias due to instrument-to-instrument variability. Each OPC was also equipped with a Grimm Model 1.152 isokinetic sampling probe with a 3.0 mm nozzle (for sampling in air flow velocities in the range of 2–4 $m \cdot s^{-1}$) and sampled parallel to the air stream at a rate of 1.2 $L \cdot min^{-1}$, since the measured air velocity through AHU 8 was 2.6 $m \cdot s^{-1}$.

To conduct the total system efficiency testing, one of the paired OPCs was placed upstream of the final filters with the isokinetic sampling probe facing the air stream at the center of the filter bank to measure particle concentration from the ambient outside air and particle generation by the fan motor. The second OPC was placed downstream of the final filters with the isokinetic sampling probe facing the final filters at the center of the filter bank (Figure 1) to measure the particle concentration, including particles penetrating the filter and leaking around the filters and through the filter housing. After stabilization, they were operated under normal conditions while recording particle concentrations to a data storage card every minute for each size of the fifteen different channels. The OPCs were run for approximately 5 days (the capacity of the data card) each month of the study. After each sampling period, the data storage cards were downloaded to a computer and then readied for the following month's data collection.

Microbiological Testing

Air Samples

Two air samples were collected using a BioStage-1® Sampler (SKC, Eighty Four, PA), just outside of the air inlet and directly upstream and downstream of the filters in each fan-bank. The Biostage-1 sampler is an aluminum device consisting of an inlet jet, a jet classification stage, and a base plate. The base plate held a sterile standard-size plastic Petri dish of Reasoner's 2A agar (R2A) [17]. The air sampling time was five minutes for all samples. A rotary vane vacuum pump was calibrated with each sampler to draw 28.3 $L \cdot min^{-1}$ of air through the sampler toward the agar collection surface, where the particles were retained. Following the sampling, the Petri dishes were placed in an incubator at 30 ± 2°C and read for both total bacteria and yeast-and-mold counts at 24 and 48 h.

Water Samples

Water samples were collected in the re-humidification chamber and at the clean steam generator in order to investigate the clean steam, which was used to humidify the air. Within one hour of collecting the water samples in sterile containers, 0.1 mL of each was cultured on sterile plates [17] of R2A. The plates were incubated at $25 \pm 2^{\circ}C$ for 5 days and the number of colonies quantified.

Surface Samples

Surface sampling in each fan-bank was conducted at the air intake, in the coil chamber, and before and after the final filter banks. Hycheck™ (Becton, Dickinson, and Co., Sparks, MD) hygiene contact paddles were used to assess the microbiological contamination of surfaces inside the ventilation filter banks. The contact slides are double-sided, hinged plastic paddles containing two agar surfaces. The agar surfaces extend above the paddles so that the agar can contact the surface to be tested. Two different types of paddles were used in the study: one for yeast-and-mold (Hycheck Yeasts and Molds, Cat. No. 290006) and the other for bacteria (Hycheck Total Counts, Cat. No. 290005).

For the Hycheck yeast-and-mold contact paddles, side one is for the selective isolation of yeasts and molds. Side two is for microbial limit testing and gives a total aerobic count. For the Hycheck bacteria contact paddles, both sides provide the total bacterial count. On one of the sides, a chemical is added to aid in the counting of normally translucent or colorless bacterial colonies.

Two sets of paddle samples were employed. Identical samples were collected in both the control and UVGI sides. A set of six samples (three paddles each of the bacteria and yeast/mold type) were collected within each fan-bank at the coil chamber, upstream of final filters, and downstream of final filters. A set of four samples (two paddles of each type of paddle) were collected outdoors just below both air intakes. All paddle samples were taken at the same approximate area for each sampling time. The paddle samples were incubated at $30 \pm 2^{\circ}C$ and counted for both bacteria and yeasts-and-molds at 24 and 48 h. The colony counts were determined by visual inspection using a magnifying glass, and colony formation on the agar paddles was reported employing a semi-quantitative scale with the following ordinal seven categories: no colonies found, 1–10 colonies, 11–20 colonies, 21–30 colonies, 31–40 colonies, 41–50 colonies, or more than 50 colonies found.

Data Analysis

Total System Efficiency for Evaluating Filter Holders

The overall total system efficiency of the control versus the side with the modified filter holders was evaluated for any change in efficiency. Only particles in the interval 0.3–3.0 μm were evaluated, since aerosol particles above 3.0 μm were not detected downstream of the filters. Coincidence and/or overloading were not an issue, since all of the particle-count data were below the instruments' upper count limit of 2,000,000 particles per liter.

The percent filtration efficiency (E) of the ventilation system for each minute for each particle size interval was calculated as follows:

$$E_n = \left[1 - \left(\frac{C_D}{C_U}\right)\right] \times 100 \quad (1)$$

where n is the number for the minute of testing in each particle size range, C_D is the downstream aerosol particle concentration at n minute, and C_U is the upstream aerosol particle concentration at n minute. The overall mean efficiency ($\bar{E}$) and standard deviation of the estimated efficiencies were then calculated for each particle size range and over each sampling period [18]. Estimates of the mean efficiencies were calculated at the start of the study, at 6-month intervals, and at the end of the study, resulting in 40 estimates (i.e., from five time intervals and eight channels) for each of the fan-banks. The reduced efficiencies per year of use were estimated and compared for the treatment levels (i.e., with or without filter holders) using analysis-of-covariance models [19], such as the following:

$$y_{ij} = \alpha_i + \beta_i X_{ij} + \varepsilon_{ij}$$

where y_{ij} and X_{ij} denote the outcome and independent variables from the i-th treatment and j-th time interval, and where we assume that the errors ε_{ij} are independent as well as identically and normally distributed. Because the system efficiencies were generally better for the larger sized channels, the model which calculated the difference for the overall regression coefficients (i.e., over all the channels), also included the variable, which gives the size of the channel.

Microbiological Sampling for Evaluating UVGI Lamps

For each fan-bank, surface samples were evaluated for the coil chamber, the before-filter chamber, and the after-filter chamber. Each chamber had three sampling locations. For each sample, the yeast-and-mold or total bacteria outcomes were scored in seven ordinal categories: no colonies found, 1–10 colonies, 11–20 colonies, 21–30

colonies, 31–40 colonies, 41–50 colonies, or more than 50 colonies, respectively. The median of the outcomes for the three locations within a chamber on a given sampling date was used in the analysis; however, note that the total-bacteria outcome at each location within a chamber was also based on the mean of two observations. The variables considered for the data analysis included the treatment factor (i.e., control vs. UVGI), the type of chamber within the fan-banks (i.e., coil, before-filter, or after-filter), and the date for the sample. There were 38 sampling dates that were common to all chamber and treatment combinations, and only data from these sampling dates were included in the analysis (this requirement excluded less than 10% of the data). After matching by sampling date, the biological data outcomes were compared for (1) different types of chambers within the same fan-bank, indicating changes in the air quality as it moves downstream and (2) chambers of the same type but in different fan-banks, indicating the treatment effect for specified areas in the air stream.

In order to test if levels of colony numbers were equal, the version of the Wilcoxon matched-pairs signed-ranks test, which is due to Conover [20], was applied to the matched data. This test is the nonparametric analogue of the matched-sample *t*-test, and Conover's version, which produces an approximately normally distributed statistic, is recommended when there is a relatively large sample size and there are many ties. (Note that, because the total bacteria outcomes were based on the mean of two observations at each of the three locations within a chamber, these outcomes were rounded to the nearest category before the calculation of some descriptive statistics, but the Wilcoxon statistic was always calculated without rounding.)

SAS^{TM} software (SAS Institute Inc., Cary, NC) was used to perform the statistical analyses, and a *p*-value of 0.05 was chosen for statistical significance. SAS code for calculating Conover's version of the Wilcoxon statistic is provided by Duke and Carpentieri [21].

Results

Total System Efficiency Testing for Evaluating Filter Holders

An analysis of covariance was performed using 80 estimates of efficiency for the various time periods and channels. The total system efficiency differential results for fan-bank 1 (i.e., having the new filter holders) were compared to fan-bank 2 (i.e., the control side). Table 1 shows the estimated percent change per year in system efficiency for various particle channels, as well as overall estimates of the percent change per year over the 22-month sampling period. The overall results showed that the control side was, on average, about 5.6% less efficient per year during the sampling period, whereas the side with the new filter holders was only about 2.2% less efficient per year, or a difference in efficiency of 3.4% ($p = 0.01$, 95% C.I. 0.8–5.9%). Furthermore, the control side was generally less efficient per year over all the various size ranges.

Table 1. Total system efficiency differential results which show the estimated percent change per year in filter efficiency for various particle sizes

Grimm midpoint (μm)	0.35	0.45	0.57	0.72	≥0.89	Overall
Control (%)	−7.6	−8.6	−9.0	−7.6	−3.0	−5.6
New filter holder (%)	−5.3	−5.1	−3.2	−2.6	−0.3	−2.2

Microbiological Testing for Evaluating UVGI Lamps

The inlet air samples, which were read after 24 h, gave very low bacterial colony counts except for four sampling periods from July through September when the plates were overloaded. With the exception of the four overloaded samples, the number of colonies ranged from 0 to 19, with 41 of the 58 samples being less than five. As a result, only five before-final-filter samples showed colony counts greater than five (one in filter bank 1 and four in filter bank 2). No samples downstream of the final filters gave a colony count of greater than two. All culture plate controls gave zero colonies. The inlet air samples, when read at 48 h, were overloaded with mold/yeast growth. Samples downstream of the final filters in both filter banks gave colony counts of less than five in 126 of the 132 samples. The only substantial finding from the air samples was that the before-filter samples appeared to become contaminated from an unidentified source. This resulted in an investigation of the clean steam used to humidify the air just upstream of the final filters. Steam condensate samples were collected and 0.1 mL spread on R2A. After 5 days of incubation at $25 \pm 2^{\circ}C$, the quantitative findings showed 2040 colony-forming units·mL^{-1}. Since the clean steam source showed no microorganism contamination, the large number of organisms appearing in the condensate was most likely due to it coming in contact with biofilm growth in the lines.

Only the surface measurement analyses for 24-h incubation readings of total bacteria and total aerobic yeast-and-mold outcomes are reported here, since the

patterns of the outcomes were similar for the 24- and 48-h total bacteria results and were similar for the 24- and 48-h total aerobic yeast-and-mold results. In addition, the latter two were both similar to the 48-h selective yeast-and-mold results. None of the 24-h selective yeast-and-mold results are reported, because there were very few or no colonies detected.

Tables 2–5 show the marginal frequencies for the semi-quantitative ordinal outcomes used to assess the yeast-and-mold and total bacteria measurements, along with the Wilcoxon signed-ranks statistics, which were calculated after matching data by the sampling date. Note that a statistically significant and positive Wilcoxon statistic implies that there are relatively higher levels of colonies for the first row of a comparison, whereas a statistically significant and negative statistic implies that there are relatively higher levels for the second row of a comparison. In order to aid in the interpretation of the results, we have also reported the percentages of the 38 sampling days when the first row of the comparison had a larger outcome (P^1) and the percentage of the sampling days when the second row of a comparison had a larger outcome (P^2). For example, the first comparison in Table 2 shows that, for the control ventilation fan-bank, the coil chamber had a larger number of colonies than the before-filter chamber for about 55% of the sampling days and had a fewer number of colonies for only 3% of the sampling days (hence, the two chambers had about the same number of colonies for the remaining 42% of the sampling days).

The results in Tables 2 and 3 are for the comparisons of different chambers using the same treatment. In other words, these are comparisons of different chambers within the same fan-bank and indicate any changes to the air

Table 2. Marginal frequencies for the ordinal surface-sample outcomes for the yeast-and-mold, together with the Wilcoxon statistics for (1) the coil chamber vs (2) the before-filter chamber, (downstream) and also for (2) the before-filter chamber vs (3) the after-filter chamber, (even further downstream) stratified by the treatment levels

Number of colonies: Yeast-and-mold	Between-chamber comparisons for yeast-and-mold								
	None	1–10	11–20	21–30	31–40	41–50	>50	Wilcoxon statistic[a]	(P^1 | P^2)[b]
(1) Coil control	6	15	4	0	0	1	12	4.02 ($p<0.001$) 1.65 ($p=0.10$)	(55% | 3%) (45% | 13%)
(2) Before-filter control	16	20	1	1	0	0	0		
(3) After-filter control	30	4	2	2	0	0	0		
(1) Coil UVGI	34	2	1	0	0	0	1	−3.30 ($p=0.001$) 1.94 ($p=0.053$)	(3% | 50%) (42% | 13%)
(2) Before-filter UVGI	18	13	2	0	2	0	3		
(3) After-filter UVGI	28	6	2	0	0	1	1		

[a]Wilcoxon signed-ranks statistic tests the hypothesis that the differences after matching have a median of zero.

[b]P^1 is the percentage of the sampling days when the outcome in the first-row in the comparison was larger and P^2 is the percentage of the sampling days when the second-row outcome in the comparison was larger.

Table 3. Marginal frequencies for the ordinal surface-sample outcomes for the total bacteria, together with the Wilcoxon statistics for (1) the coil chamber vs (2) the before-filter chamber (downstream), and also for (2) the before-fitter chamber vs (3) the after-filter chamber (even further downstream) stratified by the treatment levels

Number of colonies: Total bacteria	Between-chamber comparisons for total bacteria								
	None	1–10	11–20	21–30	31–40	41–50	>50	Wilcoxon statistic[a]	(P^1 | P^2)[b]
(1) Coil control	1	27	2	4	3	1	0	−0.57 ($p<0.57$) 2.83 ($p=0.005$)	(37% | 34%) (74% | 18%)
(2) Before-filter control	1	24	2	2	7	0	2		
(3) After-filter control	20	9	2	5	0	1	1		
(1) Coil UVGI	22	14	1	0	1	0	0	−4.81 ($p<0.001$) 1.62 ($p=0.11$)	(5% | 82%) (61% | 21%)
(2) Before-filter UVGI	2	23	2	3	5	1	2		
(3) After-filter UVGI	16	9	3	4	3	0	3		

[a]Wilcoxon signed-ranks statistic tests the hypothesis that the differences after matching have a median of zero.

[b]P^1 is the percentage of the sampling days when the outcome in the first-row in the comparison was larger and P^2 is the percentage of the sampling days when the second-row outcome in the comparison was larger.

stream across the fan-bank. As mentioned above, for the control ventilation fan-bank, there were many more sampling dates when its levels of yeast-and-mold were higher for the coil chamber than for the before-filter chamber (Table 2), and, as the marginal frequencies show, there were 12 sampling dates when there were more than 50 colonies in the coil chamber, but no such outcomes downstream in the before-filter chamber. In addition, the results suggest that there were higher levels for the before-filter chamber than for the after-filter chamber, although this second result is not statistically significant. On the UVGI side, the coil chamber had many fewer sampling days (i.e., 3% vs. 50%) with higher levels of yeast-and-mold than the before-filter chamber (Table 3), and there was also some weak evidence that the levels were higher for the before-filter chamber than for the after-filter chamber.

The results for total bacteria were similar to those for yeast-and-mold for the UVGI side, but not the control side (Table 3), where there were similar levels of total bacteria for the coil and before-filter chambers. In addition, there was strong evidence of higher levels of total bacteria for the before-filter chamber than for the downstream after-filter chamber ($p = 0.005$).

The results in Tables 4 and 5 are for the comparisons of the treatments for the same type of chamber. The only statistically significant results occur for the two coil chambers. When we compared the treatments for the coil chambers, there were many more sampling dates (i.e., 76% vs. 5%) when the levels of yeast-and-mold were higher for the control side than for UVGI side (Table 4) and there were also many more sampling dates (i.e., 87% vs. 5%) when the levels of total bacteria were higher for the control side than for the UVGI side (Table 5). There were higher levels of total bacteria for the UVGI-side after-filter chamber than for the control-side after-filter chamber (Table 5), but this result was not statistically significant (p-value = 0.09), and the marginal frequencies do not indicate any large differences.

Table 4. Marginal frequencies for the ordinal surface-sample outcomes for the yeast-and-mold, together with the Wilcoxon statistics for the between-treatment differences (control–UVGI), stratified by the type of chamber

Number of colonies: Yeast-and-mold	Between-treatment comparisons for yeast-and-mold								
	None	1–10	11–20	21–30	31–40	41–50	>50	Wilcoxon statistic[a]	(P^1 | P^2)[b]
(1) Coil control	6	15	4	0	0	1	12	4.41 ($p<0.001$)	(76% | 5%)
(2) Coil UVGI	34	2	1	0	0	0	1		
(1) Before-filter control	16	20	1	1	0	0	0	−1.10 ($p=0.27$)	(21% | 24%)
(2) Before-filter UVGI	18	13	2	0	2	0	3		
(1) After-Filter Control	30	4	2	2	0	0	0	−0.38 ($p=0.71$)	(16% | 24%)
(2) After-Filter UVGI	28	6	2	0	0	1	1		

[a]Wilcoxon signed-ranks statistic tests the hypothesis that the differences (control–UVGI) after matching have a median of zero.
[b]P^1 is the percentage of the sampling days when the outcome in the first-row in the comparison was larger and P^2 is the percentage of the sampling days when the second-row outcome in the comparison was larger.

Table 5. Marginal frequencies for the ordinal surface-sample outcomes for the total bacteria, together with the Wilcoxon statistics for the between-treatment differences (control-UVGI), stratisfied by the type of chamber

Number of colonies: Total bacteria	Between-treatment comparisons for total bacteria								
	None	1–10	11–20	21–30	31–40	41–50	>50	Wilcoxon statistic[a]	(P^1 | P^2)[b]
(1) Coil control	1	27	2	4	3	1	0	4.59 ($p<0.001$)	(87% | 5%)
(2) Coil UVGI	22	14	1	0	1	0	0		
(1) Before-filter control	1	24	2	2	7	0	2	−0.26 ($p=0.79$)	(26% | 29%)
(2) Before-filter UVGI	2	23	2	3	5	1	2		
(1) After-filter control	20	9	2	5	0	1	1	−1.71 ($p=0.09$)	(13% | 34%)
(2) After-Filter UVGI	16	9	3	4	3	0	3		

[a]Wilcoxon signed-ranks statistic tests the hypothesis that the differences (control–UVGI) after matching have a median of zero.
[b]P^1 is the percentage of the sampling days when the outcome in the first-row in the comparison was larger and P^2 is the percentage of the sampling days when the second-row outcome in the comparison was larger.

Discussion and Conclusions

The treatment for this study included two distinct modifications: the installations of the UVGI lamps and the new filter holders. However, only two side-by-side large and expensive filter banks were available for the experimental design, and there were insufficient resources to provide an experimental design (e.g., by adding more filter-banks or additional time intervals), which could have looked at the effects of these modifications separately. However, we have found no reason to believe that the new UVGI lamps would have an important impact on the total system efficiency. For instance, there was no indication that UV lights degraded filters in our laboratory studies (unpublished NIOSH data). On the other hand, it is possible that the increased efficiency provided by the new filter holders could have prevented the migration downstream of some microbiological colonies.

The data generally indicated a reduced efficiency for the submicrometer-sized particles compared to the larger sized particles, but the treated fan-bank had a smaller reduction in efficiency, overall. The results from the analysis of covariance showed that the control-side fan-bank was, on average, about 5.6% less efficient per year during the study, whereas the fan-bank with the new filter holders was only about 2.2% less efficient per year, and this difference of 3.4% per year is unlikely to be due to chance alone (p-value = 0.01). Therefore, the incorporation of the new filter holders appears to have had a positive impact on total system efficiency, which includes filter efficiency and other factors (such as the fact that V-panel filter media is fragile and can be easily damaged). Since the V-panel filters are mechanical, they should become more efficient with time as they load. Therefore, a reduction in efficiency over time could be explained by the seal between the filters and the frame becoming looser due to vibration, etc.

The previous 3-year NIOSH study by Moyer et al. [15] concluded that the V-panel filters could have been left in the ventilation system longer than three years, because there were no substantial increases in filter bank resistance. The results were similar for this 22-month study, and the use of the new filter holders should not affect the filter change-out schedule. When the filter pressure drop was measured directly across the filter after installation, this indicated a pressure difference of about 25 Pa higher for the side with the new filter holders, indicating a tighter fit, which remained constant as the filters loaded.

In summary, a sampling procedure, which used matched OPCs, proved effective in monitoring the total system efficiency for the particle size range from 0.3 to 3.0 μm. The particle detection method used in this study allows for the routine evaluation of AHUs to verify that they are functioning properly. Total system efficiency includes filter efficiency, gasket material integrity, weld integrity, and filter rack integrity. They are all important factors to consider in total system integrity. The results of this study indicate that the addition of a simple mechanical filter holder can improve the long-term total system efficiency of a ventilation filter bank.

The most striking finding for the surface sampling was that the level of viable bacteria in the coil chamber was reduced by the installed UVGI unit. It was also discovered that the humidification system, which uses clean steam, was contaminated and introduced viable bacteria into the system just before the final filters. Although the V-bank filters removed the bacteria introduced, this suggests that the location of the UVGI system after the final filters might result in improved indoor environmental air quality. However, the reason for locating the UVGI system in the coil chamber was to prevent the growth of bacteria on the coils, which the study did confirm.

Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of commercial product or trade name does not constitute endorsement by the Centers for Disease Control and Prevention or the National Institute for Occupational Safety and Health.

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