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Indoor air quality (IAQ) in a naval ship after refit program: a time variation analysis

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Abstract. Refurbishments of the ship's external and internal structures are the main scopes of a refit program. These activities may affect the indoor air quality (IAQ) inside ships and increase the indoor air pollutants (IAP) concentrations onboard. Therefore, continuous IAQ monitoring is needed to determine IAP exposure to the ship's crew. This study evaluates the changes in IAQ conditions inside a naval ship over a two-time interval to determine the effect of compliance with the recommended engineering control measures proposed in the first assessment. Following the standard of the Industry Code of Practice on Indoor Air Quality 2010 (ICOP on IAQ 2010), seven IAQ parameters (temperature, relative humidity (RH), carbon dioxide (CO_2), respirable particulates/particulate matter (PM_{10}), total volatile organic compounds (TVOC), bacterial count, and fungal count) were measured in two assessment phases. The first phase was conducted after the ship completed the refit program, and the second phase began three months later, following the execution of the recommended engineering control measures. According to the findings of this study, all IAQ parameters improved when compared to the first phase assessment. However, some of the readings were still non-compliance with the standards of ICOP on IAQ 2010. In conclusion, the ship's IAQ parameters were improved following the recommended engineering control measures, although more enhanced approaches were required to ensure all parameters complied with the ICOP on IAQ 2010.

Keywords: Indoor air quality (IAQ); Naval ship; Engineering control; Ship refit program.

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1. Introduction

Air pollutants may cause adverse effects on the environment and health. The adverse effects of indoor air pollutants (IAP) can be more critical than those effects caused by the outside air pollutants [1]. Previous studies have proved that human exposure to the IAP might be two to multiple times, in terms of the numerous harmful IAP concentrations, higher than the outside air pollutants [2]. On the other hand, low IAP concentrations indicate good indoor air quality (IAQ), leading to a positive impact on the health and productivity of the occupants [3].

Moreover, IAQ is an essential component of indoor environmental quality (IEQ) and plays an important role in ensuring a healthy and safe workplace for the workers and occupants, including those crews in ships. Poor IAQ in onboard ships may cause discomfort and health risks to the crews besides causing equipment breakdown [4]. Ships undergo several refitting programs, with major external and internal refurbishment throughout their service life [5]. Activities such as repainting, adding new furnishings, major component overhauls, and redesigning the interior spaces are among the work scopes of the refitting program [6]. These activities may affect the ship's IAQ and increase the concentrations of IAP onboard. Previously published studies are limited to local surveys with localized climate environments and specific ships condition. A study by Österman et al. (2016) explained the effects of IAQ chemical parameters on passenger ferries in temperate climate countries that specifically operate in the same environment and will not adequately represent other vessels [7]. Meanwhile, few authors have been able to draw on any systematic research into this area of studies that conduct specific IAQ research and compare it to local IAQ guidelines [8][9]. Nonetheless, little is known about the IAQ onboard ships in various conditions, and there is an urgent need to address the safety and health-related problems caused by poor IAQ onboard ships. Thus, this study was done to evaluate the changes in IAQ conditions inside a naval ship over a two-time interval to determine the effect of adhering to the recommended engineering control measures proposed in the first assessment.

2. Methodology

2.1 Sampling sites and assessment phases

The first assessment phase was conducted at the end of December 2020, and the second at the beginning of March 2021. During the first assessment, the ship had recently undergone a refitting program, which included repainting, redesigning the interior spaces, installing new furnishings, and changing other major and minor components. At the end of the assessment, several recommendations and engineering control measures were recommended to the crews to improve the IAQ inside the ship. The second assessment phase was conducted in continuity after three months with the execution of the suggestions made in the previous assessment. The sampling points involved the ship's ten compartments, which comprise accommodation and working spaces. Both assessment phases were conducted when the ship was alongside the jetty. The summary of the IAQ assessment's flow is shown in Figure 1:

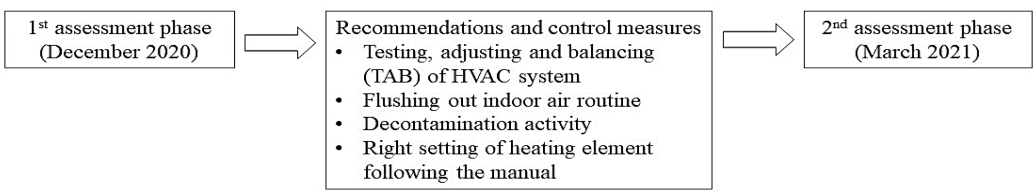

Figure 1. The flow of IAQ assessments within two-time intervals and recommendations suggested from the first sampling phase to improve IAQ onboard

2.2 Sampling campaign and instrumentation

The IAQ parameters inside the ship compartments were measured following the Industry Code of Practice on Indoor Air Quality 2010 (ICOP on IAQ 2010) by the Department of Occupational Safety and Health [10]. Prior to the sampling activity, a walkthrough inspection was conducted, including the semi-formal meeting, walkthrough observation and occupant's interview and questionnaire administration. This study measured physical and chemical parameters such as temperature (ºC), relative humidity (RH), and carbon dioxide (CO_2) which were measured using the TSI VelociCalc 9565. Total volatile organic compounds (TVOC) concentrations were measured using the RAE Systems ppbRAE, and respirable particulates/particulate matter (PM_{10}) concentrations were measured using the Kanomax Digital Dust Monitor Model 3443. The eight-hour sampling period was divided into four slots, with a direct reading taken for five minutes intervals within 30 minutes period of sampling duration for each slot.

Besides that, the bacterial and fungal counts were also assessed as biological parameters for the IAQ. The airborne bacteria and fungi were sampled using the PBI International SAS Super IAQ on trypticase soy agar (TSA) for bacteria and malt extract agar (MEA) for fungi. The sampling was conducted in triplicate for a minute at a flow rate of 100 L/m following the National Institute of Safety and Health (NIOSH) Manual Analytical Method (NMAM) 0800 [11].

2.3 Data analysis

The average total bacterial and fungal count was determined by calculating the colony-forming unit per cubic meter (CFU/m³) from the previous sampling culture media using the formula (1).

$$\text{Total bacterial or fungal count, CFU/m}^3 = \frac{Total\ count\ X\ 1000}{Volume\ of\ sampled\ air} \quad (1)$$

The 8-hour total weighted average (TWA_8) of the IAQ parameters was calculated to estimate the average readings of the 8-hour exposure in the compartments. The TWA_8 readings were then compared to the acceptable limit from the ICOP on IAQ 2010. Based on the normality test on the sample data, a non-parametric Wilcoxon signed-rank test was used to analyze the comparison of TWA_8 readings for physical and chemical parameters of each ship's compartment between the two phases of assessment.

3. Results and discussions

3.1 Physical parameters

Data in Table 1 shows that the temperature readings during the second assessment phase were significantly reduced in all compartments except electrical room 2 (Z = -0.715, P = 0.475). However, the temperature drop from the first phase is too low and falls below the standard set by the ICOP on IAQ 2010 (23–26°C). This result can be explained by the fully functional heating, ventilation, and air conditioning (HVAC) system and execution of the testing, adjusting, and balancing (TAB) done by the engineering department as recommended in the first phase assessment. The RH readings in all sampling points show a positive change from the previous assessment as the temperatures drop. As shown in Table 1, all RH levels in the compartments were within the standard's acceptable limit. These factors could explain the relatively good correlation between temperature and RH [12]. In addition, the heating element was set according to the manufacturer's recommendations in order to control the humidity onboard, and the heating setting was adjusted after the first assessment.

Table 1. TWA_8 reading for physical parameters.

Sampling point	Temperature, °C				Relative humidity, %			
	1st phase	2nd phase	Z score	p value	1st phase	2nd phase	Z score	*P*-value
Galley	29.1 ± 0.2[a]	24.8 ± 1.1	-4.293[b]	< 0.001[c]	72.3 ± 4.0[a]	55.0 ± 2.7	-4.286[b]	< 0.001[c]
Common room 1	26.7 ± 0.3[a]	19.3 ± 0.5[a]	-4.291[b]	< 0.001[c]	75.2 ± 2.5[a]	68.2 ± 2.1	-4.287[b]	< 0.001[c]
Officer's cabin 1	25.6 ± 0.6	20.2 ± 0.8[a]	-4.291[b]	< 0.001[c]	73.5 ± 3.8[a]	61.3 ± 1.5	-4.287[b]	< 0.001[c]
Common room 2	26.6 ± 0.3[a]	20.0 ± 0.4[a]	-4.294[b]	< 0.001[c]	75.2 ± 2.2[a]	65.4 ± 1.2	-4.286[b]	< 0.001[c]
Officer's cabin 2	25.6 ± 0.6	22.6 ± 0.1[a]	-4.291[b]	< 0.001[c]	66.0 ± 4.1	68.3 ± 3.3	-2.029	0.042[c]
Gym	29.3 ± 0.9[a]	27.1 ± 1.4[a]	-4.305[b]	< 0.001[c]	72.0 ± 4.2[a]	57.1 ± 5.2	-4.286[b]	< 0.001[c]
Electrical room 1	25.0 ± 1.5	22.7 ± 0.6[a]	-3.987[b]	< 0.001[c]	67.1 ± 7.0	64.0 ± 3.3	-1.958[b]	0.05
Electrical room 2	19.5 ± 2.3[a]	21.3 ± 10.4[a]	-0.715	0.475	69.1 ± 3.4	64.2 ± 4.5	-2.972[b]	0.003[c]
Officer's cabin 3	23.9 ± 0.9	21.0 ± 1.0[a]	-4.299[b]	< 0.001[c]	67.9 ± 2.8	66.4 ± 3.0	-2.788[b]	0.005[c]
Bridge	25.7 ± 0.6	22.1 ± 1.5[a]	-4.289[b]	< 0.001[c]	70.2 ± 13.3[a]	64.4 ± 3.1	-2.029[b]	0.043[c]

[a] Noncompliance reading with ICOP on IAQ 2010
[b] 1st phase assessment > 2nd phase assessment
[c] Significant different at $P < 0.05$

Table 2. TWA_8 reading for chemical parameters

Sampling point	Carbon dioxide (CO_2), ppm				Total volatile organic compound (TVOC), ppm				Particulate matter (PM_{10}), mg/m^3			
	1st phase	2nd phase	Z score	*P*-value	1st phase	2nd phase	Z score	*P*-value	1st phase	2nd phase	Z score	*P*-value
Galley	890 ± 99	754 ± 36	-3.743[b]	< 0.001[c]	19.30 ± 10.33[a]	4.09 ± 0.81[a]	-4.286[b]	< 0.001[c]	0.108 ± 0.032	0.007 ± 0.010	-4.258[b]	< 0.001[c]
Common room 1	1092 ± 117[a]	761 ± 97	-4.286[b]	< 0.001[c]	36.27 ± 24.45[a]	4.13 ± 0.29[a]	-4.286[b]	< 0.001[c]	0.072 ± 0.024	0.002 ± 0.002	-4.287[b]	< 0.001[c]
Officer's cabin 1	1229 ± 90[a]	913 ± 145	-4.143[b]	< 0.001[c]	12.76 ± 2.9[a]	2.96 ± 0.18	-4.286[b]	< 0.001[c]	0.040 ± 0.018	0.004 ± 0.002	-4.287[b]	< 0.001[c]
Common room 2	1126 ± 83[a]	816 ± 81	-4.286[b]	< 0.001[c]	16.37 ± 3.96[a]	4.27 ± 0.26[a]	-4.286[b]	< 0.001[c]	0.154 ± 0.230[a]	0.003 ± 0.007	-4.287[b]	< 0.001[c]
Officer's cabin 2	1247 ± 328[a]	713 ± 93	-4.287[b]	< 0.001[c]	8.70 ± 2.13[a]	3.27 ± 0.14[a]	-4.286[b]	< 0.001[c]	0.314 ± 0.306[a]	0.002 ± 0.001	-4.288[b]	< 0.001[c]
Gym	911 ± 379	781 ± 58	-1.571[b]	0.116	5.03 ± 4.13[a]	3.50 ± 0.37[a]	-1.209[b]	0.304	0.235 ± 0.200[a]	0.004 ± 0.001	-4.287[b]	< 0.001[c]
Electrical room 1	2040 ± 404[a]	977 ± 172	-4.286[b]	< 0.001[c]	14.19 ± 1.92[a]	4.02 ± 0.39[a]	-4.286[b]	< 0.001[c]	0.035 ± 0.037	0.005 ± 0.005	-4.289[b]	< 0.001[c]
Electrical room 2	1008 ± 294[a]	960 ± 223	-1.243[b]	0.214	4.93 ± 2.02[a]	3.20 ± 0.16[a]	-2.4[b]	0.016[c]	0.022 ± 0.045	0.045 ± 0.003	-2.645	0.008[c]
Officer's cabin 3	1213 ± 203[a]	987 ± 139	-2.286[b]	0.022[c]	5.14 ± 1.42[a]	3.42 ± 0.26[a]	-4.256[b]	< 0.001[c]	0.022 ± 0.006	0.016 ± 0.008	-3.304[b]	0.001[c]
Bridge	1265 ± 169[a]	828 ± 156	-4.172[b]	< 0.001[c]	1.47 ± 0.56[a]	1.79 ± 0.34	-1.743	0.081	0.063 ± 0.146	0.004 ± 0.002	-4.287[b]	< 0.001[c]

[a] Noncompliance readings with ICOP on IAQ 2010
[b] 1st phase assessment > 2nd phase assessment
[c] Significant different at $P < 0.05$

3.2 Chemical parameters

In the case of chemical parameters, a Wilcoxon signed-rank test in Table 2 shows that the difference in CO_2 concentration between the first and second assessments was statistically significant in all compartments except the gym ($Z = -1.571$, $P = 0.116$) and electrical room 2 ($Z = -1.243$, $P = 0.214$). All compartments improved their ventilation by demonstrating a decreasing CO_2 concentration in the second assessment phase and falling below the acceptable limit set by the ICOP on IAQ standard (< 1000 ppm). The data from the gym and electrical room 2 must be interpreted with caution because the source of the CO_2 during sampling could be human respiration [13]. Overall, the decreasing CO_2 trend could be attributed to the engineering control measures activities conducted by ship crews. To reduce the CO_2 concentration, fresh air must be introduced into the compartment, causing the concentrated IAP to dilute away. According to Fang et al. (2019), forced ventilation is typically used in tunnel construction because it is a cost-effective method to provide large amounts of fresh air. A similar outcome in this study was found to be significant when compared to previous findings [14].

Furthermore, Table 2 shows a statistical difference in TVOC concentration between the first and second assessment in all compartments except the gym ($Z = -1.209$, $P = 0.304$) and the bridge ($Z = -1.743$, $P = 0.081$). Apart from the bridge, all readings showed a decrease in TVOC concentration during the second assessment. All compartments recorded exceeded the value of TVOC during the first assessment due to the major and minor refurbishment activity of the ship, as expected from the refitting program. This is supported by the idea that new furniture, painting, and surrounding materials such as carpets cause TVOC emissions [15]. Despite some inconsistency, the concentrations of TVOC were interestingly reduced from the initial IAQ assessment. Presumably, it was due to routinely flush out activity taken by the crew as recommended in the first assessment. The three months of an activity practice, however, was insufficient to dilute the TVOC emission, as most of the compartments still recorded an exceeding concentration from the acceptable limit as prescribed in the ICOP on IAQ 2010.

The statistical analysis results for PM_{10}, similar to other parameters, show a significant difference in concentration between the first and second phase assessments in all compartments. All readings showed positive feedback from the engineering control measures taken, which routinely flushes out the indoor air. The ship's refurbishment activity indeed increased the concentration of PM_{10}, as seen in the common room 2, officer's cabin 2, and gym during the first assessment. According to studies, renovation and refurbishment activities increase the concentration of PM_{10} in the surrounding air [16]. Since PM_{10} can adversely affect the health of the ship's crew, it can be avoided further by employing the individual prevention technique of wearing personal protective equipment (PPE) during the activity. A good practice of wearing appropriate PPE while working in areas with high concentrations of PM_{10} can reduce the risk of human inhalation of PM_{10}. This corroborates the ideas of Shakya et al. (2017) who investigated the efficacy of facemasks in reducing particulate matter exposure [17].

3.3 Biological parameters

Most compartments reported a decrease in airborne bacterial and fungal count from the first phase assessment to the second assessment, except for fungal count in the bridge. Figures 2 and 3 show the different results for the bioaerosol count between the two phases and demonstrate the efficiency of the decontamination activity and the right setting of humidity controller on the HVAC system as practiced by the crew, by referring to the manufacturer's manual. The refurbishment activity during the refitting program had caused the resuspension of the microorganisms in the air and explained the exceeding CFU for the bacteria and fungi during the first assessment. Mousavi et al. (2020) found that renovation and refurbishment activities increase the resuspension of PM as well as microorganisms since PM can be a potential carrier for the microorganisms [18]. High CFU count of microbial is related to the high concentration of PM [19][20].

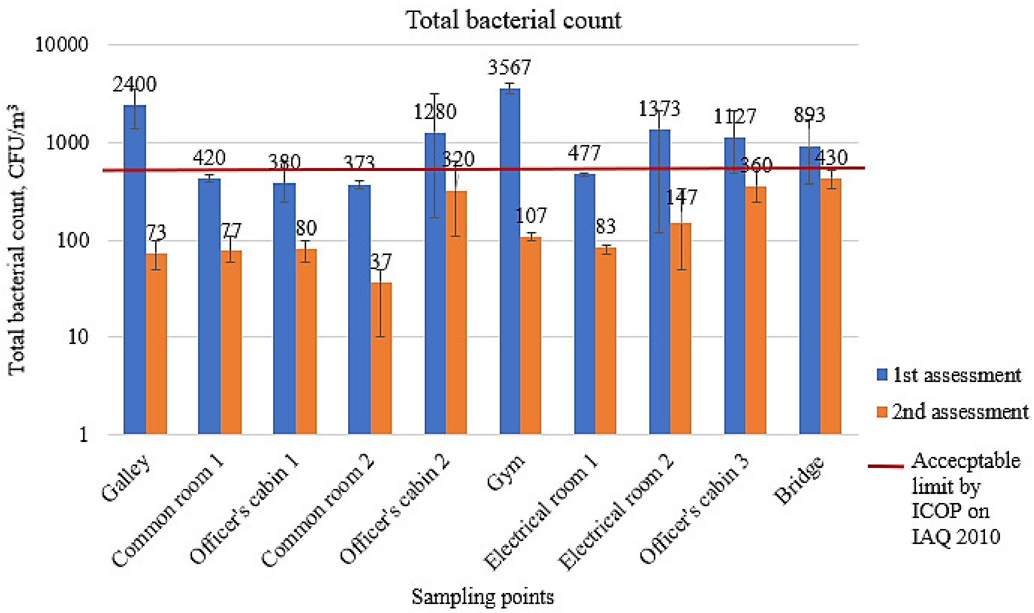

Figure 2. Total bacterial count during assessment phases

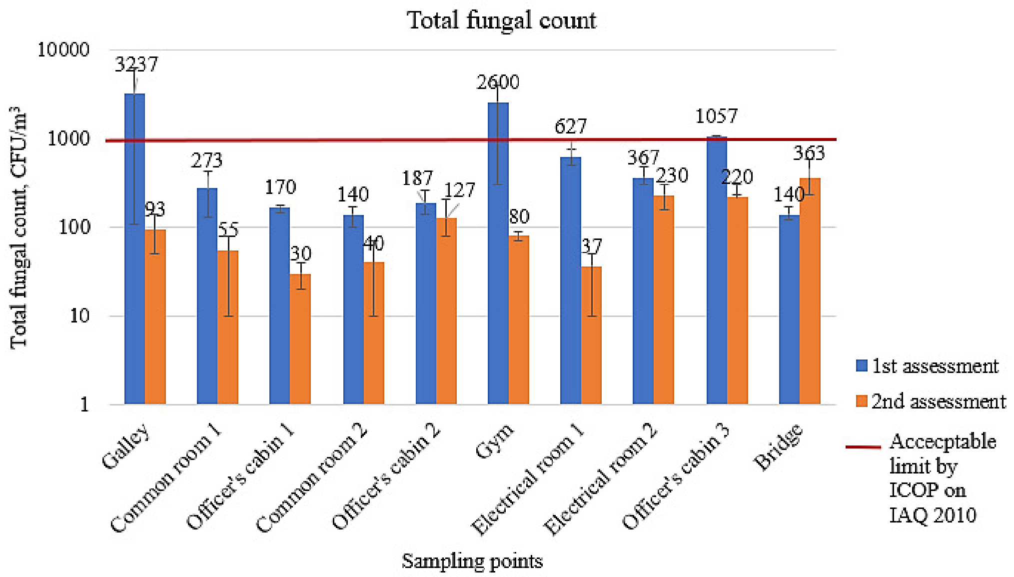

Figure 3. Total fungal count during assessment phases

4. Conclusions

Overall, this study found that the IAQ parameters improved after a three-month interval of assessment and execution of recommended control measures from the first assessment. The findings demonstrate the effectiveness of activities such as TAB of HVAC system, routinely flushing out the indoor air and decontamination activities, as well as the proper setting of heating elements to control humidity, in reducing IAP concentrations and the dilution process over the months. Even though this study was based on limited samples on a ship, the findings proved that proper maintenance and a high level of awareness of IAQ among the crews onboard would sustain a healthier environment inside the ship. Hence, further studies regarding the IAQ onboard ships would be worthwhile.

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