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Journal of Ship and Marine Structures

Journal homepage:
https://karyailham.com.my/index.php/jsms/index
ISSN: 3036-0137

Indoor Air Quality (IAQ) Mitigation Strategies for Marine Transportation: A Call for Ship IAQ Guidelines Development

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ARTICLE INFO

Article history:
Received 2 December 2024
Received in revised form 17 January 2025
Accepted 25 February 2025
Available online 30 March 2025

Keywords:

Indoor air quality (IAQ); ship; guidelines; mitigation strategy; indoor air pollutants (IAP)

ABSTRACT

Indoor air quality (IAQ) greatly influences human health, comfort, and life productivity. Ships with confined spaces and limited ventilation demand more attention for a good IAQ due to the accumulation of indoor air pollutants (IAP) and the long time spent onboard. Nevertheless, studies have found ships recorded noncompliance with IAQ parameters to available standards, especially after shipbuilding and refurbishment programs. The lack of appropriate mitigation strategies to reduce the IAP onboard has contributed to this issue, as there are no available IAQ guidelines designed explicitly for ships. Hence, to highlight the importance of having ship IAQ guidelines, this study evaluated the effectiveness of building IAQ mitigation strategies practised in a ship after a refit program. The effectiveness was evaluated by conducting IAQ assessments in two ship situations: ship-not-practising IAQ mitigation strategies and ship-after-practising IAQ mitigation strategies. The mitigation strategies involved open fresh air intake and overnight air flushing, which are the usual practices of IAQ mitigation strategies in buildings. The compliance of IAQ parameters was compared between the two situations, and data were statistically analysed using the Wilcoxon Signed Ranks test. Results showed a positive increment from 57.8% to 68.8% of IAQ parameters compliance after the ship practised the mitigation strategies. However, this study observed only two parameters showing significant changes in the increment, which were air movement (AM) and total volatile organic compounds (TVOC). In comparison, the other six parameters gave no significant changes between the situations. This study concluded that the IAQ mitigation strategies adapted from building practice managed to improve the IAQ onboard. However, more enhanced mitigation strategies needed to be implemented to provide better dilution of IAP and sufficient ventilation onboard. Therefore, this study emphasised the importance of having ship IAQ guidelines in order to advise effective IAQ mitigation strategies and good IAQ practices for ship setting. This will lead to an improvement in crew habitability and equipment performance onboard.

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https://doi.org/10.37934/jsms.8.1.1118

1. Introduction

Indoor air quality (IAQ) in marine transportation receives a lack of attention despite the importance of having a safe and healthy indoor environment for the crews and passengers. Ship with confined and enclosed spaces provides limited ventilation and potential accumulation of indoor air pollutants (IAP). The emissions of the IAP onboard cannot be negligible due to various possible sources, for example, fuel burning, infiltration of exhaust smoke, off-gassing process from ship materials, and crews' activities such as cooking, smoking, and housekeeping. These would expose the crews and passengers to the adverse effects of the IAP onboard. Based on Wang *et al.,* [1], the vaporisation of paint and coating emits concentrations of toluene, octane, tetrachlorobenzene, and undecane, which are toxic to the crew. Short-time exposure to high concentrations of these IAP leads to acute health effects in humans, such as weakness, fatigue, confusion, nausea, and irritation to the throat, eyes, and nose [2,3]. The off-gassing process of furniture and furnishings also emits formaldehyde, which is classified as a human carcinogen (Group 1) by the International Agency for Research on Cancer [4]. In addition, there are also associations of chemical exposure onboard to dermatologist disorders such as eczema, dermatitis, and allergic reactions among the crew [5]. The highest incidence of dermatologic and respiratory illness also was reported occurred among merchant seafarers due to chemical exposure during onboard [6]. The IAP exposure onboard raises health concerns for crews and passengers, who spend extended periods onboard, thus inadvertently risking their lives.

Alleviating the potential health risks among the ship crew demands extensive IAQ standards or guidelines, specifically for ships in order to monitor and mitigate the detrimental effects of the IAP. The absence of IAP standard limits for ship setting is another challenge for ship management to monitor the risk exposure. The proposition strategy of adopting the building's IAP standard limits might be unsuitable for the ship setting due to the different exposure duration of the crew onboard. However, this is among the appropriate strategies even though the authors acknowledge the strategy is for building settings. The limitation to reducing IAP onboard is because the current standards or guidelines related to IAQ and ships issued by international standards and ship classification societies are regulated separately and do not comprehensively cover good practices of IAQ and mitigation measures that can be employed in the ship setting.

Studies found that emissions of high concentrations of IAP onboard, especially after shipbuilding and refurbishment programs urge ample and effective mitigation strategies to reduce the IAP accumulation [7-10]. Mitigation strategies applied in buildings, such as performing air flushing is a common practice after renovation activities before the habitation of occupants. In spite of that, there are required techniques and methods to perform the efficient air flushing strategy. As mentioned by Lestinen *et al.,* [11], there are variance factors affecting the effectiveness of the strategy, including the flushing period, amount of flush air volume, room size, occupancy, and others. Lee *et al.,* [12] also add that those key factors also affect the concentration reduction of different types of IAP. Due to different settings, ships might require different approaches to reduce the IAP onboard. Therefore, this study is conducted to evaluate the effectiveness of reducing the IAP concentrations by practicing building mitigation strategies in a ship after a refit program, which are overnight air flushing and open fresh air intake louver.

2. Methodology

2.1 Sampling Strategy

IAQ assessments were carried out in two situations of an alongside ship after a refit program. The first IAQ assessment was conducted on the ship without practicing mitigation strategies to reduce the IAP onboard post the refit program. Meanwhile, the second IAQ assessment was conducted after the ship performed an overnight air flushing and practiced open fresh air intake as the mitigation strategy. The assessments involved the IAQ parameters measurement using calibrated instruments, which included temperature (Temp), relative humidity (RH), air movement (AM), carbon monoxide (CO), formaldehyde (CH_2O), total volatile organic compounds (TVOC), particulate matter (PM_{10}) and carbon dioxide (CO_2). Eight ship compartments were chosen, representing the crew's workplace and accommodation. The IAQ assessments adapted the protocols in the Industry Code of Practice on Indoor Air Quality 2010 (ICOP IAQ 2010) established by the Department of Safety and Health [13] for workplaces in the buildings. Intermittent sampling was employed for 15 minutes of measuring for four-time slots in eight hours of the assessments. The sampling strategy was chosen due to the limitation of sampling time.

2.2 Data analysis

The total weighted average of eight hours (TWA8) of the parameter readings was calculated and compared to the ICOP IAQ 2010 acceptable limit for parameter compliance. The percentage of compliances for the two situations was calculated and compared to evaluate the effectiveness of practicing mitigation measures to reduce the IAP. In addition, the effectiveness also was analyzed statistically using the Wilcoxon Signed Rank test.

3. Results

By adapting building practices, the mitigation strategies in this study proposed open fresh air intake and overnight flushing to dilute the IAP and allow better ventilation in the ship. The effectiveness of practicing mitigation strategies on the ship was evaluated based on the percentage of compliances, and statistical analysis for the IAQ parameters resulted in the two situations of IAQ assessments.

3.1 IAQ Parameters Compliance

Table 1 shows the results of the assessments and the percentage of compliance to the acceptable limit prescribed in the ICOP IAQ 2010. Even though the guideline was regulated for building settings, this study had to refer to this guideline due to the lack of IAQ guidelines for the ship. Based on Table 1, the IAQ assessment during ship practicing mitigation strategies recorded a higher percentage of parameter compliances compared to not-practicing mitigation strategies. The increment percentage of compliances from 57.8% to 68.8% showed the improvement of the IAQ in the ship study. Therefore, based on this case study, the practices of open fresh air intake and overnight flushing in the ship after a refit program could provide better ventilation and dilution of IAP onboard.

Table 1
Results of IAQ Assessments for Ship Not-Practising Mitigation Strategies (NP) And Practising Mitigation Strategies Situations (P)

Compartment		Temp (°C)		RH (%)		AM (m/s)		CO (ppm)		CH_2O (ppm)		TVOC (ppm)		PM_{10} (mg/m^3)		CO_2 (ppm)	
		NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P	NP	P
P1 Fwd mess		28.3	28.8	62.3	58.1	0.13	0.16	0.6	0.0	0.260	0.278	3.234	1.326	0.009	0.005	1406	1247
P2 CO cabin		23.5	22.7	62.9	69.1	0.06	0.25	0.0	0.0	0.133	0.137	6.476	4.350	0.007	0.026	940	1045
P3 XO cabin		24.4	23.3	66.6	69.4	0.06	0.10	0.0	0.0	0.148	0.291	6.685	3.525	0.013	0.011	875	981
P4 Aft mess		24.3	24.4	60.5	64.3	0.16	0.20	0.0	0.0	0.157	0.120	2.361	0.728	0.006	0.006	1066	690
P5 Wardroom		25.8	26.5	60.4	60.6	0.07	0.14	0.0	0.0	0.171	0.071	4.298	1.381	0.007	0.007	976	859
P6 Office		25.8	23.0	63.2	68.7	0.10	0.34	0.0	0.0	0.129	0.113	1.450	1.915	0.007	0.007	1135	1300
P7 Bridge		25.2	25.8	57.0	61.6	0.06	0.22	0.4	0.0	0.173	0.138	5.143	0.935	0.006	0.006	1228	865
P8 MCR		21.2	26.1	58.5	53.7	0.07	0.03	0.0	0.0	0.102	0.128	4.867	3.519	0.014	0.006	910	829
ICOP IAQ 2010 acceptable limit		23-26		40-70		0.15-0.50		10		0.10		3.000		0.150		1000	
Percentage compliance	NP	57.8%															
	P	68.8%															

Note: Red text shows noncompliance reading of parameter to the acceptable limit as prescribed in ICOP IAQ 2010

Nevertheless, as looking at Table 1, only half of the IAQ parameters (AM, CH_2O, TVOC, and CO_2) recorded a higher number of compartments that complied with the ICOP IAQ 2010 acceptable limit. Meanwhile, the other half of the parameters, which were RH, CO, and PM_{10} showed a similar number of complied compartments, regardless of practicing or not-practicing mitigation strategies. Adversely, this study also recorded more complied compartments when not practicing mitigation strategies for temperature parameter. The lower temperature recorded was due to the recirculated air practiced during the day of assessment. These results revealed that the mitigation strategies did improve the IAQ onboard, but were not effective for some parameters.

3.2 Statistical Analysis

The findings of this case study were supported by the statistical analysis, as shown in Table 2. The Wilcoxon Signed Rank test was applied to observe the notable positive result for the mitigation strategies practiced.

Table 2
Results Of the Wilcoxon Signed Rank Test for Practising Mitigation Strategies Situations (P) and Not-Practising Mitigation Strategies (NP)

Parameters	P - NP	
	z-score[a]	p-value
Temp, °C	0.000	1.000
RH, %	1.120	0.263
AM, m/s[b]	2.111	0.035
CO, ppm	-1.342	0.180
CH_2O, ppm	-0.280	0.779
TVOC, ppm[b]	-2.380	0.017
PM_{10}, mg/m^3	-0.943	0.345
CO_2, ppm	-0.980	0.327

Notes:
[a] z-statistic is based on positive sum ranks (P > NP), negative sum ranks (P < NP) and equal sum ranks (P = NP)
[b] shows significant differences of Wilcoxon Signed Rank test at 95% of the confidence interval, when p < 0.05, z < -1.96 or >1.96

Based on the Wilcoxon Signed Rank test, only AM and TVOC parameters showed significant efficiency of the strategies in the ship compartments ($p = 0.035$ and $p = 0.017$, respectively). Even though other IAP recorded negative sum ranks (P < NP) when practicing the mitigation strategies (CO: -1.342, CH_2O: z = -0.280, PM_{10}: z = -0.943, and CO_2: z = -0.98), the reduction of the IAP concentrations was not significant enough to for the effective mitigation strategies.

4. Discussion

It is good to highlight that ship after refit has a high potential to have accumulated IAP, which is derived from the recent renovation and refurbishment activities. At some moments, the IAP concentrations after the ship refit program could be higher than during ship sailing [10]. A study by Lin *et al.,* [14] has verified the concentrations of IAP in newly renovated houses using prediction modeling may depict a similar situation after a refit program. Among the common activities involved in the ship refit program were painting, flooring, and furnishing setup, which contributed to the high emission of CH_2O and TVOC concentrations onboard. This study anticipated that without practicing

IAQ mitigation strategies, the ship recorded high and exceeded CH_2O and TVOC concentrations in almost all compartments in this study, as shown in Table 1. A study done by Wagdi *et al.,* [15] also supported the finding by discovering higher CH_2O and TVOC concentrations in a new building compared to an old building in their study. In addition, Gabriel *et al.,* [16] also reported on the higher CH_2O in newly refurbished rooms based on their study. Besides refurbishment activity, it should be noted that the concentrations of CH_2O and TVOC could also be derived from fuel vaporization and exhaust gases, potentially infiltrating the ship [1]. Not only that, the CO and PM_{10} concentrations would increase with the presence of a combustion process onboard, for example from cooking and fuel burning. Therefore, in order to ensure low and safe concentrations of IAP onboard, the ship IAQ guidelines should provide IAQ good practices and mitigation measures, not only after shipbuilding and refurbishment programs but also during the operation of the ship.

The overnight flushing performed on the ship was intended to flush out the IAP onboard by supplying volumes of outdoor air and exhausting the indoor air. This practice is usually effective as a mitigation strategy in a building setting. A study by Lee *et al.,* [12] managed to reduce about 41% and 61% of CH_2O and TVOC concentrations in new buildings after nine days of air flushing. The study also observed a higher efficiency for TVOC reduction compared to CH_2O. A study by Lestinen *et al.,* [11] also managed to reduce PM_{10} concentration after 30 minutes of flushing in a workspace area.

Performing open fresh air intake on the ship as shown in Figure 1 allowed more volume of outdoor air to be introduced inside the ship. The intention of this strategy was to increase the ventilation rate and dilution of the IAP onboard.

Fig. 1. Open fresh air intake

The open fresh air intake provided more airflow onboard, thus resulting in a significant change of AM in the ship compartments ($z = 2.111$, $p = 0.035$). Along with that, supplying fresh air to the indoor area would introduce the outside humidity and temperature into the indoor environment [17]. However, the ship HVAC managed to control the influence, based on the findings of the equally positive and negative sum ranks (P = NP) for temperature and the non-significant higher for RH ($z = 1.120$, $p = 0.263$). In addition, supplying the outdoor air through this practice was expected to dilute and reduce the CO_2 concentration in all compartments. However, contrast results were recorded in the P2 CO cabin, P3 XO cabin, and P6 Office, as shown in Table 1. This study assumed the influence of occupancy factors on this finding. According to Zhang *et al.,* [3], the main source of CO_2 indoors was derived from human exhalation. Considering the limited area with high occupancy of these compartments might explain the inefficiency of CO_2 concentration dilution at the compartments.

5. Conclusion

Based on the case study, the proposed IAQ mitigation strategies managed to improve the IAQ in the ship. However, enhanced strategies need to be applied to provide more efficient concentration reduction onboard. The different factors of ship settings, including the IAP emission sources and ventilation design, might contribute to the effectiveness of the building's mitigation practices. In conclusion, this study emphasized the need for having IAQ guidelines specialized for ships in order to outline good IAQ practices and IAP reduction strategies. The ship IAQ guidelines should cover the good IAQ practices to be employed at the early design phase and implemented both after the refit program and during the ship's operation to ensure the safety and health of the crew and their habitability throughout the duration onboard. In addition, considering the continuous exposure of the crew and localized IAP emitted onboard, the ship demands its own IAP standard limit to ensure the crew are exposed to low and safe IAP concentration. The established IAP standard limit specialized for ship setting would help the management to monitor the IAP concentration onboard, thus contributing to the risk control onboard. A good IAQ is not only critical for crews' health but also for their work productivity and morale.

Acknowledgement
The authors extend their gratitude to the Chief Engineer of the Royal Malaysian Navy, Rear Admiral Datuk Ir. Ts. Mohd Shaiful Adli Chung bin Abdullah and Rear Admiral Farizal bin Myeor, Naval Area 1 Fleet Commander, Royal Malaysian Navy Naval Base, Pahang, for their invaluable assistance, which contributed significantly to the success of this study. The authors would also like to express our sincere gratitude to First Admiral Ir. Ts. Franklin Jeyasekhar Joseph, First Admiral Ts. Rozaide bin Megat Othman and First Admiral Ts. Shaiful Bahri bin Baharuddin for the continuous support and professional advice on this research.

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