ASM Sc. J., 18, 2023

https://doi.org/10.32802/asmscj.2023.1015

Concentration of Indoor Air Chemical Parameters at Different Ship Conditions and Engine Sequences

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Good indoor air quality (IAQ) is crucial for navy crew due to longer periods onboard, especially during pandemic. Increased frequency of the ship's operations is required to prevent trespassing and illegal border crossings. This study aims to determine and compare the indoor air chemical parameters; carbon dioxide (CO_2), carbon monoxide (CO), and total volatile organic compounds (TVOC) at different ship conditions (alongside and sailing) and engine sequences (idling, cruising, full ahead and slowing down). The parameters were measured in four compartments, following the Industry Code of Practice on Indoor Air Quality 2010 (ICOP IAQ 2010). At different ship conditions, there were significant differences of indoor air chemical parameters in the common room, electrical room, and accommodation area 2. However, no trend of higher or lower concentrations was observed between the conditions due to ship operation, human activities, and occupancy. The engine sequences affect the indoor air chemical parameters, where the CO concentrations were recorded higher in all compartments, especially when the engine was running at 1000 rpm. In conclusion, the navy crew could be exposed to unacceptable IAQ conditions regardless of ship conditions and engine sequences. It is good to highlight that good ventilation is crucial to dilute the air pollutants onboard.

Keywords: indoor air chemical parameter; ship; alongside; sailing; engine sequences

I. INTRODUCTION

The main concern for IAQ onboard is the infiltration of toxic exhaust substances from the engine's fuel combustion into the ship's compartment, especially while sailing (Abdullah & Ariffin, 2013). The IAQ condition worsened when the air pollutants accumulated onboard, primarily due to the inefficiency of air circulation, which increased the risk of exposure among the navy crew (Reynolds, 2005; Correia *et al.,* 2020).

The navy crew onboard were exposed to the chemicals from the fuel combustion process, such as carbon dioxide (CO_2), carbon monoxide (CO), and total volatile organic compounds (TVOC), including benzene, acetylene, naphthalene, and particulate matter (PM) (Ge *et al.*, 2018). Studies by Kim and Lee (2010) and Langer *et al.* (2014) detected a higher concentration of CO_2, CO, and TVOC in ship compartments while the ships were in operation. Langer *et al.* (2014) also stated that the concentration of TVOC and PM were highest in the engine room compared to the other compartments due to the engine's fuel combustion. This finding is supported by Österman *et al.* (2016), where a high concentration of TVOC (exceeded 300 μg/m^3) was detected and exposed to the crews working inside the engine room. In addition, a preliminary study on the IAQ by Yahaya *et al.* (2012) has found the readings of CO2 exceeded 1000ppm in a naval ship, indicating the poorly ventilated space onboard and depicting

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the unacceptable IAQ. Since the accumulation of indoor air chemical parameters were recorded, this situation allowed the exposure of these air pollutants to the crew onboard.

This exposure could increase the health risk of the crew since the air pollutants could be carcinogenic and can also cause other health deterioration such as respiratory problems, nervous system deterioration and cardiovascular disease (Tran *et al.,* 2020). This is alarming due to the prolonged exposure to the navy crew, especially during the pandemic. There has been an increase in illegal activities and trespassing over the pandemic period. Navy crews need to remain onboard for longer periods of time because of the increased frequency of the ship's operations.

Furthermore, exposure to air pollutants also varies according to the ship's conditions. During sailing, the main engines will be operated as a ship propulsion system and the generators will be operated to provide the electricity needed to run lighting and equipment onboard the ship. However, when the ship is at the jetty, only the generators are operated to run the systems and equipment onboard. Thus, there is more production of toxic exhaust gaseous during sailing compared to alongside conditions (Pham *et al.,* 2022).

Hence, this study was conducted to determine and compare the concentrations of CO_2, CO, and TVOC exposed to the navy crews, at different ship conditions (sailing and alongside) and engine sequences (idling, cruising, full ahead and slowing down).

II. MATERIALS AND METHOD

A. Indoor Air Chemical Parameters Sampling

This study was a cross-sectional study conducted in December 2020. The indoor air chemical parameters, which were CO_2, CO, and TVOC concentrations were measured inside a naval ship at different conditions; ship alongside and sailing. Two days of sampling were allocated in this study for both of the ship conditions. Similarly, both samplings were conducted in 8 hrs, following the Industry Code of Practice on Indoor Air Quality 2010 (ICOP IAQ 2010) by the Department of Occupational Safety and Health (2010). Direct readings were recorded every 5 mins for 30 minutes in four-time slots, throughout the 8 hrs of sampling periods, as follows: 1st slot (9–11 a.m.), 2nd slot (11–1 p.m.), 3rd slot (1–3 p.m.), and 4th slot (3–5 p.m.). TSI VelociCalc 9565 was used to quantify CO_2 and CO concentrations, while RAE Systems ppbRAE 3000 was used to measure TVOC concentrations.

B. Ship Conditions and Engine Sequences

This study measured the indoor air chemical parameters onboard at different ship conditions; ship alongside and ship sailing. There were four compartments of the ship involved in this study, as shown in Table 1.

Table 1. Description of sampling compartments

Compartment	Occupancy	Description
Common room	5	A lounge area where crew personnel socialise and eat
Accommodation 1	2	Living spaces for crew
Electrical room	7	Working area for the ship's technicians
Accommodation 2	1	Living spaces for crew

During ship alongside, there were some minor refurbishment works in the ship done by contractors, which involved prescribed activities such as painting, equipment installation, and system testing. The ship's engines and generators also were not running at all time slots during the day of sampling.

By contrast, the engines and generators were fully functioned on the sampling day of sailing condition. The engines were running at different sequences and revolutions per minute (rpm) during each time slot when the sampling was conducted, as shown in Table 2. Additionally, the concentration of the chemical parameters in an engine room was measured as a reference to observe the trend of chemical concentration in ship compartments during sailing.

Table 2. Engine sequences during ship sailing

Time slot	Time	Engine sequences	Engine speed (rpm)
1st	9–11 am	Idling	350
2nd	11–1 pm	Cruising	850

3rd	1–3 pm	Full Ahead	1,000
4th	3–5 pm	Slowing down	900

C. Data Analysis

The 8 hrs total weighted average (TWA_8) of the parameters for both alongside and sailing conditions were calculated to obtain the average parameters concentrations throughout the 8 hrs of sampling. The TWA_8 readings were compared to the acceptable limit of chemical concentrations provided in the ICOP IAQ 2010 guideline to observe the parameters' compliance with the available guideline. The data also were analysed using the Wilcoxon signed-rank test to compare the mean rank of the repeated readings taken during sampling in alongside and sailing conditions. The test was chosen after the non-parametric data was decided using the Shapiro Wilk test for the normality test. Besides that, the trends of chemical concentrations also were obtained throughout the ship sailing to observe the impact of engine sequence operation modes on the indoor chemical concentrations in the ship compartments.

III. RESULTS AND DISCUSSIONS

A. Carbon Dioxide (CO_2), Carbon Monoxide (CO), and Total Volatile Organic Compound (TVOC) Concentrations Between Alongside and Sailing Conditions

The TWA_8 readings of the chemical parameter concentrations for both of the ship's conditions are shown in Table 3.

Table 3. The 8 hrs total weighted average (TWA_8) of chemical parameters during sailing and alongside

Parameter (ppm)	**TWA_8**		**Z score**	***P* value**
	Alongside	**Sailing**		
Carbon dioxide (CO_2)				
Common room	1098 ± 84	1314 ± 84	-2.936	0.003*
Accommodation 1	1236 ± 312	1230 ± 81	-0.235	0.814
Electrical room	2042 ± 320	1818 ± 93	-2.197	0.028*
Accommodation 2	1188 ± 215	1400 ± 135	-3.059	0.002*
Carbon monoxide (CO)				
Common room	1.5 ±0.6	2.5 ± 2.4	-1.413	0.158
Accommodation 1	0.9 ± 0.8	1.7 ± 1.6	-1.415	0.157
Electrical room	< 0.0	3.1 ± 3	-2.668	0.008*
Accommodation 2	< 0.0	2.1 ± 2.1	-2.677	0.007*
Total volatile organic compounds (TVOC)				
Common room	34.1 ± 22.63	5.96 ± 1.37	-3.059	0.002*
Accommodation 1	8.71 ± 2.16	7.14 ± 0.72	-1.412	0.158
Electrical room	14 ± 2.12	7.92 ± 0.72	-3.059	0.002*
Accommodation 2	5.04 ± 1.28	7.52 ± 1.08	-2.589	0.01*

-TWA_8 readings in red indicate that the value has exceeded the acceptable limit in ICOP IAQ 2010
-*Significant at p <0.05

Based on the table, the CO_2 concentration readings were exceeded the acceptable limit of ICOP IAQ 2010 in all compartments for both ship sailing and alongside conditions. The exceeded readings were resulted from the overcrowded situations inside the ship due to the minor refurbishment activities and preparation for sailing during ship alongside, and also due to the ship operation during sailing. This is supported by Peng & Jimenez (2021) mentioned that human exhalation is the main source of increasing CO_2 concentrations in an indoor area. In addition, the high concentrations recorded indicate the ship compartments were poorly ventilated as the CO_2 concentrations emitted by the crews and contractor workers were not sufficiently diluted by the introduction of fresh air to the compartments. It is informed that adequate and well-air ventilation should be able to dilute the pollutants concentration, including CO_2 in an indoor area (Sandberg & Kabanshi, 2019).

In comparison between ship alongside and sailing conditions, the results from the Wilcoxon signed-rank test showed that the CO_2 concentrations were significantly higher in the common room ($Z = -2.936$, $p = 0.003$) and accommodation 2 ($Z = -3.059$, $p = 0.002$) during ship sailing. These results further support the idea that besides the occupant factor, another significant source of CO_2 onboard was the exhaust of diesel combustion engines. It could be caused by the recirculation of exhaust smoke back to the air intake or by a small leak between the engine room and other compartments. This is consistent with the findings of Tran, (2017), who discovered that ship operation activities emit a large concentration of exhaust gases into the environment.

The justification also supports the results obtained for CO concentration in this study. The difference in CO concentration between sailing and alongside shows a consistent trend with the initial expectation, with higher readings were recorded during the sailing condition. Table 3 shows that the difference in CO concentrations between alongside and sailing conditions were statistically significant in the electrical room ($Z = -2.668$, $p = 0.008$) and accommodation 2 ($Z = -2.677$, $p = 0.007$). The differences show the possibility of high infiltration of exhaust smoke into the compartments due to the diesel engine's incomplete combustion during sailing. The concentration of CO is relatively higher when sailing due to the full operation of both main engines. A similar outcome was obtained from a study by Kim and Lee (2010), where the major contributor to CO levels in two ships was fuel combustion.

Contradicting the result patterns in this study, the TVOC concentrations were recorded higher during ship alongside in all compartments, except in accommodation 2. The concentration of TVOC with significantly higher were reported in common room ($Z = -3.059$, $p = 0.002$), accommodation 1 ($Z = -1.412$, $p = 0.158$), and electrical room ($Z = -3.059$, $p = 0.002$) during ship alongside compared during sailing. Previous studies done by Kim and Lee (2010) and Langer *et al.* (2014) mentioned on the contribution of fuel combustion and exhaust gasses to TVOC concentration support the results of exceeded readings during ship sailing in this study. Nevertheless, the higher concentration measured during ship alongside was due to cleaning and refurbishment activities such as painting done by contractor workers during the sampling. Cleaning activity using detergent and degreaser emit a concentration of TVOC such as acetone and aromatic solvents (Meegoda *et al.,* 2021). Besides that, another possible source of TVOC includes the new furnishings inside the compartments, as the ship had just returned from a refit program a few months before the sampling. This is supported by Mečiarová *et al.* (2017), stating that the furnishing materials can emit VOC into the environment. It also seems possible that this TVOC lingers in the air rather than being securely deposited on the sensitive environment receptor due to the structural vibration of the ship while sailing. Data of the elevated readings during the third and fourth time slots in this study also parallel with the justification as the higher temperature during the time slots increases the emission of the TVOC. A study by Adeyemi, Kanee and Edokpa (2020) mentioned that the temperature of the compartment is a critical factor in the emission of TVOC in an area.

Regardless of the different ship conditions either ship alongside or ship sailing, the concentration of the indoor air chemical parameters exposed to the navy crew onboard for CO_2 and TVOC exceeded the acceptable limit in the ICOP IAQ 2010. But it is good to highlight that the limit set in ICOP IAQ 2010 is limited to the building setting and designated for 8 hours monitoring only.

B. Differences in Carbon Dioxide (CO_2), Carbon Monoxide (CO), and Total Volatile Organic Compound (TVOC) Concentrations with Engine Sequence Variations

Limited studies are available to support the correlations between the IAQ chemical parameters and engine sequences. This study was designed to obtain the indoor air chemical parameters of engines in four sequences: idling at 350 rpm, cruising at 850 rpm, full ahead at 1,000 rpm, and slowing down to 900 rpm. The engine sequences are also related to the ship's speed, as a higher rpm engine indicates a faster ship. The CO2, CO, and TVOC concentrations trends in all compartments were discovered to increase with the increasing engine rpm, as shown in Figures 1–3.

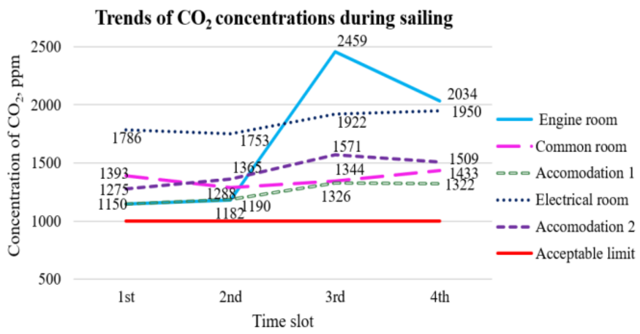

Figure 1. Trends of CO_2 concentrations during sailing

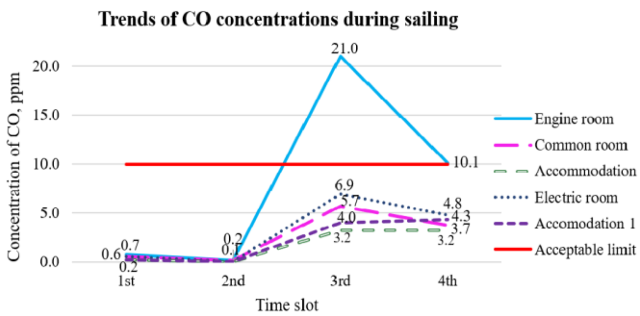

Figure 2. Trends of CO concentrations during sailing

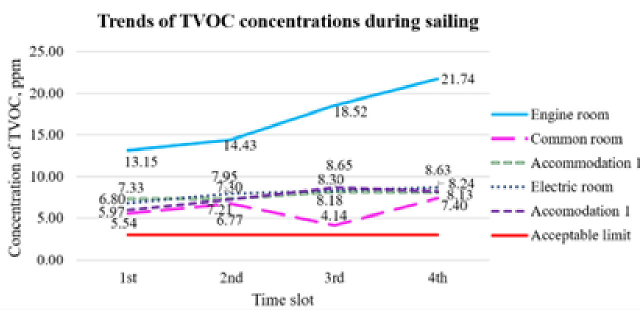

Figure 3. Trends of TVOC concentrations during sailing

However, it is quite astounding that the concentration of CO_2 in the common room keeps increasing even though the engine rpm has been reduced (Figure 1). This contradictory result may be due to the sources of CO_2 in the common room are not solely related to exhaust smoke. It could be due to the human exhalation as high occupancy was observed in the compartment for ship operation activity. These findings cannot be generalised to all compartments because the variation in the parameters recorded depended on the ventilation system within the compartment itself. Furthermore, given the speed of the ships, these variations may be due to the fact that ship exhaust smoke disperses quickly into the environment. The possibility of air being circulated back into the ships through air intake was minimised as the ship's speed increased (Langer *et al.,* 2020).

As CO is an incomplete combustion product of diesel engine, the CO concentration trend increases and decreases respectively with engine sequences (Ghadiyaram & Bovik, 2016), as shown in Figure 2. This relationship may partly be explained by the idea of recirculated exhaust smoke flowing back inside the ship through the air intake. This factor could account for the relatively good correlation between CO concentration and engine sequences.

The concentration trend of the TVOC shown in Figure 3 indicates that TVOC sources may not be solely from exhaust gases. Aside from the engine, crew activities such as cooking and cleaning could also contribute to releasing these chemical IAP inside the ship. According to Österman *et al.* (2016), the increase of TVOC concentration in a vessel is caused not only by diesel engine emissions but also by cooking and cleaning activities. Kim & Lee (2010) also supported the finding that high concentrations of CO and CO_2 were found on the cruise ship as a result of cooking activity and engine activity.

IV. CONCLUSION

Based on the findings, this study concluded that the crew could be exposed to the unacceptable limit concentration of indoor air chemical parameters, regardless sailing or alongside ship conditions. This study found the effects of ship's conditions and engine sequences on the concentration levels of CO_2, CO, and TVOC inside the ship's compartments. However, other factors such as human activities and occupancy also are greatly affecting the concentrations as some of the compartments recorded higher chemical concentrations even during ship alongside. Therefore, detailed information on the situation, such as the number of occupants and activities should be noted to assist in determining the sources of pollutants at the sampling locations. Besides that, the recirculation of exhaust smoke inside the ship's compartment needs to be aware as the incidence was observed during this study, based on the results of concentration trends recorded between the engine room and ship's compartments.

The exceeded concentration readings of chemical contaminants recorded in this study conclude that the factors affecting the pollutants concentration in a building also apply to ship environment. Moreover, the crew is exposed to the additional pollutants from fuel burning and exhaust gasses during ship sailing, with longer exposure due to the longer time spent onboard. Therefore, it is crucial to ensure a well and sufficient ventilation is applied inside the ship in order to introduce fresh air to the crew and dilute the air pollutants inside the ship. The ship should ensure minimal recirculation of exhaust gases caused by the engine activity to the compartments.

Considering the constant exposure to the unacceptable IAQ onboard, especially during the work demand during the pandemic, ventilation is the paramount factor to reduce the risk of exposure to the indoor air chemical parameters, thus ensuring the readiness and vigilance of the navy crew onboard.

V. ACKNOWLEDGEMENT

The authors would like to thank the International Islamic University of Malaysia (IIUM) and the Royal Malaysian Navy (RMN) for their assistance with this work (grant ID: RMCG20-044-0044). We would like to express our sincere gratitude to the Eastern Maintenance Overseer Unit, RMN for granting us access to the ship, as well as all of the crews who generously assisted during the study.

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