Influence of fuel change on indoor environmental quality on-board a passenger ferry

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SUMMARY

This study intends to investigate how a change of fuel type from Heavy Fuel Oil to a ultra-low sulphur hybrid oil affects the indoor air quality on board a passenger ferry. The indoor air quality was assessed with respect to the concentration of NO_2, SO_2 and TVOC, temperature and relative humidity. The efficiency of the ventilation system on the ferry was estimated by measurements of the levels of CO_2. The air on-board the ferry was rather dry and in the engine space also warm. CO_2 levels exceeded 1 000 ppm extremely seldom, thus indicating well designed and functioning ventilation. The concentrations of the air pollutants were below the guidelines values for good IAQ. They were also much below the occupational limit values. Living and working on-board this ship is comparable to any other indoor environment. The change of the fuel influenced only the concentrations of SO_2.

PRACTICAL IMPLICATIONS
The indoor environment on-board ships has been quite neglected in the literature. Because of not knowing, the crews may be worried about the actual air quality. The results of this work increase the amount of knowledge about the identities and concentrations of indoor air pollutants on-board ships.

KEYWORDS
Ship, indoor air quality, fuel change, gaseous air pollutants, particles

1 INTRODUCTION
Indoor air quality on ships has not received much attention in spite of the crews' experience of indoor related health symptoms and seafarers' elevated cancer morbidity. The indoor environment on ships is a combined working and living environment. The crews generally spend prolonged periods of time on board without possibility to change or influence the indoor environment. Seafaring is a risky occupation in many other aspects of working life and good indoor air quality, important for the crews' health, work efficiency and well-being should be an obvious requirement. Many ships are in the process of changing fuels to cleaner alternatives to fulfil international requirements on the engine exhaust emissions to ambient air.

Surprisingly few studies on the indoor environmental quality on ships have been published in the open literature. The indoor thermal environment was assessed on Chinese air-conditioned ships. Questionnaires to appraise the thermal sensation were collected and they were evaluated together with field measurements performed (Liu et al., 2011). Another study presents results from the measurements of temperature and relative humidity in the engine room and the engine control room on-board a merchant ship (Orosa and Oliveira, 2010). The indoor air quality was investigated with respect to the volatile organic compounds, formaldehyde, CO, CO_2 and PM_{10} on-board a then newly launched Korean passenger ship and a cargo ship. The temperature and relative humidity were found acceptable and the concentrations of the air pollutants were lower than the levels recommended in international and national standards in the accommodation spaces (Kim and Lee, 2010). In an older study, the indoor environmental quality (IEQ) was investigated on-board of a Swedish submarine equipped with independent propulsion during more than one week of continuous submerged operation (Persson et al., 2006). The measured parameters were representative for a thorough indoor study and they were pressure, temperature, relative humidity, oxygen, hydrogen, CO_2, formaldehyde, volatile organic compounds, ozone, NO_2, particulate matter and microbiological contaminants. The concentration of the pollutants from the study did not indicate any build-up of hazardous compounds during the operation.

The work environment on Swedish flagged ships is regulated by the Swedish Transport Agency's regulations and general advice about working on ships (TSFS, 2009). This regulation also puts the occupational exposure limits in force (AFS, 2011). The indoor air quality on-board a ship in the personal spaces may be assessed from the existing recommended guideline values provided by the World Health Organization (WHO, 2005; 2010).

The aim of the study presented in this paper was to 1) investigate the quality of the indoor environment on-board a passenger ferry through comprehensive detailed measurements of a number of parameters relevant for indoor air; 2) compare the results with existing occupational limit values or recommended guideline values for indoor air; and 3) compare the IEQ for two different fuels. The project did not consider any health aspects.

2 MATERIALS/METHODS

The actual measurements were performed on-board the ship during its regular cruises in the Baltic Sea during two campaigns: the first one in late autumn (24 November – 1 December 2014) and the other one in spring (13 – 20 April2015). The cruise ferry can accommodate 1 800 passengers and does not carry any other cargo. The ferry is operated by approximately 150 persons and is 177 m long, 27 m wide and with a gross tonnage of 35 000 tonnes. The ship is powered by four Wärtsilä 6L46 diesel main engines with total power of 23 400 kW. During the first campaign the main engines were fuelled with heavy fuel oil (HFO) with 1% sulphur and during the second campaign the fuel was ultra-low sulphur marine residual fuel RMB30 (0.1% S).

The selected sampling sites on-board were: main engine room, purifier room, engine control room, as representatives for work spaces; the bridge, two cabins, mess room, galley, and a storage room, as representatives for the personal spaces. Outdoor samples were collected on upper deck approximately 20 meter above the sea level.

The measured parameters were concentrations of gaseous and particulate air pollutants as well as temperature (T) and relative humidity (RH). Temperature and relative humidity were monitored by HOBO U12-012 data loggers (Onset Computer Corp., USA). CARBOCAP® CO2 monitors (GMW22, Vaisala, Finland) were used to measure the CO_2 concentration and the data were logged using the HOBO logger.

Concentrations of ozone, NO and NO_2 (NO_x) and SO_2 were measured using IVL diffusive samplers (Ferm and Rodhe, 1997). The formaldehyde samplers were DSD-DNPH Aldehyde Diffusive sampling Device (Supelco, Bellefonte, PA) and for VOC, Tenax adsorbent tubes

(Perkin-Elmer) were used. Polycyclic aromatic hydrocarbons (PAH) were collected on polyurethane foam sampler (diffusive sampling). Particles $PM_{2.5}$ were sampled on PTFE and quartz filters using impactors for separation of particles of the required size. Additionally, particles in the size range of 0.3 – 20 µm were continuously monitored by Grimm Portable Dust Monitor model 1.108 (Grimm Aerosol Technik GmbH & Co).

The concentrations of ozone, NO_x and SO_2 were analyzed by wet chemical techniques. Formaldehyde was analyzed, after eluting from the sampler, by liquid chromatography/UV detection. VOCs were thermally desorbed from the solid adsorbent and analyzed by gas chromatography/mass spectrometry (GC/MS; GC 6890, MS 5973N, Agilent, USA) and quantified as Total Volatile Organic Compounds (TVOC) in toluene equivalents. PAH samples were extracted to organic solvent and analyzed by gas chromatography with mass selective detector. The particle mass concentration was determined from sample weights and sampled volumes.

3 RESULTS

The results presented below represents a selection from a very large amount of collected data. We show comparison of some of the parameters observed on the ship with the same parameters measured in a survey of indoor air quality in the Swedish housing stock as presented by Langer and Bekö (2013). These are temperature and relative humidity, air, and concentrations of NO_2 and TVOC. The reason for such a comparison is to give an idea for the crew about the indoor air quality onboard the ship in relation to an average Swedish residence.

Temperature, relative humidity and carbon dioxide

The temperature and relative humidity recommended for indoor environments by Swedish authorities should be within the intervals 20 – 24 ^oC and 30 – 70%. These values constitute the comfort zone indicated as a box in Figures 1 and 2. The Figures summarize the results of temperature and RH measurement during the cruises with the old (HFO, 1% S) and the new fuel (RMB30, 0.1%S).

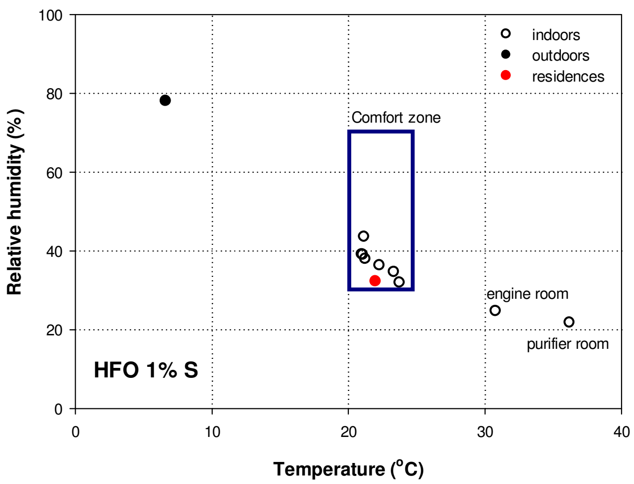

Figure 1. Temperature and relative humidity in the spaces on-board the ferry during the autumn 2014 measurements. The values are 1-week averages.

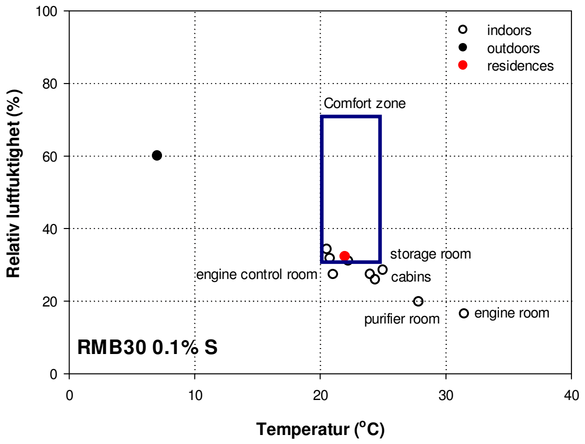

Figure 2. Temperature and relative humidity in the spaces on-board the ferry during the spring 2015 measurements. The values are 1-week averages.

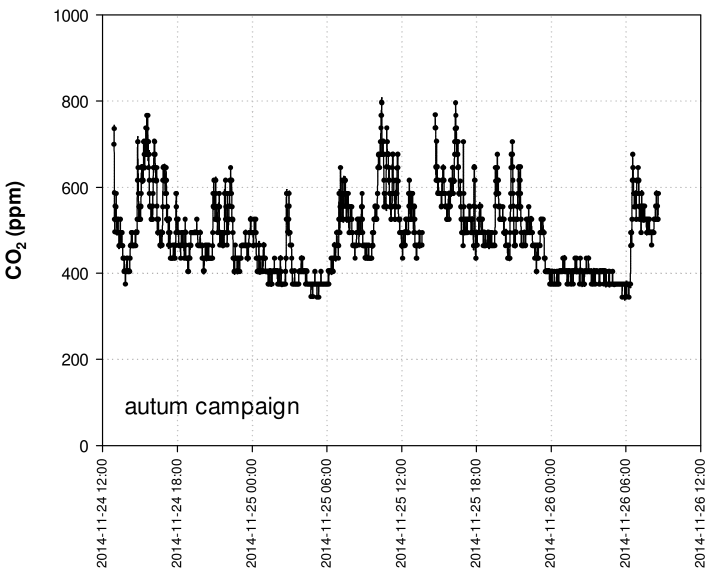

Figure 3. Example of measured concentration of CO_2 in the mass.

The average concentration of carbon dioxide during both campaigns and in all indoor spaces was 370 – 480 ppm. Figure 3 illustrates typical concentration-time profile of CO_2.

Air pollutants

The next Figures present the concentration of NO_2, SO_2 and TVOC in all sampled spaces and for both measurement campaigns.

The concentration of NO_2 in the engine room was 33.4 µg/m^3 (both campaigns); the average concentration in all the other spaces was 11.8 µg/m^3 (autumn) and 9.6 µg/m^3 (spring). The corresponding outdoor air concentrations were 11.9 and 7.1 µg/m^3, respectively. Median NO_2 concentration in the Swedish residences is 8.0 µg/m^3 (Langer and Bekö, 2013). For comparison, NO_2 concentration in the typical marine boundary layer is in the region of 0.4 – 3 µg/m^3 (EMEP, 2011)

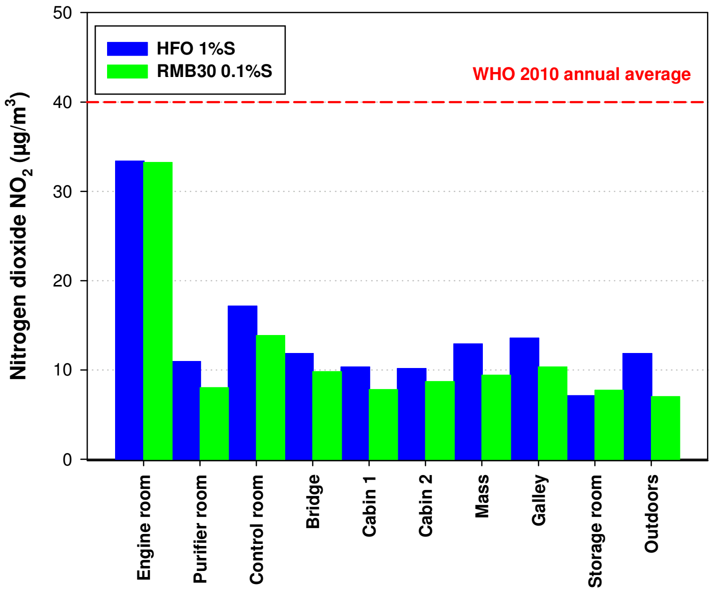

Figure 4. Concentration of NO_2 for both campaigns as an average of one-week sampling. Indoor air guideline value for NO_2 is 40 µg/m^3 as annual average. Occupational limit value is 4 mg/m^3 = 4 000 µg/m^3.

The concentration of SO_2 in the engine room was 11.4 µg/m^3 during the autumn measurements (HFO 1%S). It decreased 2.1 µg/m^3 after the change of fuel to the ultralow-sulphur HFO. The average SO_2 concentration in all the other spaces was 1.2 and 0.8 µg/m^3 for the operation with the old and new fuel, respectively, and it was quite similar to outdoor air concentration of 2.0 and 0.6 µg/m^3.

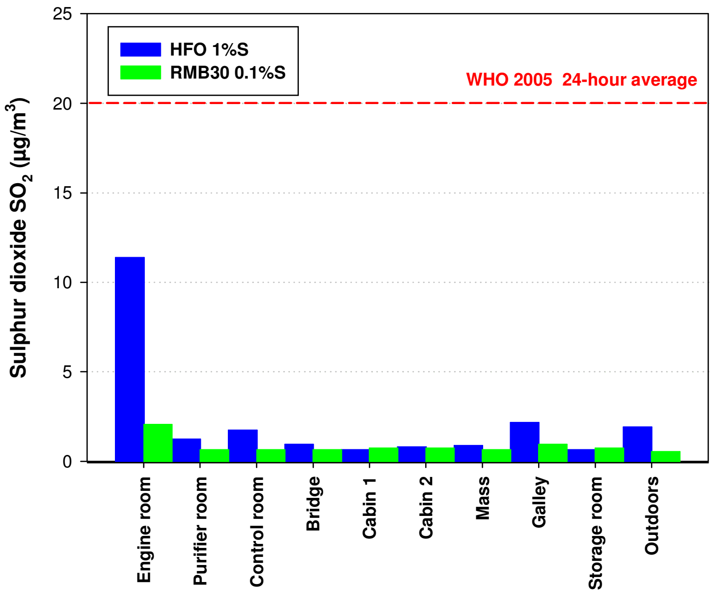

Figure 5. Concentration of SO_2 for both campaigns. Average of one-week sampling. Indoor air guideline value for SO_2 is 20 µg/m^3 as 24-hour average. Occupational limit value is 5 mg/m^3 = 5 000 µg/m^3.

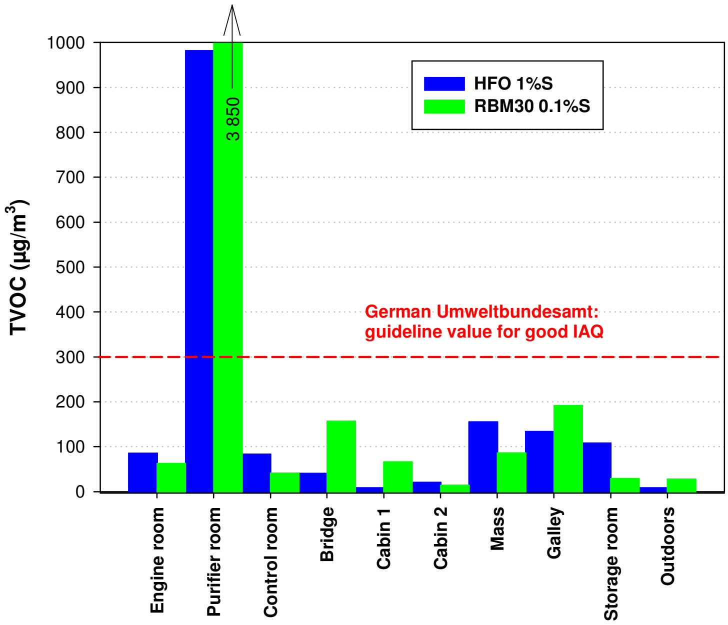

Figure 6. Concentration of TVOC for both campaigns. Average of one-week sampling.

The concentration of TVOC in the purifier room was 980 µg/m^3 (autumn) and 3850 µg/m^3 (spring). The average TVOC concentration in all the other spaces was 83 µg/m^3 (both campaigns) and the corresponding outdoor air concentrations were 11 and 30 µg/m^3 for the autumn and spring measurements. Median TVOC concentration in the Swedish residences is 180 µg/m^3 (Langer and Bekö, 2013). Non-Methane HydroCarbons (NMHC) in the marine boundary layer are typically 0.5-1 µgC/m^3 in summer and 1.5-2 µgC/m^3 in winter (Solberg, 2013).

4 DISCUSSION

Regardless the campaign (autumn or spring) and fuel, the air in the engine room and the purifier room was too warm and dry. During the autumn campaign, all the other measured spaces were within the comfort zone, quite similar to an average Swedish residence. During the spring campaign, the temperature was generally within the comfort interval but the air was too dry even in the other indoor spaces. The levels of CO_2 never exceeded 1 000 ppm during prolonged periods of time, thus indicating that the ventilation flows were well designed for the number of occupants in the personal spaces. These results are in agreement with our previously reported measurements on the Swedish icebreaker Oden (Langer et al., 2014).

The concentrations of NO_2 and SO_2 were below the guideline values recommended by WHO for good indoor air quality and much below the occupational limit values in all places on the vessel. They were elevated in the engine room due to the proximity to the combustion processes. The indoor-to-outdoor ratios of NO_2 and SO_2 (with exception for the engine room) were approximately 1.0 indicating that the source of these compounds was infiltration from the outdoor air. The NO_2 concentrations were approximately similar to those observed in average Swedish dwellings; no such comparison is available for SO_2.

In the purifier room the crew member handle the fuel, lubricant oils and solvents. It is the explanation to the greatly elevated levels of TVOC. In the other spaces on-board, the TVOC concentrations was on average below the hygienically safe level of 300 µg/m^3 proposed by the Federal Environment Agency of Germany (UBA) and they were also lower than those observed (median value) in the Swedish residences. The composition of the individual indoor VOC found in the sample chromatograms from the purifier room, the engine room and the engine control room was mainly made by aromatic compounds (BTEX = benzene, toluene, ethylbenzene, xylenes, and higher substituted benzenes) and long-chain aliphatic hydrocarbons, originating from the ship's fuel (HFO). In the other spaces, the chromatograms contained organic compounds that can be found in any typical indoor environment of residences or offices, such as terpenes and glycol ethers from cleaning agents, ethanol and isopropanol from disinfectants and $C_6 - C_{10}$ aldehydes from the building and furnishing materials

5 CONCLUSIONS

The indoor environment on-board the passenger ferry is good with respect to existing recommended guideline values, much better with respect to the occupational limit values and is also comparable with or better (with the exception of the purifier room) than average Swedish residences.

The change of fuel from HFO with normal/low content of sulphur (1%) to ultra-low sulphur HFO (0.1%) had major effect of the concentration of SO_2, most remarkably in the engine room. Generally, the indoor air quality in the engine spaces was characterized by the compound originating from the ship fuel evaporative emissions and operation of the engines. Nitrogen dioxide levels in the other working and living spaces on-board were similar to those in outdoor air, indicating well designed ventilation and spatial separation from the engine areas. The volatile organic compounds in the spaces other than engine spaces were similar, both in concentrations and chemical composition, as any other indoor environments.

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