# Ventilation and COVID-19 transmission risks on board of Dutch governmental ships

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**Abstract.** The Dutch government (specifically the 'Rijksrederij', the governmental shipping company) owns a fleet of just under 100 ships that are equipped to service the internal waterways and parts of the North Sea. Think in this context of e.g. Coast Guard ships, ships that help to fight oil accidents or ships that maintain buoys. Just after the COVID-19 pandemic had started the 'Rijksrederij' decided that it was necessary to investigate to what extent the fleet might pose a risk for cross-contamination of this new disease on board. This was approached with a specific focus on ventilation and the airborne route. The objective was to find out whether the most important spaces on board of the ships were adequately ventilated and to evaluate how ships can be made or kept 'COVID-resistant' as far as the airborne route is concerned. A sample of 16 ships of different types, most of them mechanically ventilated, were surveyed. This included a general inspection, an inspection of relevant HVAC system characteristics and measurements of e.g. air supply flows. Also, ships were equipped with monitors that measured $CO_2$ concentration (e.g. in galleys and wheelhouses) that were left on board for at least one week. As reference for the supply flow measurement outcomes we used ISO 7547 guideline values and the Germanischer Lloyd ventilation requirements. On board of 6 of the 16 ships that were investigated we found serious problems with the fresh air supply and/or measured $CO_2$ concentrations. On the positive side, the majority of the ships had ventilation capacities in line with the two reference standards, and almost all did not use central recirculation. We also found that many of the ships had adequate options, at room level, for individual control of both fresh air supply and temperature. The results of the study will be used to further improve 'COVID safety' on board of the whole fleet and to ameliorate future, new ships and their HVAC systems.

**Keywords.** Airway infections, cross contamination, Corona disease, $CO_2$ concentration, dilution, fresh air supply, recirculation.
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## 1. Introduction

At the beginning of the COVID pandemic (spring 2020) the Rijksrederij (Dutch governmental shipping company, linked to the Directorate General for Public Works and Water Management) conducted general risk evaluations related to COVID-19 AND occupational health on board. One conclusion was that it made sense to further evaluate the effectiveness of the ventilation systems of the ships.

It is well known that ships are particular vulnerable when it comes to cross infection risks of airway diseases in general and COVID-19 specifically (see e.g. [1] and [2]). Not surprisingly as on board of ships people have limited personal space, while from the general literature [3] [4] we know that viruses are easily transmitted from person to person especially when people spend a lot of time together in relative small spaces. This is even more likely when these spaces are poorly ventilated and people are in relatively close distance to each other. For good reason Japan has developed, in this context, the so-called 3 C policy [5] stating that to avoid cross infection people should avoid i. Closed spaces with poor ventilation, ii. Crowed places with many people nearby, and iii. Close contact settings with e.g. close-range conversations.

The Rijksrederij operates just under 100 ships, some smaller (used for day trips) and some larger (used for 'over-the-horizon' patrols that can last for up to one week). See figure 1 for an impression.

**Fig. 1** - Two example ships used by the Rijksrederij; the upper one is for week patrols, the lower one is for day patrols

The Rijksrederij already had taken several 'regular' measures to decrease cross-infection risks on board of these ships, related to handwashing, mask wearing and e.g. cleaning in between shifts. Apart from that, the organisation was determined to further improve 'COVID safety' by addressing the airborne route and thereby focusing on ventilation.

The core objective of this study was to find out whether the most important (most intensively used) spaces on board of the ships were adequately ventilated and to evaluate how the ships can be kept or made more 'COVID-resistant' as far as the airborne route is concerned.

The research questions were as follows:

1. Is the fresh air supply in line with the ISO and Germanischer Lloyd requirements?

2. Are there any other airway infection risks related to the design, operation and maintenance of the ventilation systems?

3. Which measures could be taken to further improve the situation on board of these ships and future new ships?

Note that the focus was to not only measure mechanical fresh air supply but also to investigate options for natural ventilation, possible issues with recirculation etc..

# 2. Research Methods

## *2.1 General approach*

A total of 16 ships (this is about 1 in 6 of the total amount of ships) were evaluated. These ships came from different home ports all over The Netherlands (from Harlingen in the upper North to Vlissingen in the South). The ships were selected with the different subgroups (ship types e.g. large vs. small) in mind, also taking into account patrol schedules and general availability.

The surveys on board were conducted during the winter of 2020/2021. Each time we went through the following steps:

1. Beforehand relevant technical documentation of the ship was studied (desk research).

2. Next an on board inspection was conducted; this involved a general survey of relevant spaces, inventory of normal use practices (e.g. amount of people on board), a check-up of relevant technical appliances (air handling units etc.) and short on-site interviews with contact persons (e.g. the captain or a marine engineer in charge of on-board technology). In this context we used the REHVA COVID-19 guidance document [6] and the WHO ventilation roadmap document [7] as base references.

3. During the inspection day we also measured air supply rates in randomly selected spaces (with a calibrated ACIN flow finder device); this was done in the most intensely used spaces (especially messrooms, wheel houses and sleeping quarters). Before the measurements started we asked those present to put the ventilation system in 'the setting normally used when out on patrol'.

4. At the end of the inspection day, one or more $CO_2$ loggers were placed in the living spaces at breathing zone height (Aranet 4 Pro devices). These loggers where retrieved about one week later (sometimes after 2 weeks depending on patrol schedules).

5. Afterwards, all data and qualitive findings were analyzed. First for the ships individually, at the end of the project for the batch as a whole.

Note that some ships did not have a mechanical ventilation system (only natural supply and exhaust). In those cases we only measured the $CO_2$-concentration.

## *2.2 Reference values measurements*

Beforehand we had to decide what reference levels to use when interpreting the air flow and $CO_2$ concentration measurements. In that context we first made an inventory of relevant legal requirements specifically applicable for marine vehicles and inland vessels.

Article 73 of the Dutch 'Schepelingenbesluit' (Sailors Decree) for example states: 'All on board spaces for personnel shall be effectively ventilated in such a way that the air indoors remains in a satisfactory condition.'

Article 11.07 of the Dutch 'Binnenschepenbesluit' (Inland Vessel Decree) asks for something similar, also without specific requirements in terms of minimum amount of fresh air that should be provided at room level or per person.

More concrete reference requirements are presented in an ISO standard for marine vehicles that is often used e.g. when new ships are being built: ISO 7547: 2005 'Air-conditioning and ventilation of accommodation spaces on board ships, Design conditions and basis of calculations' [8]. Also the Germanischer Llyod document 'Rules for classification and construction of seagoing ships' [9] gives some clues about what is considered 'adequate ventilation' in the shipbuilding context. Note that the ISO requirements are stated in terms of minimum requirement fresh air supply per person (in l/s) and that the German Lloyd requirements are stated in terms of minimum allowed air exchange rates (with different values for sleeping quarters and non-sleeping quarters). The quantitative requirements of the two standards are summarized in table 1.

**Tab. 1 –** Reference values.

| | ISO 7547 | Germa-nischer Lloyd |
|---|---|---|
| Minimum fresh air supply per person | 8 l/s = 28,8 $m^3$/h | - |
| Minimum Air Exchange Rate messrooms, offices | - | 12 $h^{-1}$ |
| Minimum Air Exchange Rate sleeping quarters, wheel houses | - | 6 $h^{-1}$ |

In the context of COVID cross-transmission via the airborne route one might pose the question whether these values are high enough to substantially mitigate infection risks. The World Health Organisation stated spring 2021 (at a time that the Omicron variant did not exist yet) that normally speaking, in 'standard work situations' 10 l/s fresh air supply per person and a minimum Air Exchange Rate (AER) of 6 should be enough to at least provide some level of safety [7]. The reference values that we used, that are mentioned in table 1 are quite in line with that.

The reference level that we used when interpreting the continuous $CO_2$ measurements was 1000 ppm. This is the steady-state concentration that will occur when a fresh air supply is provided in accordance with the previously mentioned ISO standard. That is assuming an outdoor (above-sea) $CO_2$ concentration of 350 ppm, a metabolism of not more than 1,4 met and a $CO_2$ production of 0,006 l/s or less [10]. Also assuming an error margin of 10%. Moreover, this 1000 ppm also tunes in with the often used reference value (in the Netherlands) when investigating indoor climate problems in offices.

# 3. Results & discussion

First we present the quantitative results. The air flow measurement data are presented in paragraph 3.1, the $CO_2$ measurement outcomes are presented in paragraph 3.2. After that, in paragraph 3.3 the qualitative results of the survey are presented. The results per ship are presented using codes like L-A2 and S-R1. This has been done to ensure confidentiality.

## *3.1 Results air flow measurements*

The results of the air flow measurement are presented in Table 2.

A special note in relation to the 8 smaller ships that are used for day patrols (bottom half of table 2): the main space on board here was the wheel house (often with an integrated pantry). No measurements were conducted in messrooms or sleeping quarters as these smaller boats did not have those kind of spaces. Some of the smaller ships were not equipped with a mechanical ventilation system: these were ventilated naturally via sliding windows and / or air scoops (elbow pipes). This applies specifically to the ships S-A1, S-C1 and S-S1, This explains why no measurement data are presented for those three ships in Table 2.

As far as the Air Exchange Rates (AER's) in table 1 are concerned: Conclusion in relation to the 8 larger ships for week patrols was that the ventilation performance varies significantly from ship to ship. The best ships allow for Air Exchange Rates (AER's) at room level of about 15-25; while in the worst ventilated spaces AER's were as low as 2-3. As far as air supply per persons on the larger ships is concerned: also here a large variation was found: with e.g. less than 20-30 m3/h air supply person in some spaces and more than 300 m3/h in others.

Conclusion in relation to the 8 smaller ships for day patrols: AER's in the wheel houses in the 5-10 range; air supply per person in the 50-200 m3/h range.

Median values of AER's and per person air supply rates for can be found in the last row of Table 2. In two of the 16 ships (both larger ones) the ISO and/or Germanischer Lloyd ventilation requirements are clearly not met: this applies to L-M2 and L-Z1. In two others (L-T1 and L-W1) we identified suboptimal ventilation only in the mess rooms.

**Tab. 2** – Results air flow rate measurements. Suboptimal values (not in line with ISO / Germanischer Lloyd reference values) are indicated in bold. Ships that mainly had suboptimal outcomes are highlighted with grey backgrounds.

| | ship | wheel house | | mess room | | sleeping quarters | |
|---|---|---|---|---|---|---|---|
| | | AER | m³/h pp | AER | m³/h pp | AER | m³/h pp |
| | *reference* | *6* | *28,8* | *12* | *28,8* | *6* | *28,8* |
| *Larger ships (week patrols)* | L-A2 | **5,9** | 597 | **10,3** | 43 | **5,8** | 107 |
| | L-B1 | 23,7 | 424 | 13,4 | 84 | **4,9** | 113 |
| | L-I1 | 14,7 | 271 | 13,0 | 34 | 17,7 | 184 |
| | L-M2 | **3,1** | 112 | **1,9** | **16** | **1,6** | 38 |
| | L-R2 | **5,1** | 215 | 16,7 | 184 | 12,8 | 338 |
| | L-T1 | 7,2 | 186 | **5,9** | 46 | 9,1 | 124 |
| | L-W1 | 6,1 | 211 | **4,1** | 31 | 9,5 | 48 |
| | L-Z1 | **3,3** | 44 | **10,6** | 48 | **2,5** | 64 |
| *Smaller ships (day patrols)* | S-A1 | - | - | - | - | - | - |
| | S-C1 | - | - | - | - | - | - |
| | S-M1 | 8,7 | 77 | - | - | - | - |
| | S-R1 | 9,7 | 79 | - | - | - | - |
| | S-R3 | 5,7 | 62 | - | - | - | - |
| | S-R4 | 8,6 | 226 | - | - | - | - |
| | S-R5 | 6,3 | 167 | - | - | - | - |
| | S-S1 | - | - | - | - | - | - |
| | Median | 6,3 | 186 | 10,5 | 45 | 7,5 | 110 |

**Tab. 3** – Results $CO_2$ concentration measurements (measurement duration: at least 1 week; results presented are the most representative day in that week). Suboptimal values (not in line with ISO / Germanischer Lloyd reference values) are indicated in bold. Ships that mainly had suboptimal outcomes are highlighted with grey backgrounds.

| | ship | wheel house | | mess room | | sleeping quarters | |
|---|---|---|---|---|---|---|---|
| | | max. (P95) $CO_2$ conc. repr. day | minutes >1000ppm per 24 h | max. (P95) $CO_2$ conc. repr. day | minutes >1000ppm per 24 h | max. (P95) $CO_2$ conc. repr. day | minutes >1000ppm per 24 h |
| | *reference* | *1000* | *-* | *1000* | *-* | *1000* | *-* |
| *Larger ships (week patrols)* | L-A2 | 520 | 0 | 810 | 0 | 630 | 0 |
| | L-B1 | **1030** | **10** | 960 | 0 | 900 | 0 |
| | L-I1 | 840 | 0 | 800 | 0 | 860 | 0 |
| | L-M2 | **1480** | **110** | **1500** | **690** | **1010** | **10** |
| | L-R2 | 670 | 0 | 900 | 0 | 650 | 0 |
| | L-T1 | 650 | 0 | 720 | 0 | 560 | 0 |
| | L-W1 | **1050** | **30** | **1320** | **50** | 930 | 0 |
| | L-Z1 | 640 | 0 | 780 | 0 | 810 | 0 |
| *Smaller ships (day patrols)* | S-A1 | 880 | 0 | - | - | - | - |
| | S-C1 | **1620** | **190** | - | - | - | - |
| | S-M1 | **1870** | **500** | - | - | - | - |
| | S-R1 | 1070 | 30 | - | - | - | - |
| | S-R3 | **>2000** | **300** | - | - | - | - |
| | S-R4 | 890 | 0 | - | - | - | - |
| | S-R5 | 910 | 0 | - | - | - | - |
| | S-S1 | 850 | 0 | - | - | - | - |
| | Median | 900 | | 855 | | 835 | |

### 3.2 Results $CO_2$ measurements

The $CO_2$ measurement results are presented in table 3. Not every ship was used every day during the measurement period. Also: we found that the $CO_2$ -concentration fluctuated over time substantially (more than e.g. in an average office or class room) because people moved around on the ships quite a bit. Due to these two reasons we selected, for each ship, a *representative* day (a day with normal use) within the sampling period for analysis. See table 3, One column in the table describes the maximum concentrations that were measured (P95 values) and one column describes the amount of minutes (during the whole period of 24 hours) that the upper limit of 1000 ppm was exceeded.

Conclusion in relation to the 8 larger ships (upper half of table 3): in 5 of the 8 ships $CO_2$ concentrations stayed well below the limit of 1000 ppm. Two ships (L-M2 and L-W1) showed serious exceedances of the limit value, especially in the mess rooms. The last large ship showed performance around reference value level. We found peak values of 1500-2000 ppm in the less favourable spaces and 500-700 ppm in the best ventilated spaces. In one case (mess room L-M2) the limit of 1000 ppm was exceeded more than 10 hours (600 minutes). For other cases that were less well ventilated, exceedance was limited to half an hour up to 2 hours.

Conclusion in relation to the 8 smaller ships are comparable: in 5 of the 8 smaller ships $CO_2$ concentrations stayed well below the limit of 1000 ppm. Three ships (S-C1, S-M1 and S-R2) showed serious exceedances of the limit value (in their main space, the mess room). Here we found peak values of a 1500 ppm till well over 2000 ppm in the less favourable spaces. In the better ventilated smaller ships peak levels were in the 800-1000 ppm range. In the mess rooms of the three smaller ships that were under ventilated we found that the limit of 1000 ppm was exceeded more than 3 hours, in one case this occurred more than 8 hours.

### 3.3 Qualitative results

Below the most relevant qualitative findings are summarized:

*Overall maintenance*

The on-board ventilation systems were inspected both in terms of technical functionality and overall (internal) hygiene. Despite an adequate amount of fresh air (par. 3.1), if outside air is transported via polluted air handling units and ventilation ducts towards living spaces than the end-result is still suboptimal indoor air quality. The inspections identified very little general issues with overall maintenance or internal hygiene problems. With just one exception: on board of one of the smaller ships we found a (small) air handling unit that was internally polluted (with rust, unidentified debris, sooth). Also in all ships, filter sections were found to be in good shape. Filter exchange frequencies were also in line with manufacturer's instructions. The overall conclusion was that the systems on board of the ships were well-maintained, especially when compared with standard HVAC maintenance levels in offices and schools.

*Recirculation*

The majority of the ships that were surveyed were not equipped with central air recirculation sections or had central recirculation sections that were indefinitely in '100% outside air mode'. Though, there were exceptions: one of the larger ships used recirculation, only when in 'heat-up' mode before patrols started (usually with 50% outside air). Another ship was equipped with a 100% recirculation option that was only used when this ship was involved in oil spill cleaning / chemical disaster mitigation (to prevent polluted air from entering the ship).

As far as decentral recirculation (at room level) is concerned: this was quite common especially in wheel houses, both in the larger and the smaller ships. Often decentral recirculation was part of an separate cooling system (split unit) that could be operated independent of the ventilation system (Fig. 2). Such decentral recirculation are seen as less of a problem than central recirculation [6]. That is, as long as 'other systems' (the basis ventilation systems) provide for adequate fresh air amounts independent of whether additional cooling systems are on or off (independent of outside whether).

*Personal control of mechanical air supply*

On board of most ships we found quite adequate options for end-users to control the mechanical air supply. For example, in many sleeping quarters of the larger ships, we found *adjustable* supply grills integrated in the ceiling (figure 3). This is positive as we know from several studies, that when people are provided with effective options to finetune fresh air supply and e.g. temperature that people are more satisfied with their indoor climate and less likely to develop certain health symptoms [11]. On the other hand, in many of the living spaces there was no option for additional natural ventilation (see also under 'operable windows').

Moreover, nearly all ships had good options at central level to influence ventilation for the ship as a whole: in all cases overall air supply for all living spaces could be manipulated in the wheelhouse from a central HVAC system dashboard. Sometimes this was an advantage and sometimes not: none of the rooms were equipped with $CO_2$ monitors to help those on board to timely identify underventilation situations. Also in once specific case (ship S-M1) we found that ventilation control knobs were used sub optimally due to noise problems: ventilation capacity of the system in place here was very adequate (with fresh air supply of 77 $m^3/h$ per person with system in highest setting) but this generated such high installation noise levels that in real live situations people decided to keep the system in a very low setting, resulting in  in $CO_2$ levels far above 1000 ppm despite an 'adequate' (but noisy) system in place.

Other examples related to central manual operation of the on board ventilation system: in three of the 16 ships we found problems related to issues with inappropriate use of control knobs for i. the central ventilation system and ii. a decentral, locally recirculating cooling system (split system). Especially with warm weather it probably happens a lot that people turn on the cooling system (recirculation) only, but do not switch on the fresh air supply. This leads to high $CO_2$ and human bio effluent concentrations that are not easy to detect with the human nose [12]. A situation that should also be avoided as far as cross infection risks during pandemics and epidemics are concerned [4][13].

*Operable windows*

Most of the 16 ships were not equipped with operable port-holes or other types of operable windows. On the one hand this does not make sense as the ships involved, when on patrol, find themselves in excellent outside air (e.g. at sea). Nevertheless, operable parts in ships nowadays often are avoided due to insurance requirements and to avoid that ships take in too much spray- and rainwater during stormy, rainy weather. We found that the wheel houses, especially those of smaller ships, often did  have operable windows (see figure 4) and/or doors with access to the deck. Some of these were well-designed (with devices that helped to keep windows and doors fixed in certain positions also with fluctuating winds), some lacked such devices.

*Cross flow grills*

To ensure that supplied air is distributed well within a ship as a whole it is essential not just to ensure enough air supply in living spaces and adequate exhaust 'further down the hall' (for example in the galley, in toilets and in bathrooms), but also that air can flow from living spaces to the adjacent hall. This is especially important on board of the larger ships that were only provided with mechanical supply *and* exhaust at room level. To enable cross-ventilation it is essential that internal doors are equipped with overflow grilles in entrance doors or substantial cracks under those doors. On many of the larger ships we noticed a lack of such 'overflow options'. In one case we found cross flow grills in cabin-doors that were adjustable but that according to end-users were often closed as they were perceived as not well sound-insulated.

**Fig. 2** - Example of additional, separately operated, cooling system in wheel house of one of the smaller ships for day patrols (fan coil unit).

**Fig. 3** - Example of supply grill in the mess room of one of the larger ships; note the red handle that can be used to influence the amount of air supply.

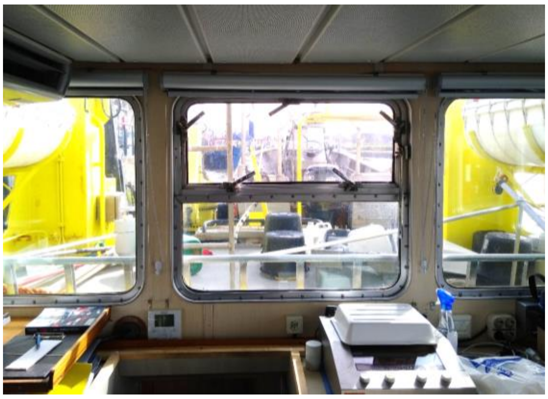

**Fig. 4** - Example of on-board operable window

## 4. Study Limitations

This field study has a few limitations.

We worked with a sample that is supposed to given insight in the situation on board of the whole fleet (97 ships). To be able to do this, it is necessary that the objects studies were selected truly ad random. This in real live was only partly possible because of practical aspects (e.g. patrol schedules, non-proximity to some harbours that are used by the Rijksrederij). This is something that should be kept in mind when interpreting the results.

Also, the indirect assumption during this study was that when one ventilates in accordance with the ISO and Germanischer Lloyd requirements that this implies a space was 'safe enough' in terms of COVID-19 transmission risks (as far as the airborne route is concerned). In real live it is not just air supply per person that matters but also aspects like in-between-person distance that can be kept, ceiling height, overall space volume, air distribution patterns etc that determine how 'safe' spaces are. [4] [13] Another aspect that should be kept in mind when interpreting the results.

As far as the calculated fresh air supply per person is concerned (see table 2): we calculated these values based on the overall air supply that we measured in each space (for all supply grilles combined) and divided that by the amount of persons that normally should be present in a 'full use' situation (full use as normal during the COVID period). These occupancy estimates were made based on on-site verbal information provided by the captain or marine engineer. The actual occupancy at times in the different spaces of course could differ a bit from our estimated occupancy. Yet another aspect that should be taken into account.

A remark related to the $CO_2$ measurements: these were primarily done to objectify olfactory discomfort and to identify possible issues with actual fresh air supply during patrols. Elevated $CO_2$ concentrations, that people are exposed to for a considerable amount of time, also influence task performance negatively [14]. Something that is especially important e.g. in the wheel houses. In that context we reported back to the Rijksrederij that in some of their ships (4 of the 16 ships that we investigated) they had task performance risks related to suboptimal fresh air supply. An extra reason (apart from the COVID-19 airborne transmission risk) to 'repair' the situations on these 4 ships.

As far as actual infection risks on board are concerned: we also calculated the theoretical probability of airborne cross-infection making use of the Wells-Riley method making used of a method as described in [15]. These results will be published at a later stage and are outside the scope of this article. Just to get an idea of orders of magnitude, however: we found P-values (probabilities of infection with I=1; one infected person in the room) in the range of 10-30% in the worst ventilated wheel houses and mess rooms (assuming 4 hour shifts in wheel houses and 2 hour dinner/relax session in mess rooms). In well ventilated larger wheel houses and mess rooms P-values often were < 1%. As far as the living quarters were concerned: often P-values were 0% as in most situations people slept alone in a cabin. There were people did share cabins we found P-values >50%. (Input values used for the Wells Riley calculations were as follows: virus type assumption: original Wuhan variant; source strength assumption 25 quanta/hour (assuming that people on board now and then talk with each other); breathing volume assumption 0,6 $m^3$/hour; other assumptions: no mask wearing on board; nobody vaccinated or immune).

## 5. Conclusions

Objective nr. 1 was to find out whether the most important spaces on board of the ships were adequately ventilated or not. We found out that 3 of the 8 larger ships and 3 of the smaller ships suffered from too little fresh air supply and elevated $CO_2$ concentrations. This implies, assuming a representative sample, that about 65% of the whole fleet is ventilated adequately (in line with ISO / Germanischer Lloyd requirements) but that 35% is not.

The 2[nd] objective was to find out whether there were any other ventilation related risk factors of importance on board. On the positive side: many of the ships had adequate options, at room level, for individual control of fresh air supply (e.g. with adjustable ceiling grills). We also found that central recirculation was shut off or absent anyhow on most ships. Installation noise was an issue on a few boats, especially in wheel houses. Leading to people shutting off systems. Sometimes control knobs for i. fresh air supply and ii. separate, local cooling were mixed up / not used optimally. Operable windows were not available in most cases for additional natural ventilation at will. And in some of the larger ships cross ventilation from living space to hall to e.g. galley was hampered by overflow grills in cabin-doors that were closed at all times.

## 6. Recommendations

Apart from tailored improvement measures for the 6 ships that scored suboptimal, the following general advice was presented (for whole fleet):

1. We recommended that all wheelhouses and ideally also all mess rooms should be equipped with $CO_2$ monitors to provide feedback to the end-user. Additionally personnel would have to be instructed to keep $CO_2$ levels below 1000 ppm, ideally below 800 ppm. This should help people to better make use of both existing (adjustable) mechanical ventilation systems and of operable windows and doors.

2. We also instructed the Rijksrederij to try to organize multiple day patrons in such a way that people were able to sleep alone in separate spaces (not with 2 or 4 persons in one cabin sharing the same air all night), especially during pandemics and epidemics. A recommendation that is easier to follow in the newer ships than in the older ones as the newer ones mostly only had 1-person cabins.

3. Furthermore we recommended that a general 'indoor climate & ventilation guideline should be developed for the governmental ships. Normally when a new ship is built or when an existing one is renovated the shipyards decide what requirements to use. To make sure that in the long run the health and comfort performance of the on-board installations is in line with what the 'Rijksrederij' would like to achieve, a dedicated own standard works better.

Apart from this, we also suggested to start a pilot-project on e.g. three of the larger ships for week patrols with additional, stand-alone, recirculating air cleaning devices with HEPA or electrostatic filters. This could further reduce COVID-19 infection risks especially there where occupant density is high and people spend a lot of time, like in mess rooms.

# 7. Acknowledgements

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### *Data Statement*

The datasets generated during the current study are not publicly available due to confidentiality issues. In specific situations the data are available from the corresponding author, assuming permission of the Dutch Directorate General for Public Works and Water Management.