COVID-19 transmission inside a small passenger vessel: risks and mitigation

Luofeng Huang[a, b, *], Soegeng Riyadi[c], IKAP Utama[c], Minghao Li[d], Peiyign Sun[e], Giles Thomas[a]

[a]Department of Mechanical Engineering, University College London, UK

[b]School of Water, Energy and Environment, Cranfield University, UK

[c]Department of Naval Architecture, Institut Teknologi Sepuluh Nopember, Indonesia

[d]Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Sweden

[d]School of Engineering and Informatics, University of Sussex, UK

Abstract: The global shipping industry has been severely influenced by the COVID-19 pandemic; in particular, a significant amount of passenger transportation has been suspended due to the concern of COVID-19 outbreak, as such voyages confine a dense crowd in a compact space. In order to accelerate the recovery of the maritime business and minimise passengers' risk of being infected, this work has developed a computational model to study the airborne transmission of COVID-19 viruses in the superstructure of a full-scale passenger vessel. Considering the vessel advancing in open water, simulations were conducted to study the particulate flow due to an infected person coughing and speaking, with the boat's forward door open and closed. The results have shown that, when the forward door is open, a significant airflow is generated within the boat, which can carry the viruses to make extensive contacts with the passengers, leading to the suggestion of keeping the forward door closed; when the forward door is close, virus particles may not transmit a distance further than a seat's length, before sinking to attach to the deck, based on which, an alternate seat arrangement is suggested. Furthermore, investigations were conducted on the influence of wall-mounted Air Conditioner (AC) on the virus transmission, and it was found that controlling the AC wind direction at less than 15° downward can effectively limit the virus spread. Meanwhile, it is demonstrated that an AC's backflow tends to gather virus particles in a nearby area, thus sitting farther from an opening AC can reduce the risk of being infected. Overall, this work is expected to inform hygienic guidelines for operators to counter COVID-19 and potentially similar viruses in the future.

Keywords: COVID-19; Passenger Vessel; Virus; Airborne Transmission; Computational Fluid Dynamics; Particle modelling.

*Corresponding author: ucemlhu@ucl.ac.uk

1. Introduction

The maritime industry has been severely affected by the COVID-19 pandemic. Ships are currently operating with reduced capacity or restricted from leaving port. In particular, the operation of passenger vessels has been reduced by up to 42.77% (Millefiori et al., 2021). Crew and passengers can be exposed to a serious risk of contagion, since the compact and crowded space of ships implies a high likelihood of COVID-19 outbreak. In this context, there is an urgent need to research the best technical solutions to ensure COVID-19 safety for ships (Thomas et al., 2021).

COVID-19 infection has been found to be primarily induced by inhalation (Jin et al., 2020). The virus can be transmitted via air, existing in a form of aerosols and droplets injected by humans coughing, speaking, breathing, singing and sneezing (Vuorinen et al., 2020). Coughing and speaking are the most likely scenarios, as coughing is one of the primary COVID-19 symptoms whilst speaking is almost inevitable in daily contacts and can actually output a significant amount of the virus (Chao et al., 2009). The transmission mechanism of the COVID-19 virus may be referred to in previous work that studied flu, as it has a similar mechanism to SARS (Gao and Niu, 2007).

During ship operations, natural winds, ACs and ventilation systems can induce airborne transmission of virus particles inside a vessel. To investigate this problem, computational modelling has the capability to understand the virus's movement and coverage, which is essential for developing effective mitigation strategies for infection control. To date, computational studies of COVID-19 transmission has been conducted for certain high-risk areas, such as hospitals (Guo et al., 2021) and buses (Zhang et al., 2021). However, relevant research has not been seen for scenarios on board ships.

In this context, the present work develops a model combining Computational Fluid Dynamic (CFD) and Lagrangian particles that can analyse the potential transmission of the COVID-19 virus inside a ship. CFD is used to simulate the airflow whilst the transmission of virus particles is tracked by the Lagrangian approach. The paper starts by introducing the theories and practicalities of the CFD-Lagrangian model, followed by validating the model against experimental measurements of velocity field and particle diffusion inside an idealised room. Subsequently, the room geometry is replaced by the superstructure of a small passenger ship, and analyses were presented on the virus distribution in different scenarios, concerning a passenger coughing or speaking when the boat's forward door is open or closed, and investigating the influence of AC winds on the virus spread. The obtained results are used to discuss measures that may minimise the spread and contagion risk of COVID-19 viruses.

2. Computational approach

2.1 Governing equations

In this work, Lagrangian particles are applied to model the COVID-19 virus aerosols/droplets, by which the particle movement is subjected to its gravity (***G***) and a drag force from its surrounding airflow ($\boldsymbol{F_d}$):

$$m\frac{\mathrm{d}\overline{\boldsymbol{V_P}}}{\mathrm{dt}} = \boldsymbol{G} + \boldsymbol{F_d} \tag{1}$$

where *m* denotes the particle's mass, $\overline{\boldsymbol{V_P}}$ is the particle's velocity, $\boldsymbol{G} = mg$ and g is set at 9.81 m/s^2. The fluid drag force is calculated through the Schiller-Naumann Correlation (Liu et al., 1993):

$$\boldsymbol{F_d} = \frac{1}{2}C_d\rho_P A_P|V_S|\,V_S \tag{2}$$

where ρ_P is the particle density, A_P is the particle project area and V_S is the relative velocity between the particle and the air. C_d is an empirical coefficient calculated based on the particle's Reynolds number (Re_P), which is defined as follows.

$$C_d\begin{cases}\frac{24}{Re_P}\left(1+0.15{Re_P}^{0.687}\right), & \text{if } Re_P \leq 1000\\ 0.44 \qquad\qquad\qquad\qquad , & \text{if } Re_P > 1000\end{cases} \tag{3}$$

The surrounding fluid flow is solved by the standard Reynolds-averaged Navier-Stokes (RANS) equations:

$$\nabla\cdot\overline{\mathbf{v}} = 0 \tag{4}$$

$$\frac{\partial(\rho\overline{\mathbf{v}})}{\partial t} + \nabla\cdot(\rho\overline{\mathbf{v}\mathbf{v}}) = -\nabla\overline{p} + \nabla\cdot\left(\overline{\tau} - \rho\overline{\mathbf{v}'\mathbf{v}'}\right) + \rho g \tag{5}$$

where $\overline{\mathbf{v}}$ is the time-averaged velocity, $\mathbf{v}'$ is the velocity fluctuation, ρ is the fluid density (ρ_{air} = 1 kg/m^3), $\overline{p}$ denotes the time-averaged pressure, $\overline{\tau} = \mu[\nabla \mathrm{v} + (\nabla \mathrm{v})^{\mathrm{T}}]$ is the viscous stress term, μ is the dynamic viscosity ($\mu_{\mathrm{air}} = 1.48\times10^{-5}$ N·s/m^2). Since the RANS equations have considered the turbulent fluid, the Shear Stress Transport (SST) $k - \omega$ model was adopted to close the equations (Menter, 1993; Pena and Huang, 2021).

In particular, a sufficiently-small particle in turbulent flow reveals a randomly-varying velocity field, which induces the microscopic particles to perform constant stochastic motions thus diffusing. This behaviour is modelled by including the effect of instantaneous velocity fluctuations on the particle (Gosman and Loannides, 1983):

$$\mathbf{v} = \overline{\mathbf{v}} + \mathbf{v}' \tag{6}$$

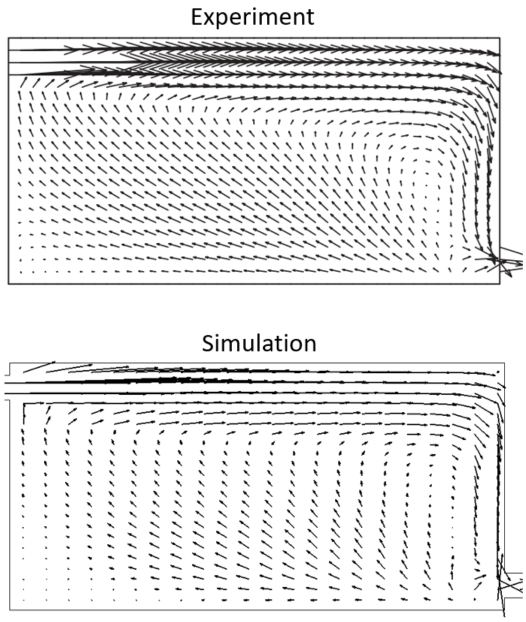
To be more specific, the applied fluid velocity in calculations is $\mathbf{v}$, which is different from a usual RANS approach for macroscopic problems where $\overline{\mathbf{v}}$ is directly used to simplify the calculation, e.g. (Huang et al., 2020).

2.2 Validation

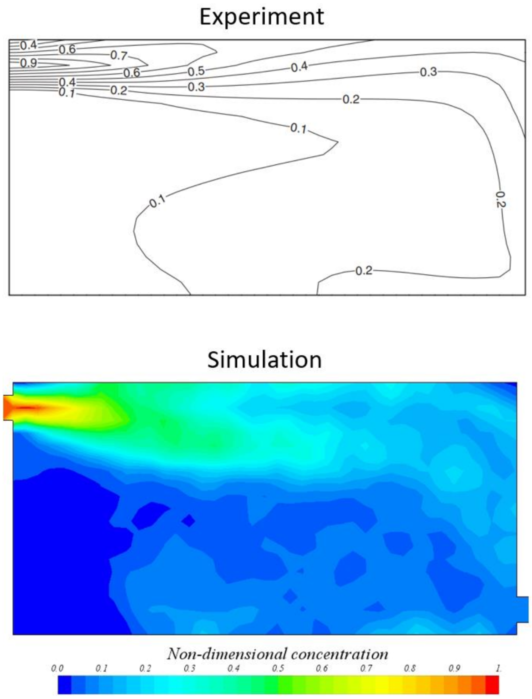
To confirm the suitability and accuracy of the applied equations for modelling the proposed problem. A validation study was conducted against experimental measurements of particle diffusion in an idealised room. As shown in Figure 1, a rectangular room is applied (0.8 m × 0.4 m × 0.4 m), where an air inlet is near the left top side and an outlet is near the right bottom side. From the inlet, an airflow is coming into the room at a constant velocity, carrying artificial particles that have a diameter of 10 μm, which is similar to the diameter of flu viruses.

Chen et al. (2006) measured the velocity profile and particle distribution inside the room, and the developed CFD-Lagrangian model was used to replicate their experiment. Figure 2 compares the experimental and computational results plotted on the central section (profile direction) of the room. It can be seen that the simulation replicated the experimental measurements well, which demonstrates the computational approach used is suitable to study the airborne transmission of COVID-19 virus that is similar to a flu virus. The validation analysis has also indicated the suitable mesh density and timestep size for the simulation, which are respectively 0.05 m and 0.001 s.

Figure 1: The room geometry to validate the computational model. Length: 0.8 m, width/height: 0.4 m



(a) Velocity profile



(b) Particle concentration

Figure 2: Experimental and computational comparison of results, measured on the central section (profile direction) of the room

3. Ship model and COVID-19 risks

Upon validation of the computational approach, the standard room geometry was replaced by the superstructure of a small passenger boat operating in Indonesia, as shown in Figures 3 and 4. This boat is used to transport workers to and from offshore installations such as drilling platforms. The vessel is 19.5 m long and 4.5 m wide, with an internal space of approximately 7 m long. The boat has 25 seats inside, and the computational representation of the internal space is in full scale, which is shown in Figure 5. There are two primary reasons for choosing this boat in the present study:

(1) The operation of this vessel type in Indonesia has been significantly impacted ships by COVID-19. The country, heavily reliant on sea transportation, is looking to recover its crew and passenger operations to aid the economic situation.

(2) The ship's superstructure is compact, and the average voyage time is 12 hours, which gives a high-risk environment of COVID-19 transmission where people stay in a crowded space for a fairly long time.

Figure 3: A small passenger ship operated by PT. Pelayaran Nasional Ekalya Purnamasari (PNEP)

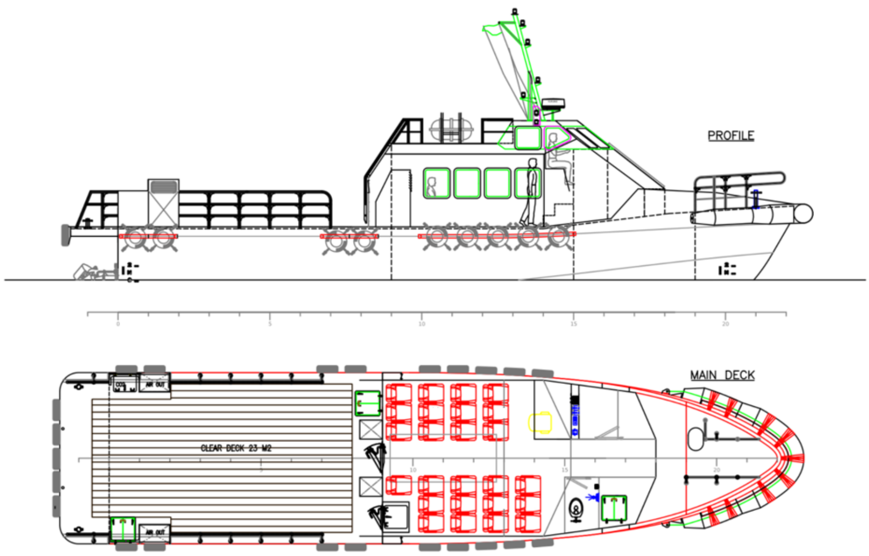


Figure 4: Profile and plan views of the boat's external and internal design

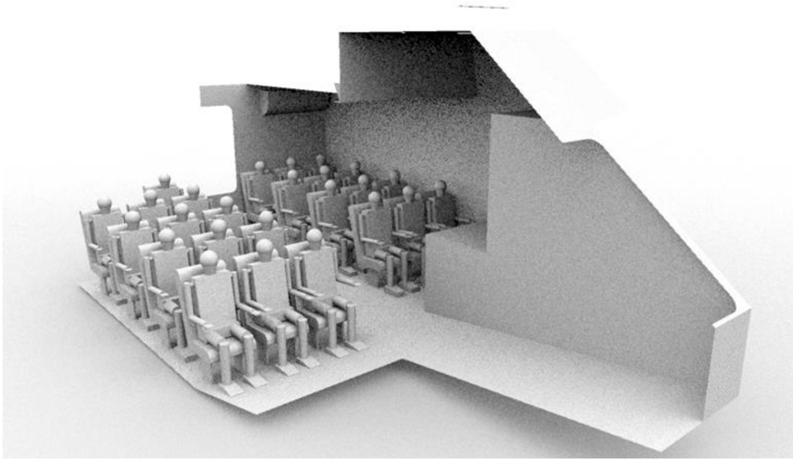


Figure 5: Computational geometry of the boat's internal space

There are two types of virus import mechanisms considered in this work: a passenger coughing and speaking. Both are the most possible initiations of how COVID-19 starts to transmit in such a ship. The simulation details of coughing and speaking were set according to the measurements of Chao et al. (2009), and the details are given in Table 1. Coughing is a short event whose duration is considered to be 0.3 s, and speaking is modelled to last 60 s. The viruses injected through coughing have a higher concentration and initial speed than those from speaking, but overall speaking produces more floating viruses as its duration is much longer. After the coughing or speaking duration, the simulations were kept running to continue tracking the virus movement.

As long as viruses were imported inside the boat, their transmission relies on airflows. There can be two typical types of airflow in the present case: (a) external airflow comes from the vessel's forward door; (b) internal airflow from ACs. Investigations of COVID-19 transmission due to these two types of airflows are presented respectively in Sections 4 and 5.

Table 1: The details of virus import due to coughing and speaking (Chao et al., 2009).

Virus source	Coughing	Speaking
Injection duration	0.3 s, short event	60 s, long event
Inject speed	11.7 m/s	3.1 m/s
Particle diameter	13.5 μm	16 μm
Inject particle number	6950 per second	443 per second

4. External airflow entering the vessel

To study the impact of external airflow entering the boat on the COVID-19 transmission, the boat is assumed to advance at a constant speed (V). When the boat forward door is open, a significant airflow forms in the passenger space (Figure 6), which can cause the viruses to move. By contrast, when the forward door is closed, no airflow is formed inside the boat, so the viruses are considered to only perform gravitational and stochastic motions.

Four case studies were been conducted for V = 6 knots, as a combination of the situations when an infected passenger is coughing or speaking in the first row, and when the forward door is open or close. The coughing or speaking occurred after a 10 s simulation of airflow, which is to ensure that the CFD solution has converged.

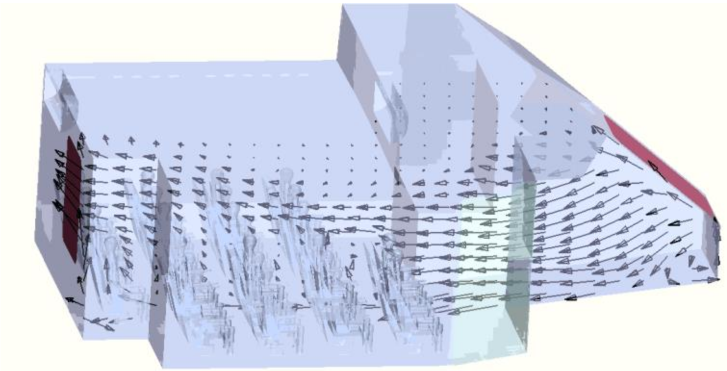
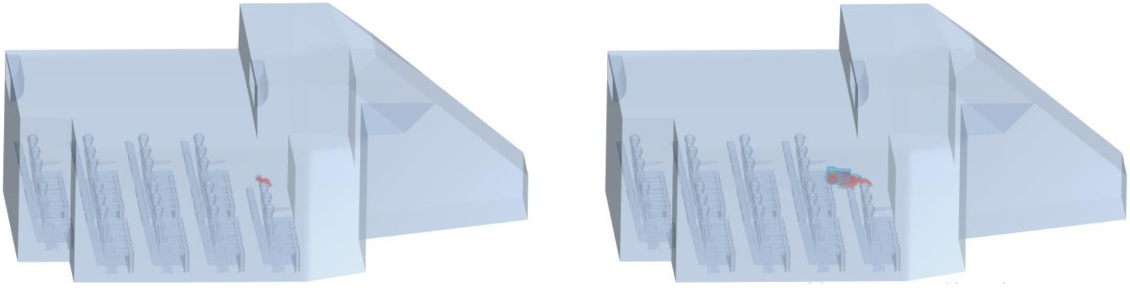


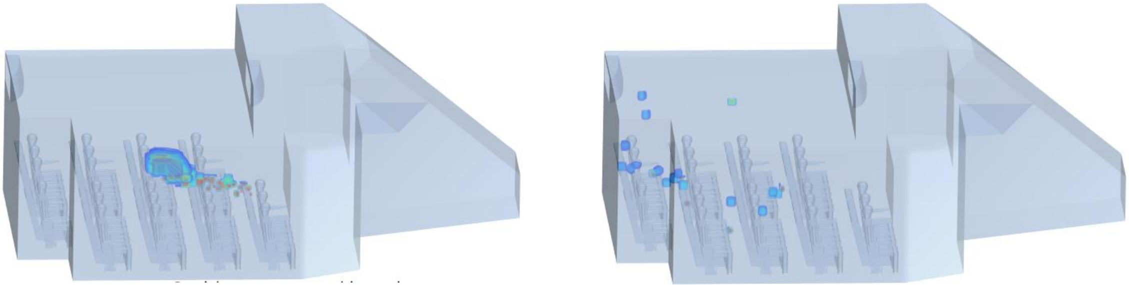
Figure 6: Velocity field inside the crew boat when V = 6 knots, with airflow entering from the forward door

For the simulation of a passenger coughing with the forward door open, it can be seen in Figure 7 that viruses were coughed out and scattered. Along with the airflow, the viruses moved rapidly towards the outlet. For around five seconds, the passengers behind the coughing person were extensively contacted by the viruses, after which the viruses were mostly blown out.

For the simulation of a passenger coughing with the forward door closed, it can be seen in Figure 8 that viruses were coughed out and then only stayed in the area where the passenger sits. The virus movement was mainly a slow sinking due to gravity, alongside a small diffusion due to stochastic motions. Although the viruses stayed in the air for around 100 s, the contagion risk appears to be minimal, based on the assumption that coughing is usually not made directly towards other people.



(a) Left: 0.1 s during coughing; right: 0.3 s during coughing



(b) Left: 1 s after coughing; 5 s after coughing

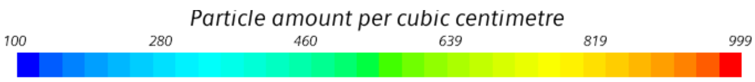
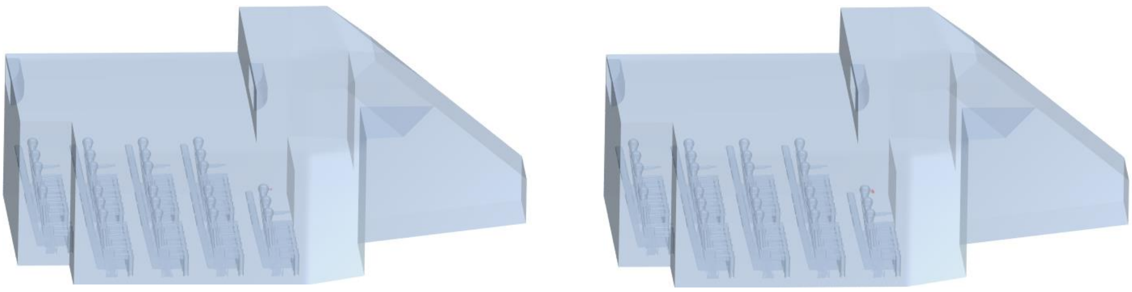
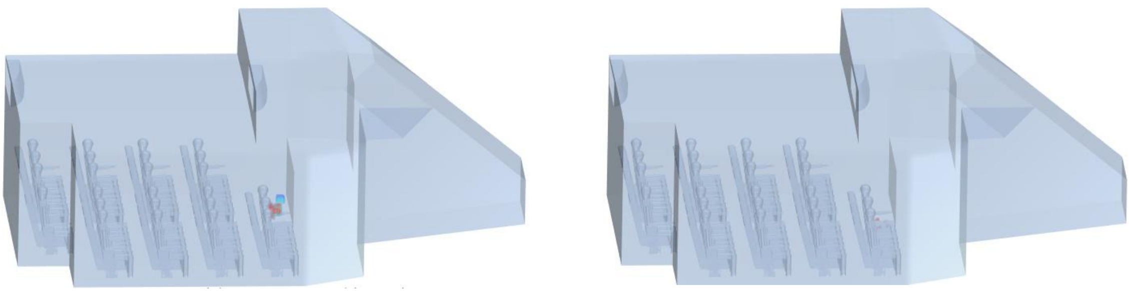


Figure 7: Coughing with the forward door open; the contour indicating the particle concentration is applicable for all following pictures.

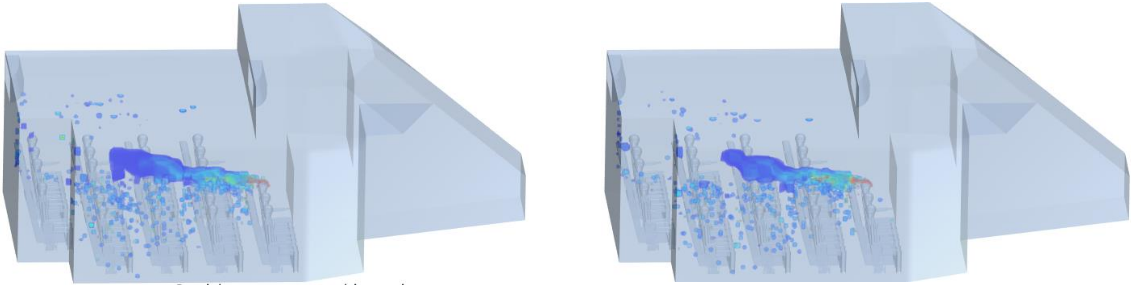


(a) Left: 0.1 s during coughing; right: 0.3 s during coughing

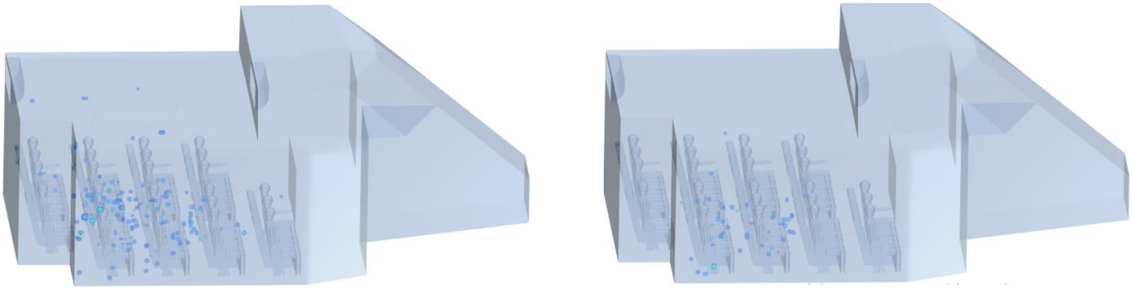


(b) Left: 50 s after coughing; 100 s after coughing

Figure 8:Coughing with the forward door closed

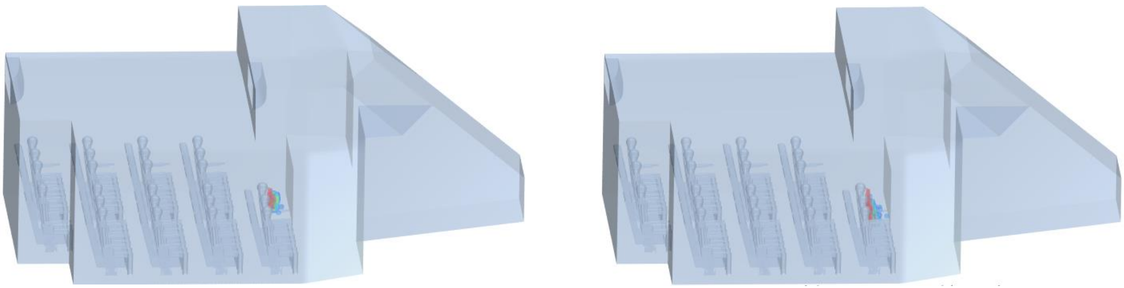


(a) Left: 30 s during speaking; right: 60 s during coughing

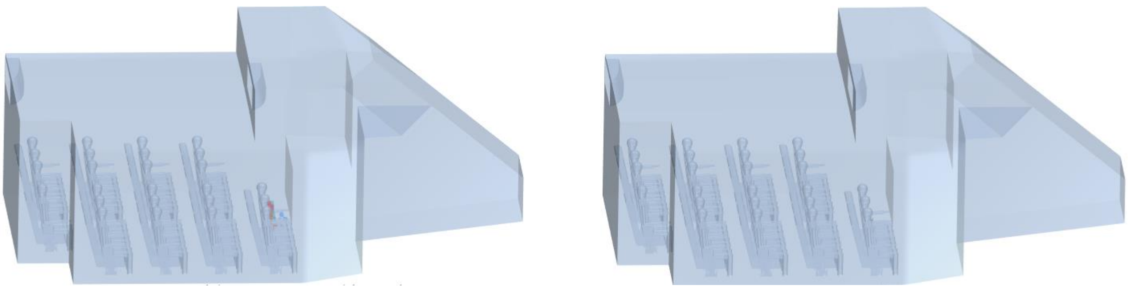


(b) Left: 5 s after speaking; 10 s after speaking

Figure 9: Speaking with the forward door open



(a) Left: 30 s during speaking; right: 60 s during coughing



(b) Left: 30 s after speaking; 60 s after speaking

Figure 10: Speaking with the forward door closed

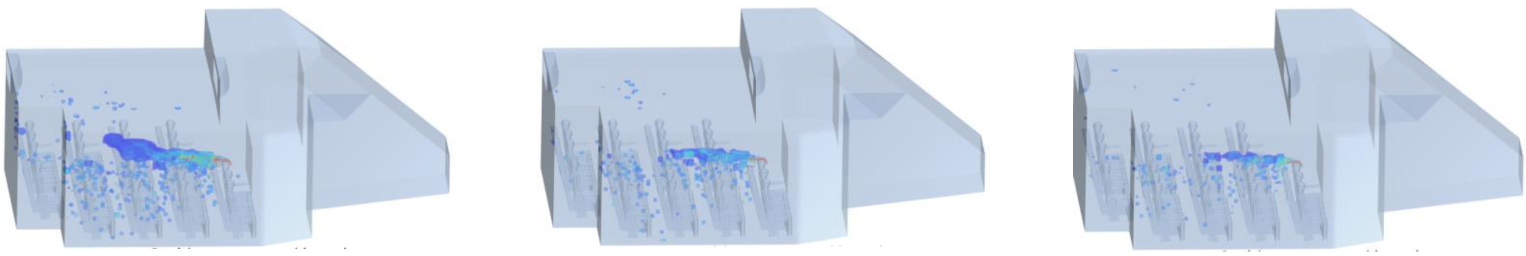
For the simulation of a passenger speaking with the forward door open, it can be seen in Figure 9 that a wake of viruses was created and severely affected the passengers behind the speaking person, especially the next two rows. When the speaking stopped, the viruses were carried away from the boat in 10s.

For the simulation of a passenger speaking with the forward door closed, it can be seen in Figure 10 that a significant number of viruses were output, and the viruses remain in a small area in front of the speaking person. However, since speaking usually occurs as one person facing another, a contagion risk remains if the conversating people are sufficiently close to each other. It is suggested that a safe distance should be at least the length of one seat, according to the virus coverage shown in Figure 10 (a). This confirms that it is necessary to keep social distancing in the installed seats.

Combining the results from the four cases, it is shown that: when the boat's forward door is open, a significant airflow forms in the boat, which carries the viruses to make extensive contacts with the passengers in the back seat rows; when the forward door is closed, the viruses mainly sink due to gravity and the diffusion is limited to a small area. These two behaviours are also observed by relevant experimental and computational COVID-19 studies for other environments, as summarised in the review of Katre et al. (2021). More ship speed conditions (V = 12 and 18 knots) have also been tested for the open-door scenario, concerning an infected passenger speaking. It is found that the virus distribution is similar to that of V = 6 knots, despite that the virus spread is smaller when V is higher, as shown in Figure 11. Overall, it is recommended to keep the forward door closed to minimise the virus's diffusion, although this might be counter-intuitive.

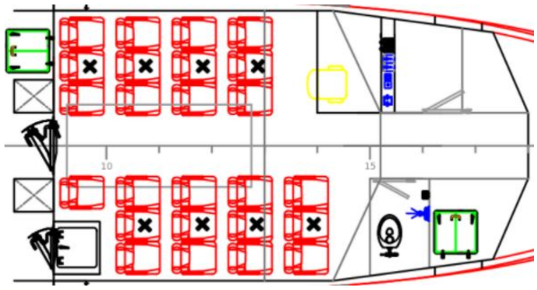
It is also found that speaking generally creates a higher risk than coughing, as speaking usually lasts a much longer duration, thereby more viruses are introduced to the air. Whilst speaking may have been less altered than coughing which is more likely to be treated as a red flag, the present research suggests that more attention should be paid to the COVID-19 risk in daily conversations.

When there is no external airflow, the modelling indicated that a conversation between two people should keep a distance of at least half a meter (a seat long). Based on this, Figure 12 presents two potential seat arrangements for the boat. The aligned arrangement shown in Figure 12(a) reduces the capacity by 33%, and the crossed arrangement shown in Figure 12(b) reduces the capacity by 50%. However, as the setting in Figure 12(a) may not avoid the risk from a front passenger who turns around and speaks with the passenger behind, the social distancing setting in Figure 12(b) is recommended.

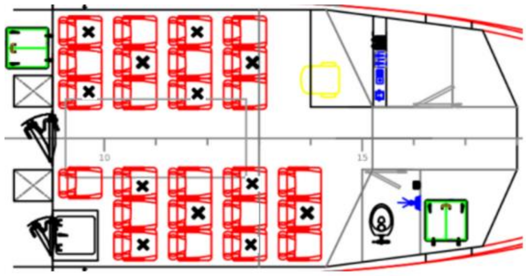


(a) V = 6 knots (b) V = 12 knots (c) V = 18 knots

Figure 11: Comparison of virus distribution for different ship speeds (a front passenger speaking 60 s with the forward door open)



(a) Aligned arrangement



(b) Crossed arrangement (recommended)

Figure 12: Social distancing for the seat arrangement of the passenger boat – black crosses indicate the seats that should not be used.

5. Internal air conditioner flow

There are two wall-mounted ACs installed inside the boat, respectively in the front and back as shown in Figure 13 (AC1 and AC2). Both ACs have an outlet near the bottom and a backflow inlet at the top. This study investigates the influence of each AC's flow direction on the transmission of COVID-19, and the virus source is assumed as an infected passenger sitting on a seat nearby the opening AC, considering the person speaking for 60 s. The wind speed is 2 m/s, which is measured on-site when the AC is operating at its middle power. The wind direction (relative to horizontal, θ) was varied between 0° and 60°, with four cases studied respectively for AC1 and AC2, where θ = 0°, 15°, 30° and 60°.

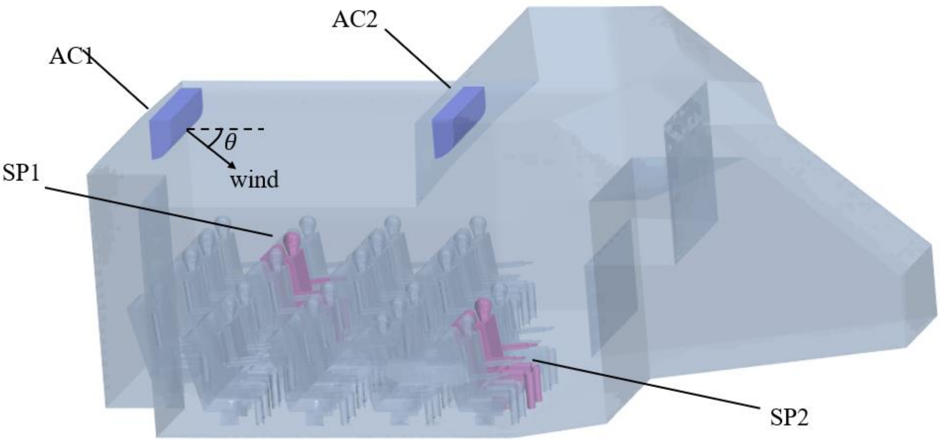
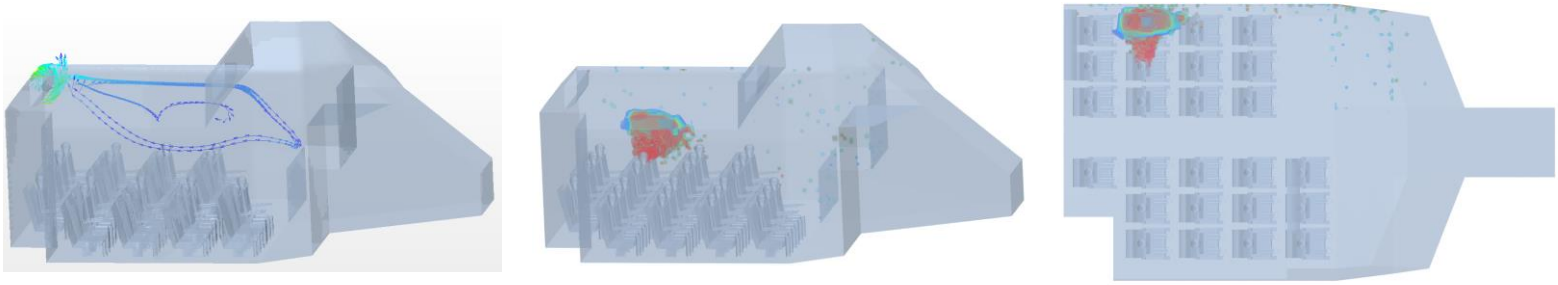


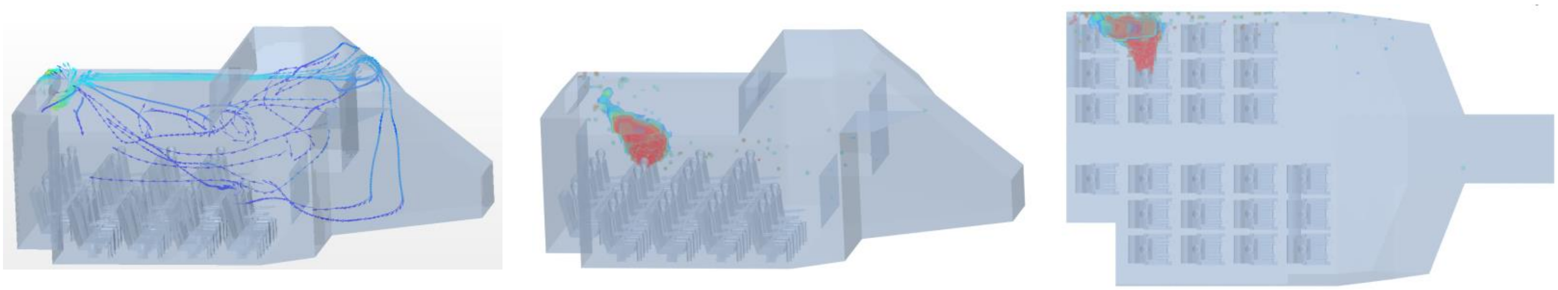
Figure 13: Illustration of two Air Conditioners (AC1 and AC2) and their corresponding virus import as a nearby speaking person (SP1 and SP2).

Figure 14 and Figure 15 show the velocity field and virus distribution inside the boat, when AC1 or AC2 is operating. It is found that a wall-mounted AC can generate a flow circle that is highly dependent on θ. When θ is 0° or 15°, the AC flow is confined in the top part of the room and within a relatively small region, so does the virus transmission. When θ is 30° or 60°, the virus spread is evidently expanded by the AC flow, which is particularly true for AC2, as shown in Figure 15(c)&(d). It is also found that the AC tends to accumulate the virus particles, as in both Figures 14 and 15 where the virus particles gather near the wall at which the AC is installed. This is because an AC's backflow attracts virus particles to move towards the device.

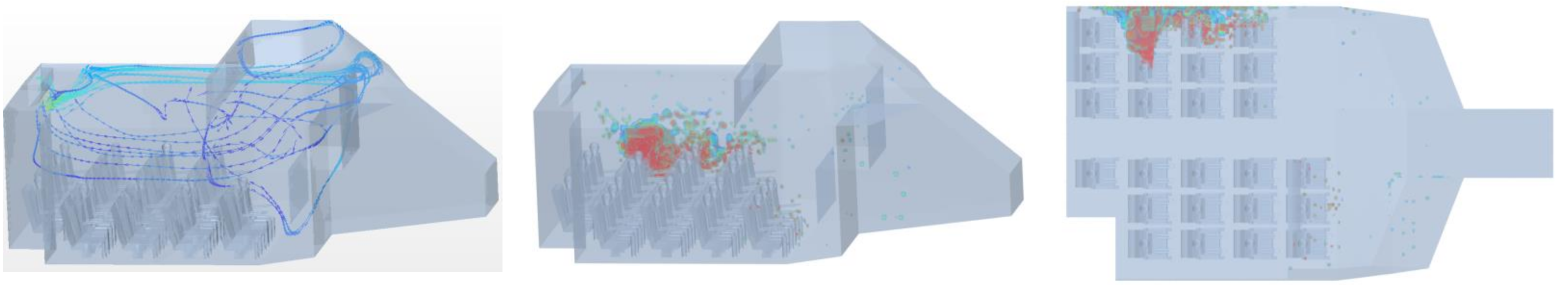
Based on the findings above, two suggestions are given for the AC operation on such a passenger vessel: (a) control the AC wind direction at less than 15° downward, and (b) arrange passengers to not sit nearby an operating AC. The second suggestion can be adapted to other AC types whose inlet and outlet are at separate locations of a room (such as the setup in Figure 1), and the suggestion is to not sit in the downstream of the AC flow.



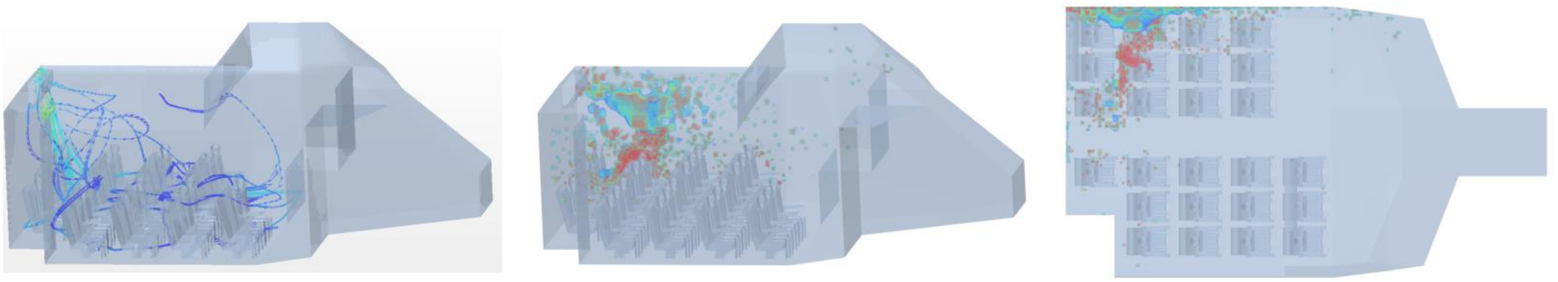
(a) $\theta = 0°$



(b) $\theta = 15°$

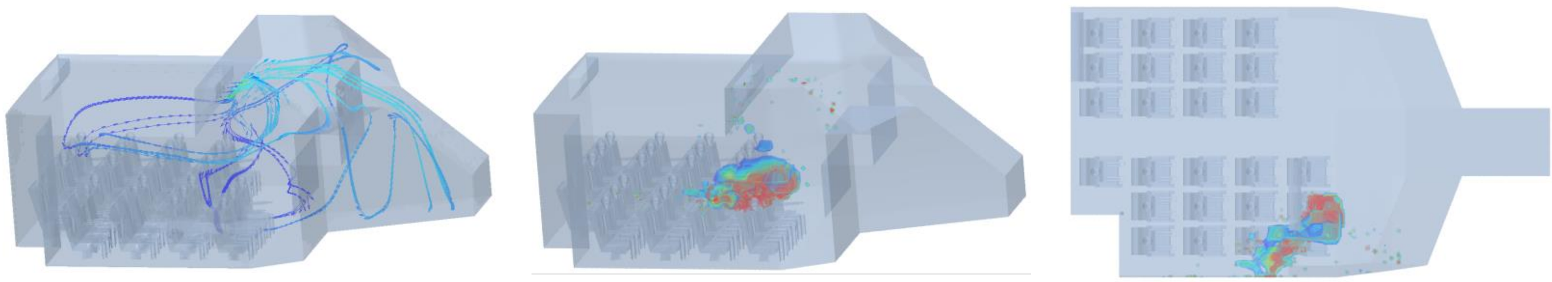


(c) $\theta = 30°$

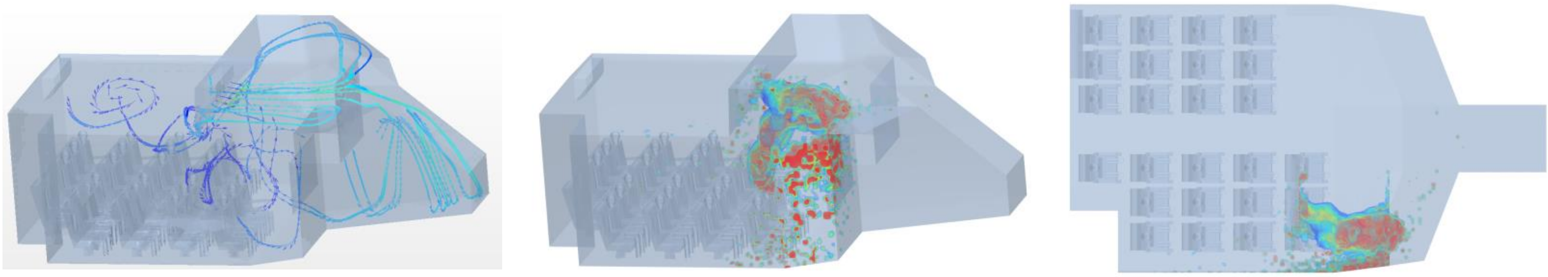


(d) $\theta = 60°$

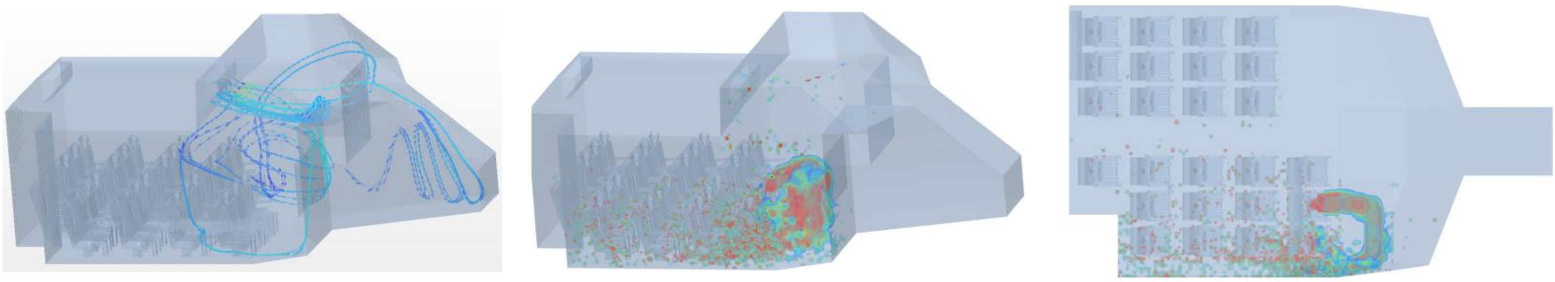
Figure 14: AC1 wind streamlines and the induced virus distribution



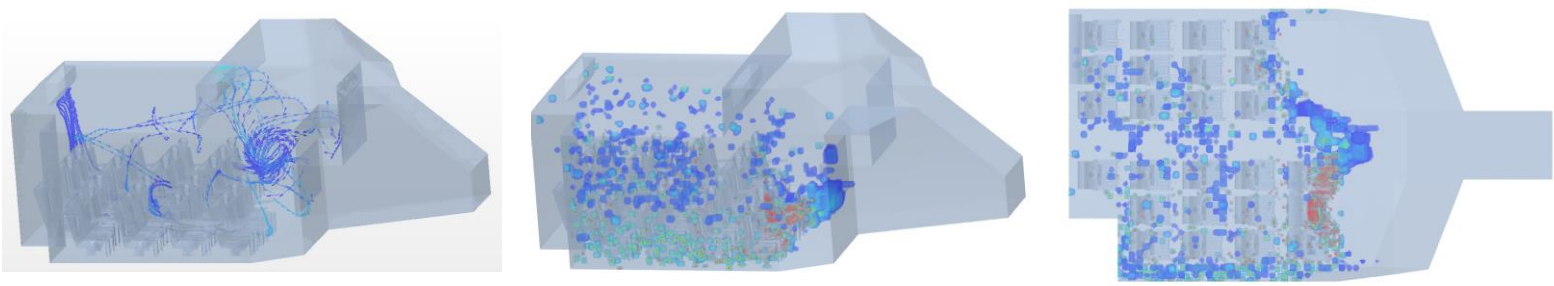
(a) $\theta = 0°$



(b) $\theta = 15°$



(c) $\theta = 30°$



(d) $\theta = 60°$

Figure 15: AC2 wind streamlines and the induced virus distribution

6. Conclusions

To provide effective measures that can minimise COVID-19 transmission for passenger vessels, a computational model has been established to investigate the airborne transmission of the virus in the superstructure of a small passenger vessel. The model was validated against experimental results to prove the capability of accurately predicting the velocity field and virus distribution inside a room.

Based on the validated model, a series of simulations were conducted to study the influence on the virus transmission from both external wind flow and internal AC flow. The simulation results have helped identify operational improvements as summarised below:

- Keep the boat’s forward door shut
- Apply a cross-type alternate seat arrangement plan
- Control the wind direction of wall-mounted ACs to be no more than 15 degrees downwards
- Try not to sit in downstream AC flows.

In future work, the computational approach can be applied to study the COVID-19 airbourne transmission in other environments. Many maritime environments are still at COVID-19 risk which requires more research, such as a large cruise ship, an open-air finishing vessel, and an offshore platform.

Acknowledgements

This work is part of a project that has received funding from the British Council under the Newton Institutional Links Grants - Ensuring the safety of Indonesian seafarers and fishers in the time of COVID-19 and beyond (agreement No. 623457938), in conjunction with the Indonesian Governmental Funding from the Ministry of Education, Culture, and Higher Education (agreement No. 2242/PKS/ITS/2021). The authors appreciate PT. Pelayaran Nasional Ekalya Purnamasari (PNEP) for sharing the vessel’s geometry and information.

References

Chao, C.Y.H., Wan, M.P., Morawska, L., Johnson, G.R., Ristovski, Z.D., Hargreaves, M., Mengersen, K., Corbett, S., Li, Y., Xie, X., 2009. Characterization of expiration air jets and droplet size distributions immediately at the mouth opening. Journal of aerosol science 40, 122–133.

Chen, F., Simon, C.M., Lai, A.C., 2006. Modeling particle distribution and deposition in indoor environments with a new drift–flux model. Atmospheric Environment 40, 357–367.

Gao, N.P., Niu, J.L., 2007. Modeling particle dispersion and deposition in indoor environments. Atmospheric environment 41, 3862–3876.

Gosman, A.D., Loannides, E., 1983. Aspects of computer simulation of liquid-fueled combustors. Journal of energy 7, 482–490.

Guo, L., Torii, R., Epstein, R., Rubin, J., Reid, J.P., Li, H., Ducci, A., Balachandran, R., Tiwari, M.K., Ventikos, Y., Lovat, L.B., 2021. Using portable air purifiers to reduce airborne transmission of infectious respiratory viruses – a computational fluid dynamics study. medRxiv 2021.11.01.21265775. https://doi.org/10.1101/2021.11.01.21265775

Huang, L., Tuhkuri, J., Igrec, B., Li, M., Stagonas, D., Toffoli, A., Cardiff, P., Thomas, G., 2020. Ship resistance when operating in floating ice floes: A combined CFD&DEM approach. Marine Structures 74, 102817.

Jin, Y., Yang, H., Ji, W., Wu, W., Chen, S., Zhang, W., Duan, G., 2020. Virology, epidemiology, pathogenesis, and control of COVID-19. Viruses 12, 372.

Katre, P., Banerjee, S., Balusamy, S., Sahu, K.C., 2021. Fluid dynamics of respiratory droplets in the context of COVID-19: Airborne and surfaceborne transmissions. Physics of Fluids 33, 081302.

Liu, A.B., Mather, D., Reitz, R.D., 1993. Modeling the effects of drop drag and breakup on fuel sprays. SAE Transactions 83–95.

Menter, F., 1993. Zonal two equation kw turbulence models for aerodynamic flows, in: 23rd Fluid Dynamics, Plasmadynamics, and Lasers Conference. p. 2906.

Millefiori, L.M., Braca, P., Zissis, D., Spiliopoulos, G., Marano, S., Willett, P.K., Carniel, S., 2021. COVID-19 impact on global maritime mobility. Sci Rep 11, 18039. https://doi.org/10.1038/s41598-021-97461-7

Pena, B., Huang, L., 2021. A review on the turbulence modelling strategy for ship hydrodynamic simulations. Ocean Engineering 241, 110082.

Thomas, G., Huang, L., Ryan, C., Utama, I., Riyadi, S., Setyawan, D., Hetharia, W., 2021. Safer onboard environments for Indonesian seafarers and fishers in the time of COVID-19 and beyond, in: International Conference on Ship and Offshore Technology. The Royal Institution of Naval Architects (RINA), Surabaya, Indonesia.

Vuorinen, V., Aarnio, M., Alava, M., Alopaeus, V., Atanasova, N., Auvinen, M., Balasubramanian, N., Bordbar, H., Erästö, P., Grande, R., 2020. Modelling aerosol transport and virus exposure with numerical simulations in relation to SARS-CoV-2 transmission by inhalation indoors. Safety Science 130, 104866.

Zhang, Z., Capecelatro, J., Maki, K., 2021. On the utility of a well-mixed model for predicting disease transmission on an urban bus. AIP advances 11, 085229.