Parametric study on ship’s exhaust-gas behavior using computational fluid dynamics

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ABSTRACT

The influence of design parameters related to a ship’s exhaust-gas behavior was investigated using computational fluid dynamics (CFD) for an 8,000 TEU container carrier. To verify the numerical methods, the results were studied by comparing with experimental results. Several test conditions, i.e. various load conditions of ship, wind angle, deckhouse breadth, radar mast height, and exhaust-pipe height and shape were considered for a ship’s exhaust gas flow around the 8,000 TEU container carrier. The influence of the design parameters on contamination by the exhaust gas was quantified, after which the principal parameters to avoid contamination were selected. Finally, the design guideline of $y_P/H = 2$ was suggested to avoid the contamination from the ship’s exhaust gas using the CFD results, model tests, and sea trials.

Nomenclature

| Symbol | Description |
|--------|-------------|
| B      | Breadth [m] |
| $C_P$  | Pressure coefficient [-] |
| D      | Depth [m] |
| H      | Deckhouse height [m] |
| $L_{OA}$ | Overall length [m] |
| $L_{BP}$ | Length between perpendiculars [m] |
| P      | Pressure [Pa] |
| $P_{ref}$ | Reference pressure [Pa] |
| T      | Draft [m] |
| $U_{ship}$ | Speed of a ship [m/s] |
| $U_{wind}$ | Speed of wind [m/s] |
| $x_P$  | Horizontal distance from the front of the compass deck to the intermediate position of the exhaust pipe [m] |
| $y_P$  | Height of the exhaust-pipe from the compass deck [m] |
| $\theta$ | Wind angle [degree] |
| $\rho$ | Density [kg/m$^3$] |

1. Introduction

With container ships becoming larger and faster in recent years, ships up to 18,000 TEU in size have recently emerged. In mega-sized container ships over 13,000 TEU, a twin island configuration that allocates the deckhouse and the funnel separately is primarily used. In terms of exhaust gas disposal, the twin island type is better than an integrated type. On the other hand, 8,000 TEU to 10,000 TEU container ships, which are the main ships operated by shipping companies, have an integrated deckhouse and funnel. In particular, 8,000 TEU to 10,000 TEU container ships cannot secure an appropriate height for the funnel exhaust pipe due to the restriction on the size of ship and air draft according to the port and harbor, making these ships vulnerable to damages related to the exhaust gas.

The exhaust gas causes negative effects on noise, vibration, and heat damage to INMASAT-C antenna by high temperature (Park, Heo, Yu, & Rhee, 2011). Also, exhaust gas includes soot, $SO_2$, or $NO_x$, which are harmful substances. The crew’s health and the air quality deteriorate when it is brought into the deckhouse (Lirn, Lin, & Shang, 2014), and can also cause economic losses due to contaminated cargo.

Many studies have been carried out on contamination and damage related to exhaust gas. Isyumov and Tanaka (1979) studied important non-dimensional parameters while discussing the similarity law required for analysis of the exhaust gas. Seshadri, Singh, and Kulkarni (2006) carried out model tests and found that the exhaust smoke exiting from the funnel was being sucked into the
gas turbine intake. Abdul-Wahab, Elkamel, Al Balushi, Al-Damkhi, and Siddiqui (2008) adopted the industrial source complex short term (ISCST) model and determined the ship’s dispersion of NOx into a port. Park et al. (2011) analyzed a case of antenna damage due to high temperature exhaust gas and mitigated the damage by moving the antenna position, proving the results through a sea trial. Vijayakumar, Singh, Seshadri, and Kulkarni (2012) carried out flow visualization tests to study the influence of many design parameters to the exhaust-gas behavior. Huang, Carrica, and Stern (2012) carried out computational fluid dynamics (CFD) analyses for the temperature and NOx concentration levels due to smoke with 6-degree of freedom in a sea state 8 condition. Ergin and Dobrucali (2014) analyzed the exhaust gas generated from a frigate and compared the result of their analysis with their findings through an experiment. Dobrucali (2012) summarized the current research activities for ship exhaust gas dispersion. The exhaust gas behavior and pollution have been studied through wind tunnel experiments, CFD, and field measurements. However, previous studies were focused on heat and fluid flows around a ship’s topside (Abdul-Wahab et al., 2008; Ergin & Dobrucali, 2014; Huang et al., 2012; Vijayakumar et al., 2012) and structural modifications to the above problems (Park et al., 2011; Seshadri et al., 2006). A design guideline that enables contamination from a ship’s exhaust gas to be avoided was urgently needed.

For this study, experiments, CFD, and sea trials were carried out to analyze the behavior of the exhaust gas. As such, the objectives of the present study are to (1) provide numerical methods for the exhaust-gas contamination analysis, (2) carry out CFD analysis on the behavior of exhaust gas with various design parameters for an 8,000 TEU container ship, and finally (3) present a design guideline that could reduce the contamination from exhaust gas.

2. Model test

2.1. Model description

For the object ship, the present study selected an 8,000 TEU container ship. The model test of the 8,000 TEU container ship was carried out at the wind tunnel experiment facility of Korea Aerospace Research Institute. The quality of the flow in the wind tunnel experiment facility was 0.07% error to the direction of a flow, 0.12% error to the vertical direction of a flow, and 0.08 angles of attack error to the direction of a flow. The principal particulars of 8,600 TEU container carrier for the model scale and full-scale ships are as shown in Table 1 and Figure 1.

In terms of the similarity of the exhaust-gas flow, the model-scale Froude number was identical to the full-scale Froude number (Kulkarni, Singh, & Seshadri, 2005; Park et al., 2011). The Reynolds and Froude numbers were calculated using the funnel diameter and exhaust-gas velocity of the main engine.

2.2. Test conditions

The model test on the visualization and concentration measurement of the exhaust gas was carried out in the Korea Aerospace Research Institute. The 1/220 scale model used in the test is shown in Figure 1. The container models were loaded and unloaded to achieve full load and ballast conditions, respectively. The wind speeds were measured using X-type hot-wire probe (Dantec 55P01). The rotation of the turntable controlled the wind angles. The SO2 volumetric concentration was measured using
Figure 3. SO\textsubscript{2} concentration measurement points.

Table 2. SO\textsubscript{2} concentration test results.

| Point | SO\textsubscript{2} concentration with ballast load condition (ppm) |
|-------|---------------------------------------------------------------|
| 1     | 2.253                                                         |
| 2     | 2.000                                                         |
| 3     | 2.153                                                         |
| 4     | 2.113                                                         |
| 5     | 1.927                                                         |
| 6     | 0.687                                                         |
| 7     | 1.693                                                         |

A hydrocarbon gas analyzer, the VA3001 made by Horiba Instruments. The hydrocarbon gas analyzer used a detector which utilized the non-dispersive infrared (NDIR) method, with range from single digit ppm to 100% concentrations.

Figure 2 shows the exhaust-gas behavior for the ballast load condition with head wind. It shows that the exhaust gas is stagnant at the back of the deckhouse. The exhaust gas visualization and concentration measurement test were carried out together. Figure 3 shows the seven points at which the SO\textsubscript{2} concentration was measured, and Table 2 lists measured SO\textsubscript{2} concentration for the ballast and full load conditions with 25-knots head wind. The SO\textsubscript{2} concentration over 2 ppm was detected from points 1 ∼ 4 located in the deckhouse. 2 ppm SO\textsubscript{2} concentration is an environment in which workers can work for 8 hours, regardless of a ship’s operating conditions (HSE, 2003). Therefore, in order for all workers to work at all points during business hours, it is necessary to improve the funnel design so that an SO\textsubscript{2} concentration less than 2 ppm is detected at all points.

3. Computational methods

3.1. Governing equations

The mass, momentum, energy, and species conservation equations were considered to obtain the velocity, pressure, temperature, and species, respectively. Once the Reynolds averaging approach for turbulence modeling was applied, the realizable \( k-\varepsilon \) turbulence model with the wall function (Park et al., 2013) was selected. The turbulent viscosity was used to close the momentum conservation equations.

The time derivative term was discretized by the first-order accurate scheme. The cell-centered finite volume method was used, and the velocity and pressure were coupled using the pressure implicit split operator algorithm. The convection term was discretized using the second-order accurate upwind scheme, and the diffusion term was discretized using the second-order accurate central differencing scheme. For the two-phase flow, the changes in the density and viscosity were calculated from the state equation. To accelerate the convergence of the solution, the algebraic multi-grid (AMG) method was used along with the Gauss–Seidel iterative algorithm method. The computations were performed using ANSYS FLUENT, a commercial CFD software package. For simulations, the energy equation, viscous model, species transport model, and mixture property of a material were activated in the ANSYS FLUENT software. The under-relaxation value of 0.5 for the velocity, pressure, turbulence kinetic energy, and turbulence dissipation rate were used.
3.2. Computational mesh, domain extent, and boundary conditions

The Cartesian coordinate was selected. The positive x-axis is to backward and aligned with the ship’s longitudinal direction, the positive y-axis is to starboard, and the positive z-axis is to vertical direction. The computational domain size was $-1L < x < 2L$, $-1L < y < 1L$, and $0L < z < 1L$, respectively, and 2.3 million tetrahedral cells were used. Figure 4 shows the typical surface mesh for the ballast and full load conditions, respectively. The antenna and handrail on the compass deck and other small equipment were not considered because their influences on the exhaust-gas behavior were seems to be ignorable.

Steady computations were done for one ship speed ($U_{\text{ship}}$) of 27 knots, two wind speeds ($U_{\text{wind}}$) of 25 and 40 knots (Lasher & Flaherty, 2009), 7 wind angles ($\theta_{\text{wind}}$) of 0, 30, 60, 90, 120, 150, and 180 degrees (Park, Park, & Rhee, 2016), and one engine load of 85% maximum continuous rating. Here, the wind angle of 0 degrees indicated head wind, and the wind angle of 180 degrees indicated following wind. Specified x- and y-direction velocities were defined as:

$$U_x = U_{\text{ship}} + U_{\text{wind}} \times \cos \theta_{\text{wind}}$$

(1)

$$U_y = U_{\text{wind}} \times \sin \theta_{\text{wind}}$$

(2)

The ship surface, inlet, outlet, side, top, and bottom boundaries are shown in Figure 5. The wind and ship speeds without a profile were applied on the inlet and port-side boundaries. For the starboard-side boundary, the Dirichlet boundary condition was applied for 0 degrees wind angle and the Neumann boundary condition was applied for 30 to 180 degrees. For the free-surface flow, the bottom boundary was treated as the slip condition. The reference pressure was used for the outlet boundary. The slip condition was used for the top boundary (Xing-Kaeding, Jensen, Hadzic, & Peric, 2015).

The SO$_2$ concentrations of the exhaust gas from the main and D/G engines were 400 and 800 ppm, respectively. This study assumed the main and D/G engines operated in normal continuous rating (NCR) condition. Thus, the mass flow rate from the exhaust gas was
constant with various loading conditions. The computations were ended after the residuals of all variables and the variation of the SO$_2$ concentration on the seven points in Figure 3 had decreased by ten to the power of four orders.

4. Results and discussion

4.1. Grid uncertainty assessment

The mesh sensitivity tests with coarse, medium, and fine meshes were done. The coarse, medium, and fine volume mesh counts are 0.7, 1.5 and 2.3 million, respectively, as listed in Table 3. The number of meshes in medium mesh and fine mesh was double, and quadruple the number of coarse mesh, respectively. The surface mesh included the hull, container, deckhouse, and exhaust pipe surface boundary meshes. In terms of the detailed description, the maximum and minimum surface mesh sizes with the model scale ship are listed in Table 3. Figure 6 shows the typical surface mesh for three cases. Figure 7 shows the 2 ppm SO$_2$ concentration contour, and Table 4 lists the SO$_2$ concentrations. It showed that the SO$_2$ concentration was converged with increasing mesh count. The fine mesh was selected, and the other computations were carried out with the fine mesh.

Layers, which are parallel to the wall, are needed to capture a boundary layer on the wall. In order to evaluate the influence of layers, both a mesh with a layer and a mesh without a layer were created. Figure 8 shows both meshes around the antenna mast.

Figure 9 shows the distribution of the 2 ppm SO$_2$ concentration for the both meshes. It could be confirmed that an almost identical distribution was shown regardless of the existence of the layer, and thus the layer was not applied to the following computations.

4.2. Validation with wind tunnel test data

To evaluate the computational accuracy of medium mesh without a layer, computational results were validated against the model test results. The computations with the ballast load condition were carried out, in which a high SO$_2$ concentration was measured from the model test results. The 25 knots wind speed with 0 degrees wind angle was considered for inflowing wind. The Spallart–Allmaast model, standard $k$-$\varepsilon$ model, realizable $k$-$\varepsilon$ model and SST $k$-$\omega$ model, which were selected effectively for engineering purposes, were used for the turbulence closure. Figure 10 shows measured SO$_2$ concentration in the model tests and computed SO$_2$ concentration for various turbulence models. There was a slight difference between the computation and the model test results. However, the result obtained by the realizable $k$-$\varepsilon$ model showed a constant difference from the model test result. The experimental uncertainty, turbulence model, discretization schemes, and boundary

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Table 3. Mesh count and size.

|                     | Coarse mesh | Medium mesh | Fine mesh |
|--------------------|-------------|-------------|-----------|
| Volume mesh count (million) | 0.7         | 1.5         | 2.3       |
| Surface mesh count | 48385       | 126055      | 247333    |
| Max. surface mesh size (m$^2$) | $3.155 \times 10^{-8}$ | $1.033 \times 10^{-8}$ | $1.033 \times 10^{-8}$ |
| Min. surface mesh size (m$^2$) | $1.459 \times 10^{-4}$ | $6.537 \times 10^{-5}$ | $4.461 \times 10^{-5}$ |
conditions could be among the reasons for the difference. For the thermal plume problem, the $k$-$\varepsilon$ model was better than the $k$-$\omega$ model (Kumar & Dewan, 2013). Therefore, the realizable $k$-$\varepsilon$ model that showed the same trend was selected, even though it showed a slightly different SO$_2$ concentration.

### 4.3. Influence of wind angle and load condition

The influences of the load condition and the wind angle were evaluated. The 25 knots wind speed was considered. Table 5 shows the SO$_2$ concentrations with the full load condition. It showed that the SO$_2$ concentrations for 7 points were lower than 2 ppm, the minimum requirement for workers to be allowed to work for 8 hours (Health and Safety Executive, 2003). This showed that a container ship that cruises with the full load condition was free from the SO$_2$ contamination.
Table 5. SO$_2$ concentration with full load condition.

| Angle | Point | 0 deg. | 30 deg. | 60 deg. | 90 deg. | 120 deg. | 150 deg. | 180 deg. |
|-------|-------|--------|---------|---------|---------|----------|----------|----------|
| 1     | 0.000 | 0.000  | 0.000   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 2     | 0.000 | 0.000  | 0.000   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 3     | 0.000 | 0.000  | 0.001   | 0.001   | 0.001   | 0.001    | 0.000    | 0.000    |
| 4     | 0.001 | 0.004  | 0.005   | 0.024   | 0.001   | 0.000    | 0.000    | 0.000    |
| 5     | 0.000 | 0.000  | 0.000   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 6     | 0.000 | 0.000  | 0.000   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 7     | 0.035 | 0.824  | 0.462   | 0.004   | 0.000   | 0.000    | 0.000    | 0.000    |

Table 6. SO$_2$ concentration with half-load condition.

| Angle | Point | 0 deg. | 30 deg. | 60 deg. | 90 deg. | 120 deg. | 150 deg. | 180 deg. |
|-------|-------|--------|---------|---------|---------|----------|----------|----------|
| 1     | 0.644 | 0.227  | 0.086   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 2     | 0.020 | 0.389  | 0.860   | 0.087   | 0.000   | 0.000    | 0.000    | 0.000    |
| 3     | 0.300 | 1.141  | 1.540   | 0.162   | 0.001   | 0.000    | 0.000    | 0.000    |
| 4     | 1.491 | 1.875  | 2.459   | 0.661   | 0.066   | 0.000    | 0.000    | 0.000    |
| 5     | 0.021 | 0.074  | 0.185   | 0.009   | 0.000   | 0.000    | 0.000    | 0.000    |
| 6     | 0.008 | 0.071  | 0.771   | 0.751   | 0.741   | 0.032    | 0.000    | 0.000    |
| 7     | 2.019 | 0.843  | 1.105   | 0.077   | 0.001   | 0.000    | 0.000    | 0.000    |

Table 6 shows the SO$_2$ concentrations with the half load condition. It showed that when wind flows in at 0° and 60° wind angles, the SO$_2$ concentration was higher than 2 ppm. Generally, the SO$_2$ concentrations with the half load condition were higher than those with the full load condition. In other words, it could be assumed that if fewer containers were loaded, the exhaust gas was not emitted smoothly.

Table 7 shows the SO$_2$ concentrations with the ballast load condition. It showed that when wind flows in at angles of 0°, 30°, and 60°, the SO$_2$ concentrations were higher than 2 ppm. Furthermore, the SO$_2$ concentrations with the ballast load condition were higher than those with the full and half load conditions. Therefore, it was expected that work environments were contaminated significantly in the sea trial.

Table 7. SO$_2$ concentration with ballast load condition.

| Angle | Point | 0 deg. | 30 deg. | 60 deg. | 90 deg. | 120 deg. | 150 deg. | 180 deg. |
|-------|-------|--------|---------|---------|---------|----------|----------|----------|
| 1     | 2.451 | 0.387  | 0.217   | 0.000   | 0.000   | 0.000    | 0.000    | 0.000    |
| 2     | 2.190 | 1.505  | 0.836   | 0.46    | 0.19    | 0.005    | 0.001    | 0.001    |
| 3     | 2.501 | 2.251  | 1.687   | 1.019   | 0.555   | 0.033    | 0.004    | 0.004    |
| 4     | 2.658 | 2.755  | 2.264   | 1.634   | 0.833   | 0.070    | 0.007    | 0.007    |
| 5     | 2.208 | 1.884  | 1.195   | 0.856   | 0.576   | 0.048    | 0.004    | 0.004    |
| 6     | 1.130 | 2.654  | 2.164   | 1.482   | 0.951   | 0.079    | 0.003    | 0.003    |
| 7     | 1.894 | 1.304  | 0.511   | 0.418   | 0.15    | 0.003    | 0.000    | 0.000    |

Figure 11. Pressure coefficient contours for full and ballast load conditions (a) Full load condition (b) Ballast load condition.

Figure 11 shows the pressure coefficient contours around the deckhouse with the ballast and full load conditions. The pressure coefficient was defined as $(P - P_{ref})/0.5U^2_{ship}$. The wind flows in from right to left. In the ballast load condition, the pressure coefficient above the deckhouse was relatively lower than that with the
full load condition. In particular, the pressure coefficient near the exhaust pipe with the ballast load condition was lower than that with the full load condition. Thus, it was expected that the exhaust pipe with the ballast load condition would not be emitted smoothly in a relative sense. This result showed that the height of the stacked containers was an important variable for the exhaust-gas behavior.

Figure 12 shows the nondimensional $x$-velocity ($U_x/U_{ship}$) contours around the deckhouse with the ballast and full load conditions. The boundary layer was developed thicker with the ballast load condition in comparison to the full load condition. When the exhaust gas was emitted from the inside of the boundary layer, it was expected that some exhaust gas would remain stagnant. It was more advantageous for the exhaust gas to be located outside the boundary layer. Therefore, it was expected that if the position of the exhaust gas was moved toward the bow, the exhaust gas would be emitted smoothly. The longitudinal position of the exhaust pipe on top of the deckhouse acted as a variable when designing the exhaust pipe.

4.4. Influence of deckhouse breadth

To evaluate the influence of deckhouse breadth on the contamination of the exhaust gas, computations were carried out for various deckhouse breadths. The 10% and 20% reduced breadths based on the baseline deckhouse breadth are considered, as shown in Figure 13. Besides the deckhouse, the hull breadth and the exhaust pipe were not reduced. Since high SO$_2$ concentration was measured, 0 degrees wind angle with ballast load condition was considered.

Figure 14 shows SO$_2$ concentration at each point according to variation in deckhouse breadth. There was no change in the case of the 10% and 20% breadth reductions, while the SO$_2$ concentration was reduced at point 6. The $x$-, $y$-, and $z$-momentum of the exhaust gas decided its behavior. The deckhouse breadth variation could affect the $y$-moment of the surrounding flow. Thus, the $x$- and $y$-momentums of the exhaust gas had significant effects on its behavior. From the results, the breadth variation was not significant, and thus it was concluded that the deckhouse breadth was not a dominant factor for the exhaust gas contamination.

4.5. Influence of radar mast height

Since a wind passed the radar mast located in front of the exhaust pipe, the influence of the radar mast was observed while changing the height of the radar mast. The truss structure and antenna located on top of the radar mast were not modeled. Figure 15 shows the baseline radar mast and modified radar mast by raising the height of 1 m. Here, 1 m indicates the full scale-based length.

Figure 16 shows the SO$_2$ concentration for the heights of the radar mast. A somewhat high SO$_2$ concentration was seen by raising the radar mast height. From the results, the radar mast height slightly influenced the SO$_2$ concentration; however, the influence of the radar mast was not an important variable.

4.6. Influence of exhaust pipe height

When the exhaust gas is emitted from the inside of the boundary layer, some will remain stagnant inside the
boundary layer, so the height of the exhaust pipe is an important variable. The influence of the exhaust pipe height was evaluated while raising the exhaust pipe height by 2 m, 3 m and 4 m as shown in Figure 17. Here, 2 m, 3 m and 4 m indicates the full scale-based length, respectively.

Figure 18 shows the 2 ppm SO₂ contour for various exhaust pipe heights. As the height of the exhaust pipe increases, the 2 ppm SO₂ concentration is emitted without being stagnant. Figure 19 shows the SO₂ concentration for the exhaust pipe heights. As the height of the exhaust pipe increased, the SO₂ concentration decreased. This result showed that the height of the exhaust pipe was an important design variable for the emission of the exhaust gas.

**Figure 13.** Variation of deckhouse breadths (a) Deckhouse breadth of baseline ship (b) Deckhouse breadth of baseline ship × 0.9 (c) Deckhouse breadth of baseline ship × 0.8.

**Figure 14.** SO₂ concentration for deckhouse breadths.

**Figure 15.** Variation of radar mast heights (a) Radar mast of baseline ship (b) Radar mast of baseline ship with raising height of 1 m.
with bent type have almost the same concentration, and the bent type shows a slightly high concentration. This showed that the average height of the exhaust pipe was important. In other words, if the average height is high, the shape is not a significant design variable.

4.8. Influence of principal dimensions and design guidance

In the computations, the container height in front of the deckhouse, exhaust pipe height and longitudinal position of the exhaust pipe on top of the deckhouse were important variables. $x$- and $z$-directional variations were more sensitive than $y$-directional variation. To derive the design guideline, new design variables are defined in Figure 22. Here, $H$ is the height of the deckhouse which is not covered with the container, $y_P$ is the height of the exhaust pipe from the compass deck, and $x_P$ is the horizontal distance from the front of the compass deck to the intermediate position of the exhaust pipe. $H$ indicates the load conditions, and $y_P$ is related to the exhaust pipe height. $x_P$ is related the boundary layer thickness, which is generated on the navigation deck. Figure 23 shows the SO$_2$ emission from a sea-trial of a 10,000 TEU container carrier, computational results of 6,000 and 8,000 TEU container carriers, and a model test result of an 8,000 TEU container carrier. Length dimension was non-dimensionalized by $H$. All of the results were summarized with the ballast load condition. 'Good'

Figure 16. So$_2$ concentration for radar mast heights.

4.7. Influence of exhaust pipe shape

To study the influence of exhaust pipe shape, computations were carried out for various exhaust pipe shapes. The straight type, 30 degree bent type and straight with bent type were considered, as shown in Figure 20. Three shapes were designed to have the same maximum pipe height.

Figure 21 shows the SO$_2$ concentration for the shapes of the exhaust pipe. Critical change of the SO$_2$ concentration was not observed. The straight type and the straight with bent type have almost the same concentration, and the bent type shows a slightly high concentration. This showed that the average height of the exhaust pipe was important. In other words, if the average height is high, the shape is not a significant design variable.

Figure 17. Variation of exhaust-pipe heights (a) Exhaust-pipe height of baseline ship (b) Exhaust-pipe height of baseline ship + 2 m (c) Exhaust-pipe height of baseline ship + 3 m (d) Exhaust-pipe height of baseline ship + 4 m.
Figure 18. 2 ppm SO$_2$ concentration contour for exhaust-pipe height (a) Exhaust-pipe height of baseline ship (b) Exhaust-pipe height of baseline ship + 2 m (c) Exhaust-pipe height of baseline ship + 3 m (d) Exhaust-pipe height of baseline ship + 4 m.

Figure 19. SO$_2$ concentration for exhaust-pipe height.

and ‘poor’ were classified depending on whether SO$_2$ concentrations were above or below 2 ppm in the computations and model test, and according to the crew’s working experience in the sea trial. This showed that $x_P/H$ was almost the same, which indicated that a designer couldn’t change the value, and there was a significant difference in $y_P/H$, which indicated that the exhaust pipe height could be changed by a designer. In particular, when $y_P/H$ was less than 2, the exhaust gas was stagnant around the deck-house. This shows that setting $y_P/H$ as larger than 2 for ships constructed in the future is a method that can be used to reduce the contamination from the exhaust gas. Many previous studies have not suggested fundamental guidance to avoid the contamination, but have instead

Figure 20. Variation of exhaust-pipe shapes (a) Straight type (b) Bent type (c) Straight with bent type.

Figure 21. SO$_2$ concentration for exhaust-pipe shape.
focused on heat and fluid flows around the exhaust pipe and top side (Abdul-Wahab et al., 2008; Ergin & Dobrucali, 2014; Huang et al., 2012; Vijayakumar et al., 2012), and shape modifications to above the problems (Park et al., 2011; Seshadri et al., 2006). Therefore, the design guidance using $y_p/H$ was the significant contribution of this study.

5. Concluding remarks

The model test and CFD analyses were carried out to investigate contamination from exhaust gas. The realizable $k$-$e$ model showed the same trend compared to the model test results and was selected for the turbulence closure. In the results for various load conditions and wind angles, a great deal of contamination due to the exhaust gas with the ballast load condition was observed, and this showed that the height of the loaded container in front of the deckhouse was an important variable for the exhaust pipe design. The computations by changing the deckhouse breadth showed that there was no significant influence on the exhaust gas, and it was not an important design variable. The computations performed by changing the exhaust pipe height showed that as the height of the exhaust pipe increased, the SO$_2$ concentration at each point decreased. This showed that the height of the exhaust pipe was an important variable. The computations performed by changing the exhaust pipe shape showed that the average height of the exhaust pipe was an important variable.

From the results, the height of the deckhouse, which was not covered with the container, ($H$), the height of the exhaust pipe ($y_p$) and the distance from the front of the compass deck to the intermediate position of the exhaust pipe ($x_p$) were important design variables as factors which influenced the contamination of the exhaust gas. The results of the model test, CFD and sea trials indicated that designing $y_p/H$ as higher than 2 led to good emission of the exhaust gas. The design guidance for $y_p/H$ was the significant contribution of this study. The design guidance was derived from the data of container ships. To apply the design guidance for $y_p/H$ to other low speed ships, more data are needed. As future work, the wind speed and angle and ships speed should be included in the design guidance.

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