Turbulent Mixing Analysis of Discharge Streams for Open-loop Exhaust Gas Cleaning System

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ABSTRACT

Due to IMO regulations on sulphur oxides (SO_x) emissions after 2020, exhaust gas cleaning systems (EGCS) or equivalent measures are commonly being adopted on ships. For open-loop type SO_x scrubbers, one of the requirements is that, during commissioning of the EGC unit, the pH-value of the discharged wash water plume shall be no less than 6.5, measured 4 meters externally from the ship at rest, verified either by means of direct measurement or by using CFD method. A uniform jet inlet from a circular hole into stationary water was built up using Star-CCM+, to conform with a cited experimental setup. The grids were carefully adjusted to resolve the core region of turbulent mixing at the jet nozzle. The axial velocity profiles at several positions were in good agreement with the experiment results. Also the universal dispersion angle of the jet envelope cone, where the axial velocity is zero, was correctly demonstrated to be about 12 degrees. The volume fraction of wash water and seawater was traced via the passive scalar method, which was then converted to pH-value by using the standard titration curve of seawater. The iso-contour of pH-value equal to 6.5 was captured so as to determine its distance from the discharge point. The test case also included a configuration with an inducer and diffuser mounted at the end of the discharge pipe, which showed considerable effects on the mixing performance and the length of streams.

1 INTRODUCTION AND LITERATURE REVIEWS

MEPC.280(70) was passed in October 2016 by the International Maritime Organization, revising regulation 14.1.3 of MARPOL Annex VI (Regulations for the prevention of air pollution from ships). To preserve the biological and marine environment, EGCS, or any equivalent devices, equipment, or alternative fuel, could be adopted to achieve a sulphur content of any fuel oil used on board ships not exceeding 0.5% m/m on or after 1 January 2020, in accordance with the regulation. However, because the uncertainty of the supply and price has made it hard to predict the commissioning cost, more and more ship owners and designers are going to choose the Exhaust Gas Cleaning System (EGCS) as the major alternative.

EGCS are classified into open-loop, closed-loop and hybrid scrubbers. In principle, the open-loop scrubber system pumps seawater inwards, sprays it through the scrubber with the exhaust gas streams, and absorbs sulphur oxides (SO_x) before discharging the water back to the ocean. The wash water disposed of by EGCS is to comply with the requirement that the pH discharge limit at the overboard monitoring position is the value that will achieve as a minimum pH 6.5 at 4 m from the overboard discharge point when the ship is stationary. The overboard pH discharge limit can be determined either by means of direct measurement, or by using a calculation-based methodology (computational fluid dynamics or other equally scientifically established empirical formulae) to be left to the approval of the Administration.

The discharge of waste fluid into ambient fluid is a classical problem in the environmental fluid dynamics field, where the phenomenon is described as a turbulent jet flow. Hussein et al. (1994) carried out turbulent jet experiments by a variety of measurement methods, finding the decaying rate along the centreline with a virtual source. Pope (2000) summarized a series of experimental findings, which is an important reference for turbulent flows. Numerically, Ashforth-Frost et al. (1996) simulated the velocity field and turbulent kinetic energy for a two dimensional wall jet by the standard *k-ε* turbulence model with a satisfactory outcome. Boersma et al. (1997) and Le Ribault et al. (1999) simulated three dimensional turbulent jet flows respectively by using DNS (Direct Numerical Simulation) and LES (Large Eddy Simulation), the results of which showed agreement with each other. To summarize, the flow characteristics of a round jet with diameter *d* and velocity *U* into still ambient water, regardless of the nature of the fluid (such as air or water) and of other circumstances (such as diameter of outlet and discharge speed), demonstrate three flow similarities, which can be noted as follows and in Figure 2:

1. After full development of the flow field, a conic envelope with zero axial velocity will be presented with a universal angle of 11.8° from the centerline. Thus, the key mechanism of turbulent mixing and dilution is the radial components of the jet flow which entrain the external flow into the envelope.

2. All cross-sections appear identical, except for a stretching factor, and the velocity profile across the jet exhibits a nearly Gaussian shape (bell curve).

3. The velocity along the centreline of the jet decreases inversely with distance from the virtual source, as shown by the constant slope of *U/u(x)* plotted against *x/d*, in Figure 2.

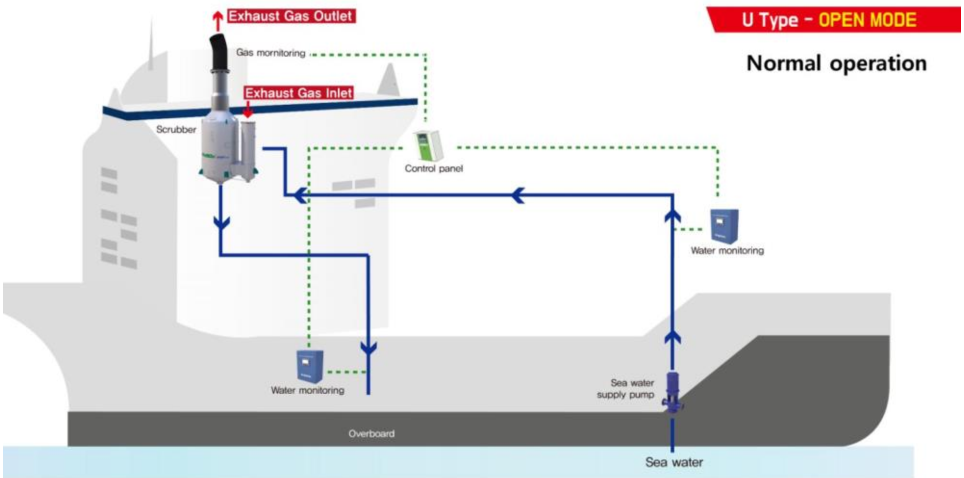

Figure 1 Open-loop type Exhaust Gas Cleaning System [6]

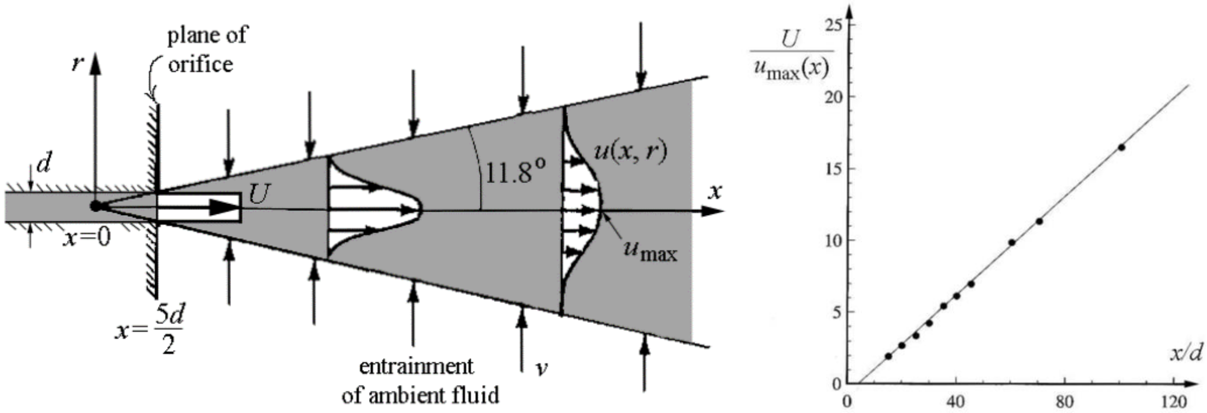

Figure 2 Illustration of flow field of round jet [7]

Another way to improve the effectiveness of the EGCS, while maintaining the original discharge pipe diameter, is to adopt a non-typical design for the discharge pipe nozzle, such as inducers or diffusers mounted at the endpoint; the former splits the jet into multiple branches (Figure 3) to increase the contact area with the seawater, thereby increasing the mixing efficiency, and the latter reduces the outlet velocity and releases the high pressure at the endpoint. The flow field of the non-typical design cannot be solved by the turbulent jet theory of round pipes and it is necessary to employ the CFD method in the analysis. Although the design and construction are complex, it is a practical way to achieve the requirements for the discharged washwater.

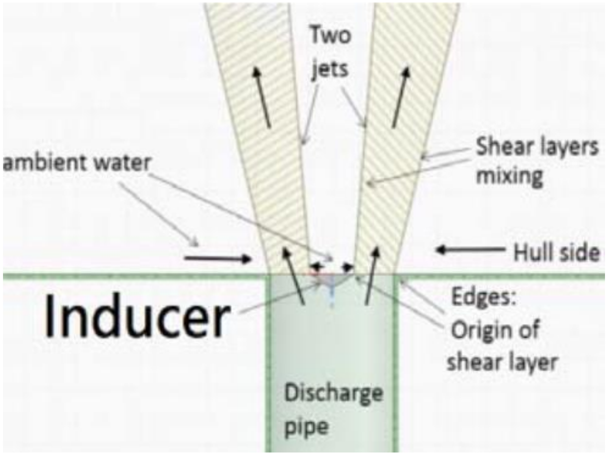

Figure 3 Discharging pipe equipped with inducer

In this study, we have replicated the classical jet flow problem by modeling a uniform jet inlet from a circular hole into stationary water, using Star-CCM+, a commercial CFD software package. Based on the results, we discuss the validity and limitations of the jet flow model. Furthermore, our CFD model also includes a configuration with an inducer and diffuser mounted at the end of the discharge pipe, which showed considerable effects on the mixing performance and the length of streams.

2 TURBULENT JET SIMULATION

In the present study, Pope 's experiment [7] is used for the validation of turbulent mixing jet flow. We used the RANS software, STAR-CCM+, and the flow parameters were defined in the computational domain as shown in Table 1. The ambient fluid in the whole domain is assumed as isothermal water. The specifications of the cylindrical computational domain, which includes a small, cylindrical discharge pipe at the inlet, are shown in Figure 4. Grids were automatically generated by the software in the Cartesian coordinate system. Additionally, refinements were made in the envelope zone with an 11.8° open angle near the inlet. The total cell number was about 9.71 million.

Table 1 Flow parameters

Re	1.00E+05
ρ (kg/m^3)	997.6
μ (N.s/m^2)	8.89E-04
d (m)	0.1
U (m/s)	0.89

In order to have the same condition as the experiments, the fluid in the domain is quiescent initially, with the same fluid injected uniformly from the center of one side of the domain. The boundary conditions in the CFD configuration are: the left hand side of the domain and the discharge pipe cylinder wall set as no-slip walls; the small inlet face on the left-hand side of the discharge pipe cylinder set as velocity inlet; and both the side wall and outlet face on the right-hand side set as pressure outlet. All boundary conditions are shown in Figure 4.

The Reynolds number of the flow though the discharge pipe was 10^5, which reached a nearly turbulent state such that the k-ε turbulence model was adopted. The steady iteration scheme was used to compare with the fully developed flow of the experiment. To capture the mixing ratio of the two fluids with the same properties, two interface capturing schemes, Volume of Fluid (VoF) and passive scalar, were used. The VoF method assigns two separate phases to different Eulerian phases, and governing equation is solved by adding the species mass fraction *M*' in a cell. Where a cell is filled with the primary phase, *M*' is one; and for a cell filled with the secondary phase, it is zero. Comparatively, the passive scalar method puts separated phases into only one phase to track fluid particles by specifying the scalar in the final solution. The former is more general than the latter because it can handle the fluid mixing problem of two different materials. That is, if there is only one material in the problem, the latter approach is preferable. For the initial condition, the scalar is set as one at the velocity inlet and zero in the ambient fluid.

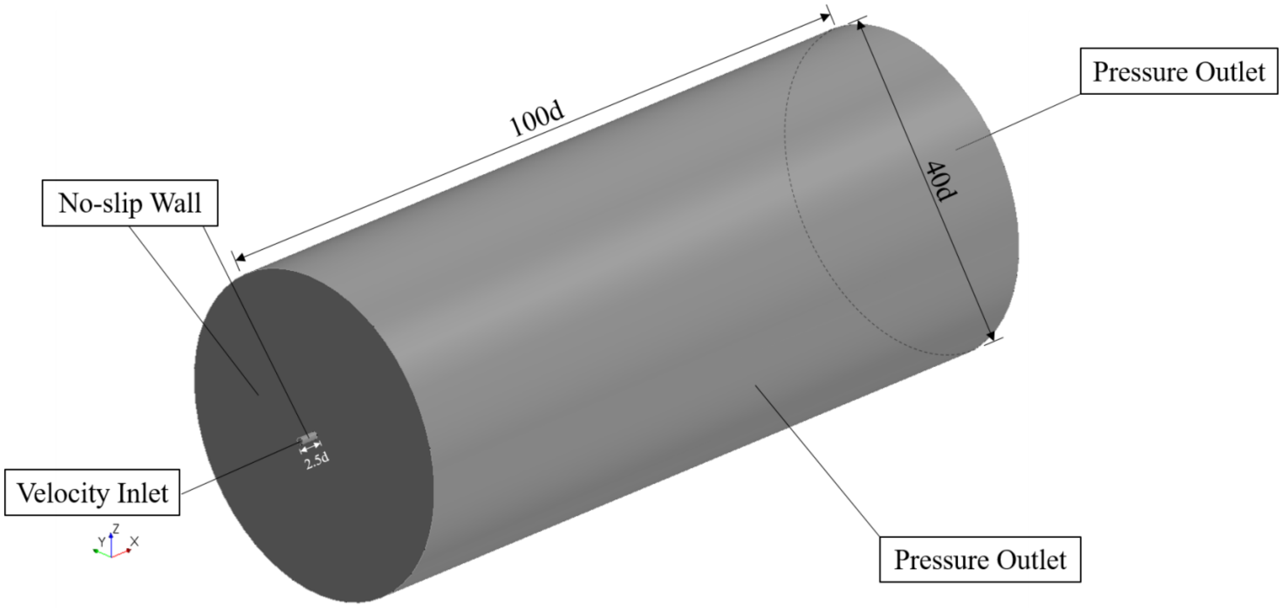

Figure 4 Computational domain and boundary conditions

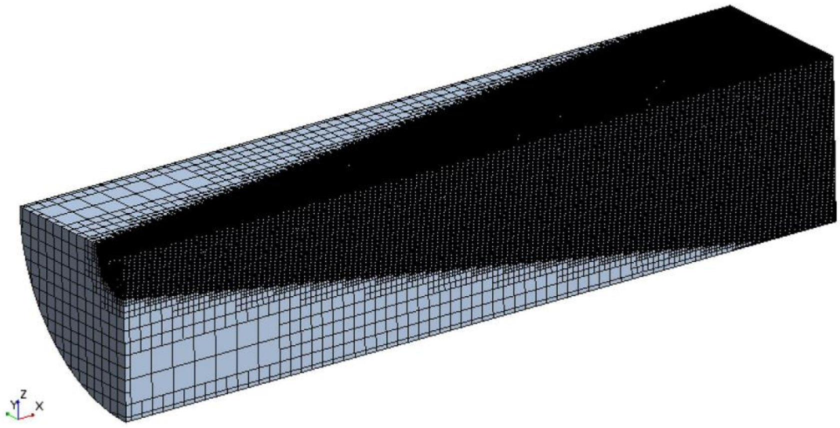

Figure 5 Arrangement of the grid (1/4 computational domain)

Finally, our CFD model also includes a configuration with an inducer and diffuser mounted at the end of the discharge pipe. Figure 6 shows the verification example for non-typical design of discharge pipe, designed in accordance with the specifications in Wartsilla [9]. The 3D geometry was first generated with CAD software and then the above-mentioned numerical settings were used for the simulation. The total cell number and calculation time are much higher than that for a simple round jet.

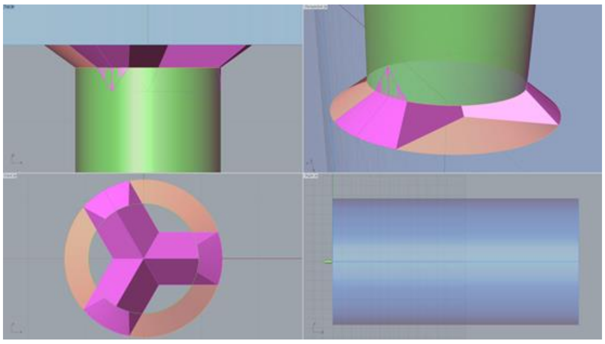

Figure 6: Non-typical design of discharge pipe [9]

3 FLUIDS MIXING AND TITRATION

The numerical residuals for the VoF method and passive scalar method have been compared, as shown in Figure 7, where both residuals converge within thousands of iterations. The residuals of the latter method are on average less than those of the former by one order, which shows that the latter method has better residual stability. Therefore, the passive scalar method was used in the subsequent analysis because of its better convergence and accuracy in the verification case.

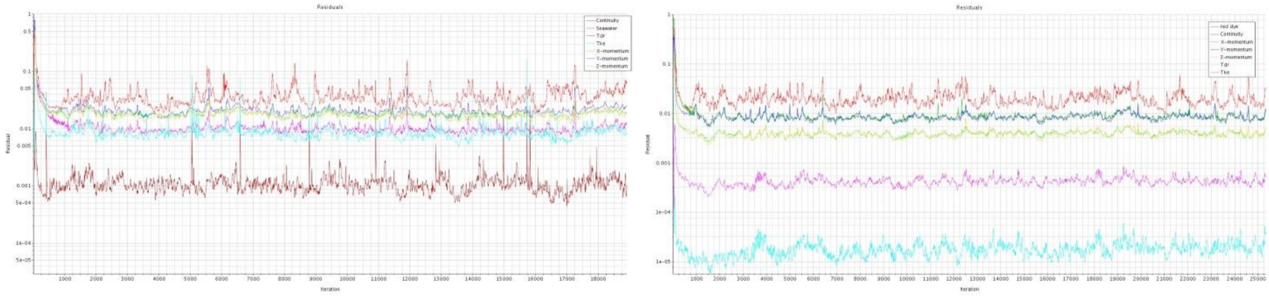

Figure 7 Time history of residuals, VoF method (left) and Passive Scalar method (right)

Based on the concept illustrated in Figure 2, axial velocity profiles in each section are visualized as vector distributions in Figure 8. Moreover, axial velocity profiles in different sections show great agreement with the experimental values, which verifies the fact that the velocity profile across the jet exhibits a Gaussian distribution, as shown in Figure 9 (left).

Finally, the inverse relationship between the maximum velocity in a round jet and distance along the axis of the jet is shown in Figure 9 (right). Although there exist errors to some extent, it still proves the trend that the value of maximum velocity decreases with increasing distance from the discharge hole. The result shows that the x-axis intercept by the linear data-fit is a constant close to that of Figure 2. All values on the left of the sharp corner equal one. That is, the axial velocity is equal to inflow velocity due to little mixing in the region.

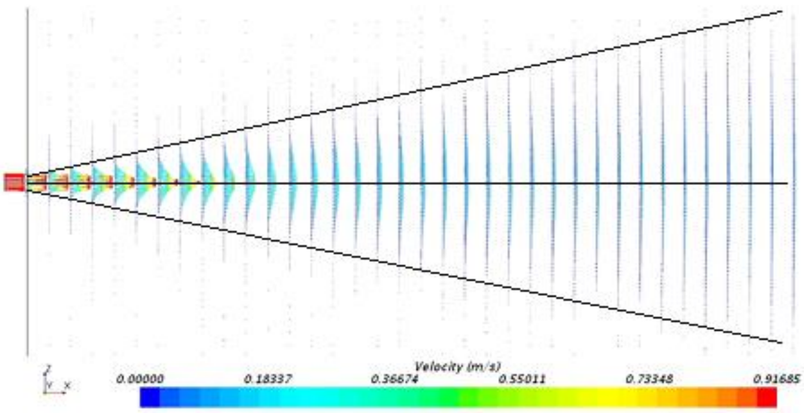

Figure 8 Cross-jet velocity profiles

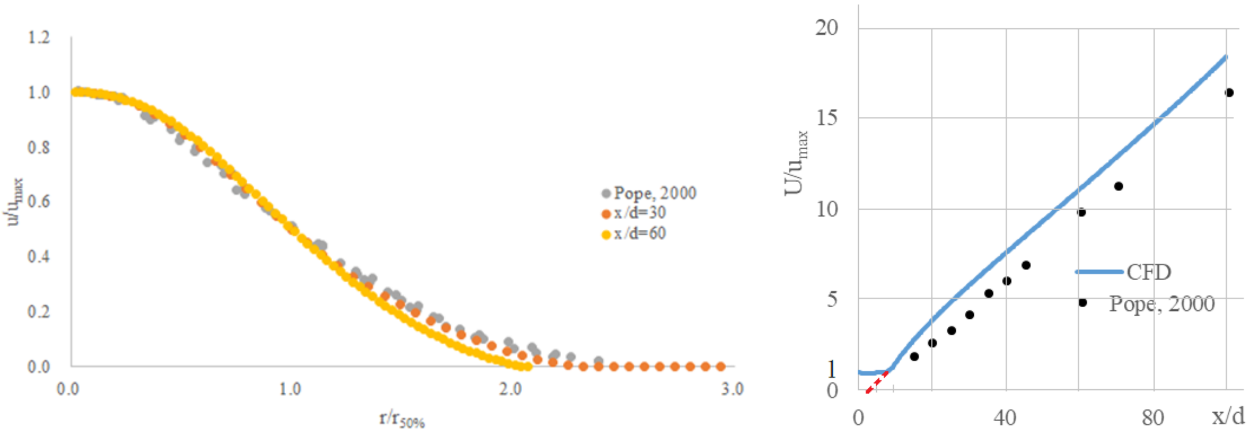

Figure 9 Radial profiles of mean axial velocity (left) and maximum velocity along the axis of jet (right)

In order to determine the chemical neutralization property of a solution, the titration method is commonly used. Typically, an acidic titrant, such as hydrochloric acid, of known concentration, is added to a solution, with the pH value of the solution simultaneously being measured, until the equivalence point is reached. Then, the alkalinity of the original solution may be calculated by measuring the volume of the titrant consumed in the titration process. Finally, the titration curve may be drawn by plotting pH against the volume fraction of the titrant in the solution.

In this study, the pH value of the discharged wash water was determined from the standard titration curve for sulphur dioxide (SO_2) in seawater, put forward by EGCSA [3] , as shown in Figure 8. The x-axis is the concentration of SO_2 that has been dissolved in the seawater and the corresponding pH response is shown on the y-axis. Pure seawater is 2200 μmol/l with a corresponding pH of 8.2. The formula for the fit curve is shown in Eq. (1).

$$pH = 3.84 - 0.2308 \cdot SO_2 + \frac{1.403}{0.0403 + e^{2.966(SO_2 - 0.189)}} + \frac{9.947}{4.605 + e^{4.554(SO_2 - 1.588)}} \tag{1}$$

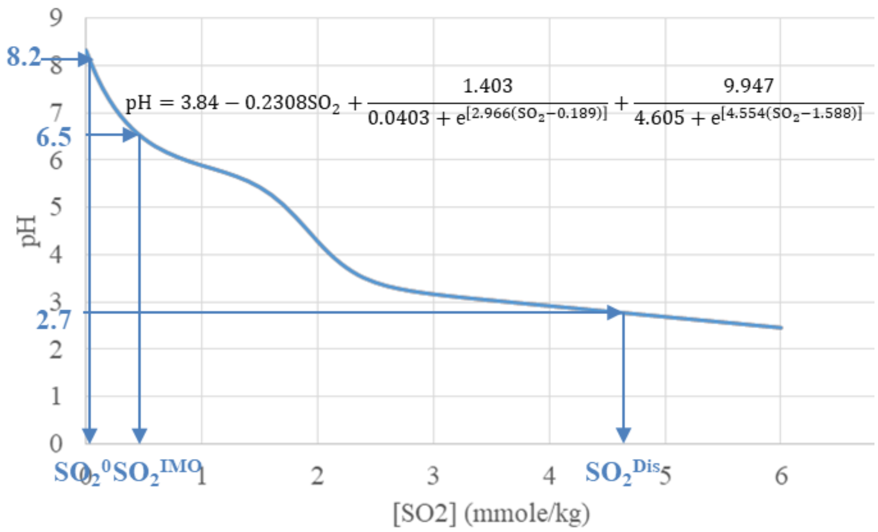

Figure 8 Clean Marine Model of seawater

As an example, let's assume the washwater has a pH of 2.7, recalling that the requirement for minimum pH overboard is 6.5. From Eq. (1), we calculate the concentrations of SO_2 as 4.95 and 0.47 for washwater with pH 2.7 and 6.5 respectively. The dilution factor S can be calculated from Eq. (2):

$$S = \frac{C_{pH@0.0m}}{C_{pH@4.0m}} = \frac{4.95}{0.47} = 10.5 \tag{2}$$

Then, the volume fraction M' of washwater to the whole solution is the inverse of the dilution factor, as per Eq. (3):

$$M' = \frac{1}{S} \cdot 100\% = 9.5\% \tag{3}$$

Namely, a pH 6.5 solution can be produced by mixing 9.5 portions of washwater with pH 2.7 and 90.5 portions of seawater with pH 8.2. The iso-surface for a volume fraction of 0.095, which represents pH 6.5, can be visualized in the software. In the end, we can examine whether the iso-surface intersects with 4 m plane away from the ship to check whether or not the requirement is met for the case.

For capturing the interface between the washwater and seawater, we use a passive scalar to track the volume fraction of the washwater and seawater in all cells. Because density is set as constant throughout the domain, volume fraction can be viewed as the mass fraction as well. From the cross-section of the domain as shown in Figure 9 (left), the red and blue regions represent pure washwater and pure seawater respectively, from which the universal angle can still be identified easily. Along the centerline, the volume fraction evidently decreases with increasing distance from the hole. On the cross-section of the jet cone, iso-lines with values from 0.9 to 0.1 are mapped for comparison. Moreover, if we hold the inlet velocity constant and scale up to two times the original discharge hole, thereby quadrupling the inlet flow rate, and then solve the flow field, as shown in Figure 9 (right), the self-similarity of the volume fraction distribution can be observed. This implies that the diameter of discharge pipe acts as the characteristic length in the turbulent jet flow, and that the normalized velocity profile and the dilution ratio are only dependent on the nondimensionalized diameter of the pipe, rather than inlet volumetric flow rate, which is the important theoretically-based conclusion for turbulent jet flow.

Next, the predicted volume fraction along the centerline is shown in Figure 9, together with the theoretical value [9] (black), as calculated by Eq. (4). Note that Fig X also shows the result for the non-typical design, as discussed below.

$$M' = \begin{cases} 1.0 \quad\quad\quad , & \text{for } x/d < 4.66 \\ 4.66 \cdot d/x, & \text{for } x/d \geq 4.66 \end{cases} \tag{4}$$

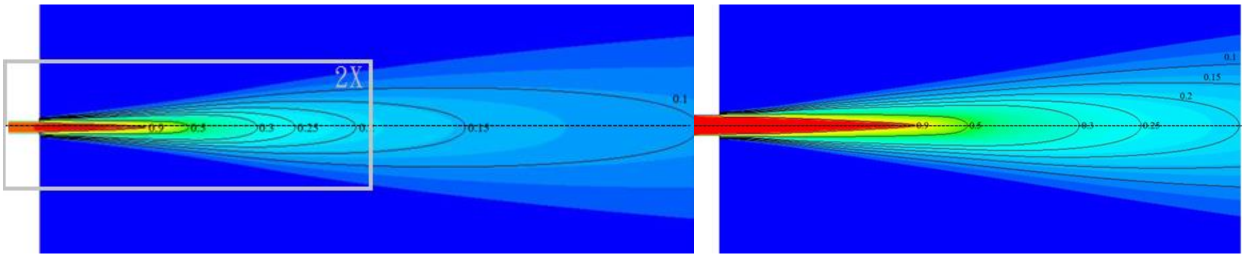

Figure 9 Volume fraction on the cross-section, original (left) and inlet scaled by two (right)

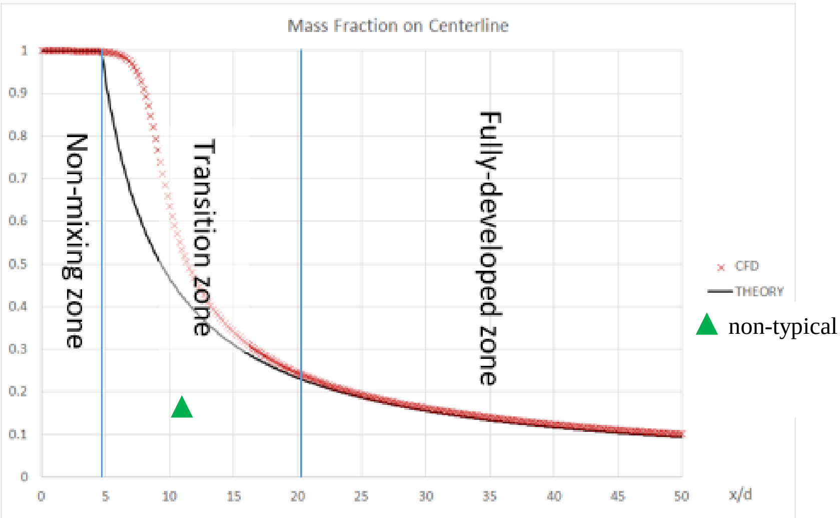

Figure 10 Volume fraction along the centerline

The empirical constant 4.66 is experimentally determined for *x*/*d* greater than 20 in the fully developed flow field. CFD results (red), shown in Figure 10, show three distinct regions:

1. Within *x*/*d* of 4.66, known as the core region, no mixing happens.
2. Over *x*/*d* of 20, known as the fully-developed zone, volume fractions are inversely proportional to the distance.
3. Between *x*/*d* of 4.66 and 20, known as the transition zone, Eq. (4) cannot be applied.

The length of core and the range of fully-developed regions are almost the same as that in the theory, while the transition zone cannot be compared meaningfully because Eq. (4) is not applicable.

In addition, using the above-mentioned titration curve and volume fractions, we calculate the corresponding axial position by substituting 0.095 into volume fraction and, for example, a diameter of d = 10 cm into Eq. (4) for pH 6.5.

$$x = 4.66 * d / M' = 4.66 * 0.1 / 0.095 = 4.9 \text{ m} \tag{5}$$

From the above results, it can be seen, assuming that both the titration curve and volume fraction curve are monotonically decreasing functions, that pH 6.5 will be achieved at a distance of 4.9 meters from the discharge point, which fails to comply with the regulation for pH 6.5 at 4 meters from the ship.

Finally, Figure 11 shows the verification example for non-typical design of discharge pipe. For the three-branched jet flow, the iso-surface of pH 6.5, coloured by distance from pipe outlet, and the contours of volume fraction at a distance of 4 m from the discharge hole are presented to prove that the mixing efficiency is effectively increased. Figure 10 above shows that the simulated non-typical design is able to achieve a washwater pH 6.5 within half of the distance required by the round jet flow.

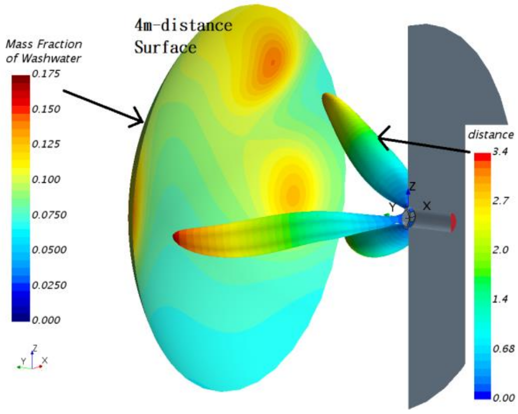

Figure 11 Non-typical design of discharge pipe and flow field visualization

4 DISCUSSION

From the previous discussion, we find that alkalinity of the washwater and seawater solution is dependent on the dilution factor *S*. On the other hand, the acidity of washwater is dependent on the main engine loads and the volumetric rate of the inlet seawater. Larger capacity main engines require larger amounts of seawater for the purpose of dilution so that the pH of washwater can be as high as possible.

Note that the alkalinity of seawater around the world differs dramatically: generally, in the Atlantic Ocean, it is higher, while the seawater is nearly neutral in the Pacific Ocean and near the equator. Hence, when designing an open-loop scrubber system, the navigation route should be taken into consideration and the condition with the lowest alkalinity should be put into the calculations.

Once the dilution factor *S* for pH 6.5 has been determined, the analysis of the flow field is then followed. If a cylindrical discharge pipe design is used, it is easy to derive the axial length of the iso-surface by Eq. (4). In this study, we also developed a spreadsheet program, as shown in Figure 12, by combining the titration model with turbulent jet model to make it easier to check whether the requirements are met. The above-mentioned analysis shows that pipe diameter is the only variable of the volume fraction, and therefore a smaller pipe reduces the characteristic length, so that it is easier to meet the requirements. Given volumetric rate of washwater, if the diameter is reduced by a factor n , the velocity should increase by n^2 and the back pressure by n^4. Although the mixing phenomenon has nothing to do with inlet velocity, higher velocity flow and pressure require strengthened piping systems. Alternatively, the velocity in the pipe may also be reduced by branching into multiple smaller pipes. However, this will definitely complicate the pipe arrangement and watertight integrity of the hull.

	Value		Criteria
Seawater Alkalinity [μmol/l]	2200		500 ~ 2500
Washwater pH	2.70		2.5 ~ 4.0
Nominal Flow Rate [m3/h]	2925		
Inlet Diameter [mm]	250.0		
Num of Struct / Width [mm]	1	0.0	Inducer Design
Num of Discharges / Distance [mm	5	250.0	Discharge Layout
Discharge Angle [deg]	90.0		
Equivalent Pupil Diameter [mm]	250.0		Deff < 267.0
Discharge / Jet Velocity [m/s]	3.31	3.31	Design Spec.
Reynold's Number	8.28E+04		Re > 3000
Neutralization Model	Dilution Test	Clean Marine	**Update DR**
Dilution Ratio	1 : 3.128	1 : 9.375	Dr < 0.38
Jet Length [m] at pH=6.5	4.81	12.09	
Volume Fraction for pH=6.5	0.242	0.096	for CFD
Jet Interference	**NO**		
Developed Turbulent Jet	**YES**	**YES**	
MEPC.259(68) Compliance	**NO**	**NO**	

Figure 12 CR open-loop EGCS spreadsheet

As mentioned, another way to improve the effectiveness of the EGCS, while maintaining the original discharge pipe diameter, is to adopt a non-typical design for the discharge pipe nozzle, such as inducers or diffusers mounted at the endpoint. By adopting such inducers to split the jet into three branches to increase the contact area with the seawater, thereby increasing the mixing efficiency, as well as a diffusing nozzle to reduce the outlet velocity and releases the high pressure at the endpoint, our simulated test case showed a 65% reduction in washwater stream length / reduction in the required distance to achieve washwater pH 6.5. Although the design and construction are complex, our study shows that it is a practical way to achieve the requirements for the discharged washwater. Finally, there are still some minor factors such as the temperature effect on fluid density, probable cavitation at the sharp edges of the inducer, interference effects among the different branched jets, and the influence of jet flow on propulsion performance in operation. These issues require further research.

5 CONCLUSION

In the present study, the numerical analysis of discharge streams for open-loop EGCS has been presented, which was also verified against regulation 14.1.3 of MARPOL Annex VI. A round jet flowing uniformly into a quiescent open area is a classical fluid dynamics problem. In this study, based on the theoretical basis due to these universalities, a series of CFD simulations have been implemented to establish a numerical analysis procedure. If the discharge pipe is a simple cylinder, the universality of the flow field enables us to quickly estimate the dilution situation as well as the pH value. In summary, the following four conclusions can be noted:

1. Different diameters and jet velocities are used in the simulation and dimension analysis. The results show an agreement with the turbulent jet theory, including the envelope with an 11.8° open angle, and non-mixing zone within $x = 4.66d$, as well as a transition zone and fully developed zone. Over the length of twenty times diameter, the dilution ratio along the centreline of the jet decreases inversely with distance.

2. The track of mass fraction by the passive scalar method can be converted into pH value by a given titration curve. The pH contours can be captured to check whether the design of EGCS complies with the regulations.

3. The velocity components in the domain are proportional to the jet velocity which has little influence on the velocity profile, while the diameter of discharge pipe plays a decisive role on the dilution ratio profile.

4. The geometry near the discharge hole, as well as the diameter of the pipe, and inclusion of an inducer or diffuser have a significant effect on the flow in terms of enhancing the mixing efficiency. Furthermore, for a non-typical design of the discharge pipe, we can use CAD and CFD software to check the conformity with the regulatory requirements.

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