PROPOSED DESIGN CRITERIA FOR A BILGE PUMPING SYSTEM: A CASE STUDY OF LARGE BULK CARRIER

Reference NO. IJME 793, DOI: 10.5750/ijme.v164iA3.793

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KEY DATES: KEY DATES: Submitted: 03/11/21; Final acceptance: 29/11/22; Published: 31/01/23

SUMMARY

The bilge pumping system is an important system that secures a ship's stability when a flooding event occurs. Furthermore, the bilge pumping system is designed according to the "2 m/s requirements" and "requirement for the internal diameter of bilge main" of SOLAS Regulation II-2/35-1. The purpose of this study was to quantitatively evaluate the bilge pumping performance of 180K class bulk carriers in service and to propose design criteria for the bilge pumping system. In this study, the performance of the bilge pumping was evaluated using an actual bilge pumping arrangement installed on a 180K class bulk carrier. To evaluate the bilge pumping performance, it was assumed that the No. 1 cargo hold of the bulk carrier was completely flooded, and the average water speed at the main bilge pipe was calculated while all flooded water was discharged. The calculation showed that the actual arrangement did not satisfy the 2 m/s design criterion. The calculations of various modified bilge pumping arrangements were performed to identify arrangements that satisfy the 2 m/s design criterion, and two cases were found. The first case involves applying a smaller main bilge pipe with the same pump capacity, and the second case involves applying the same main bilge pipe and a larger branch bilge pipe and increasing the pump capacity by 140%. Therefore, for the efficient design of the bilge pumping system, it is proposed to exclude the minimum required internal diameter requirement and to use the 2 m/s design criterion as the main design criterion.

NOMENCLATURE

A	sectional area of pipe (mm^2)
B	greatest moulded breadth of the ship at or below the deepest subdivision draught (m)
D	internal diameter of pipe (mm)
DH	discharge head of bilge pump (m)
D_R	moulded depth of the ship (m)
dH	total flow energy loss at bilge piping system (m)
d_m	internal diameter of bilge main (mm)
f	friction loss coefficient
i	iteration number of calculation (subscript)
LH	static head due to water level in flooded compartment (m)
L	length of pipe (mm)
L_E	equivalent length of valves and fittings (mm)
L_R	length as defined in the International Convention on Load Lines in force (m)
Q_b	flow rate of each bilge pump (m^3/h)
R	correlation coefficient for curve fitting
R_e	Reynolds number
SH	suction head of bilge pump (m)
V	velocity of fluid in pipe (m/s)
ΔP	flow energy loss (Pa)
ε	pipe wall roughness (mm)
ρ	density of fluid (kg/m^3)

1. INTRODUCTION

The bilge pumping system is one of the most important systems that secure a ship's stability when a flooding event has occurred. The requirements related to the bilge pumping system are described in the SOLAS Regulation II-1/35-1, which is a fairly old regulation. The major requirements for the bilge pumping system are the "2 m/s requirement" and the "requirement for internal diameter of the bilge main".

Various previous studies have focused on bilge pumping systems. Pawara et al. reviewed the stress generated in each pipe and support of the bilge system of 500 GT ferry using Autopipe (Pawara et al., p.1-12, 2021).

Perez et al. simulated a fire-fighting and bilge system to verify the applicability of the pressure-dependent model to ship piping design using EPANET (Rossman, 1994), a simulation software for water distribution systems (Perez et al., p.266-274, 2020). Tan et al., Bian et al., and Jiang et al. conducted a study on auto-routing of a bilge piping system to efficiently arrange the piping within a complex structure of a ship (Tan et al., p.1296-1301, 2018; Bian et al., p.1-15, 2022; Jiang, et al., p.63-70, 2015).

Various studies on bilge pumping or piping systems have applied the water distribution technique developed based on onshore piping systems to the piping design of ships. Furthermore, studies have focused on technology for efficiently arranging piping systems in the complex internal structure of a ship. However, studies have not focused on the pumping performance of bilge pumping systems.

According to Lee et al., the bilge pumping arrangement of 14,000 TEU class container ships did not satisfy the 2 m/s requirement of SOLAS although the bilge pumping arrangement was suitable for the rule requirements of classification societies. This is because of the correlation between water speed at the bilge main and internal diameter of the bilge main. Lee et al. proposed that the capacity of the bilge pump and actual internal diameter of the bilge main should be used as a dependent variable; however, the capacity of the bilge pump and internal diameter of the bilge main were used as independent variables according to the rule requirements of classification societies. Furthermore, according to Lee et al., the water speed at the bilge main may not satisfy the 2 m/s requirements depends on the size of common and branch bilge pipes as well as the capacity of bilge pumps. In response to the above problems, Lee et al. proposed the following three design criteria in SOLAS Regulation II-1/35-1 to secure bilge pumping performance. (Lee et al., p.A-78-A-79, 2021)

1. *The actual internal diameter of the bilge main should not be less than the required internal diameter of the bilge main according to SOLAS Regulation II-1/35-1.3.9.* **(Internal Diameter Criterion)**
2. *Each bilge pump should be of sufficient capacity with the water velocity to be greater than 2 m/s at the actual internal diameter of bilge main. The study led to the belief that Class Rules should be formulated in such a way that the internal diameter of the actual main bilge and the bilge pump capacity are addressed as dependent variable, not as independent variables.* **(Dependent Criterion)**
3. *The bilge pumping system should ensure that the average water speed at the bilge main is not less than 2 m/s during the discharge of the flooded water from the flooded compartment where it is expected to take the longest time to discharge all flooded water. In addition, when calculating the water speed at the bilge main during discharge of flooded water, the flow energy loss is calculated using Darcy–Weisbach equation and Colebrook–White's equation, and pipe wall roughness of 1.0mm should be applied.* **(2 m/s Criterion)**

In general, a ship is categorised as a passenger ship or a cargo ship; furthermore, cargo ships can be categorised as tankers, bulk carriers, container ships, and others. For large container ships, the bilge pumping performance does not satisfy the purpose of SOLAS Regulation II-1/35-1, according to the study of Lee et al. Hence, the bilge pumping performance of large bulk carriers and large tankers should be reviewed.

In the authors' view, the bilge pumping performance of tankers was not considered in this study because the bilge piping system is not installed in the forward spaces of the engine room except in special cases.

However, a similar situation may occur at the No. 1 cargo hold of bulk carriers which are the same as large container ships, and the bilge pumping performance of large bulk carriers should be considered. In particular, container ships are rarely operated with empty cargo hold in actual operation. Because container ships unload and load containers at the port, containers are always loaded in cargo hold. Therefore, even if the cargo hold is flooded in an actual situation, the amount of seawater flooded by the containers loaded in the cargo hold can be reduced.

However, bulk carriers are frequently operated when the cargo hold is empty under various situations. Hence, bulk carriers are riskier than container ships because the cargo hold will be entirely flooded if flooding occurs.

In this study, the bilge pumping performance of large bulk carriers was reviewed by applying the design criteria proposed by Lee et al. For this purpose, in this study, a bilge pump and a bilge piping arrangement actually installed on a 180K class bulk carrier were used.

2. SPECIFICATIONS OF LARGE BULK CARRIER AND ITS BILGE PUMPING SYSTEM

The 180K class bulk carrier (sample vessel) used in this study is a ship built in the early 2010s, and the dimensions of the sample vessel and the specifications of the bilge pumping system according to the SOLAS Regulation and related rule requirements of classification societies are shown in Table 1. Furthermore, the dimensions of the pipes used for the bilge piping system are listed in Table 2.

Table 1: Dimensions and specifications of the 180K class bulk carrier and its bilge pumping system.

$L_R \times B \times D_R$	292.0 × 45.0 × 24.5
Required internal diameter of bilge main (d_m)	264.3 mm
Required internal diameter of bilge main	300A, 9.5 Thk. (ID: 299.5 mm)
Required capacity of bilge pump	395.5 m^3/h
Nominal capacity of installed bilge pump	395/250 m^3/h × 30/80 m
Maximum flow rate of installed bilge pump	396 m^3/h
Water speed at bilge main	1.56 m/s

Table 2: Dimensions of pipes for the bilge piping system (Schedule 40).

ND	OD (mm)	Thk. (mm)	ID (mm)	A(m^2)
125A	139.8	6.6	126.6	0.0126
150A	165.2	7.1	151.0	0.0179
200A	216.3	8.2	199.9	0.0314
250A	267.4	9.3	248.8	0.0486
300A	318.5	9.5	299.5	0.0705
350A	355.6	9.5	336.6	0.0890

Table 2 shows the dimensions of the pipes actually used in Korean shipyards, and for pipes over 300A, thinner pipes are used in contrast to pipes required by the general industrial standards. It is assumed that thinner pipes can reduce the weights considering the low working pressure of the pipe such as a bilge piping system.

A schematic diagram of the bilge pumping system installed on the No. 1 cargo hold of the sample vessel and the specifications of the bilge piping system are shown in Figure 1 and Table 3, respectively.

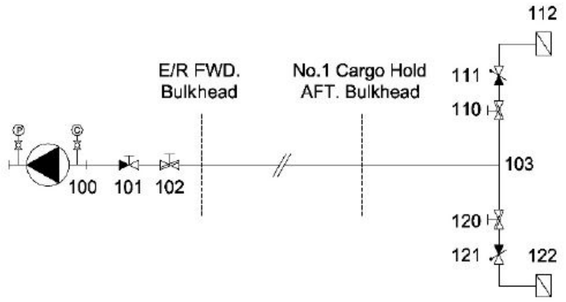

Figure 1. Schematic diagram of the bilge piping system

Table 3: Actual arrangement of the bilge piping system.

Node	Node	ND (Sch.40)	Length of pipe (m)	Fittings & Valves
100	101	300A	0.7	Check V/V
101	102	300A	1.0	Butterfly V/V
102	103	300A	212	
103	110	125A	17	Tee(branch)
110	111	125A	1	Butterfly V/V
111	112	125A	4	Check V/V
103	120	125A	17	Tee(branch)
120	121	125A	14	Butterfly V/V
121	122	125A	4	Check V/V, Elbow

The bilge piping system can be divided into “Main & Common” (Node 100-103) and “Branch” (Node 103-112, 103-122). For the branch bilge piping, we assume that the port side and the starboard side are symmetrically installed.

In addition, a rose box (Node 112, 122) is installed at the end of the bilge piping system; however, no flow energy loss related information is provided on the rose box. Considering that the net flow area of the rose box is 2-3 times the sectional area of the connected bilge pipes, the flow energy loss of the rose box was omitted in this study.

The arrangement of the bilge piping system shown in Figure 1 and Table 3 is not a perfect representation of the actual arrangement; however, because it is based on the actual arrangement, it is expressed as an actual arrangement in this study.

Figure 2 shows the performance curve of the bilge pump installed in the sample vessel, and the curve fitting function in Figure 2 was drawn based on a test report of bilge pumps installed on the vessel. Equation (1) is a fitting function formula for a suction head. Equation (1) was used to calculate the suction head corresponding to the flow rate of the pump.

$$SH = 8.53264\times10^{-6}Q_b^2 - 6.18354\times10^{-5}Q_b + 1.11569\left(R^2 = 0.99928\right) \tag{1}$$

To examine the bilge pumping performance of the sample vessel in this study, it was assumed that the No. 1 cargo hold was fully flooded. Similar to the study of Lee et al., the No. 1 cargo hold was set to the interval of the water level in the No. 1 cargo hold at 5 mm (Lee et al., p.A-77, 2021).

In general, the shape of the No. 1 cargo hold of a bulk carrier is considerably complicated, and the performance of bilge pumping should be calculated based on the tank table showing the length and breadth according to the height for the cargo hold of the complex shape.

However, because the bilge pumping performance is basically affected by the depth (suction head of bilge

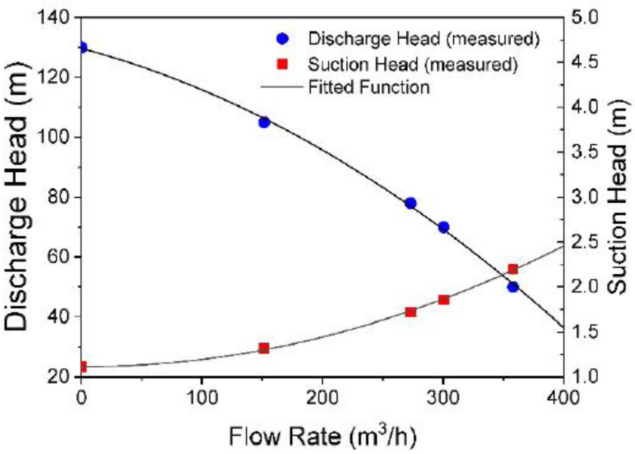

Figure 2. Performance curve of the actual bilge pump

pump) and volume (flow rate of bilge pump) of the flooded compartment, in this study, the No. 1 cargo hold was assumed to be a cube-shaped compartment which has the same volume and depth as the No. 1 cargo hold.

Because the No. 1 cargo hold has a volume of 19,980 m^3 and a depth of 22.2 m, the length, width, and depth of the No. 1 cargo hold were assumed to be 30 m, 30 m, and 22.2 m, respectively.

3. FLOW ENERGY LOSS CALCULATION

Figure 3 shows the concept of the bilge pumping performance. As shown in Figure 3, the combined energy from both the elevation head of the water level in the flooded compartment and the suction head of the pump must be larger than the flow energy loss resulting from the bilge piping system to discharge water from the flooded compartment.

The flow energy loss includes the friction loss at pipes and energy loss by pipe fittings (valve, elbow, etc.) fitted on the piping system.

Various methods can be used to calculate the friction loss; however, the Darcy–Weisbach equation is the most widely used (Casey, 1992, p.35-36; Gilley et al., p.105, 1992). The Hazen-Williams equation is also frequently used to calculate the friction loss; however, the range of applicable Reynolds numbers is limited, and it is known that the Hazen-Williams equation underestimates the friction loss compared with the Darcy–Weisbach equation under general conditions (Diskin, p.723, 1960; IMO, p. Annex1-5, 2003).

In this study, the friction loss was calculated based on the Darcy–Weisbach equation (Equation (2)). Regarding the use of the friction loss coefficient, Colebrook–White's equation (Equation (3)) was applied, instead of the Moody chart (Casey, 1992, p.35-36).

$$\Delta P = f\left(\frac{L+L_E}{D}\right)\frac{\rho V^2}{2} \tag{2}$$

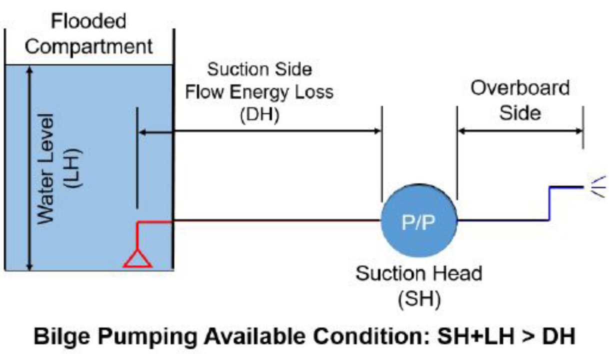

Figure 3. Concept of bilge pumping performance

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\in}{3.7D}+\frac{2.5}{Re\sqrt{f}}\right) \tag{3}$$

The density and viscosity of sea water are required to calculate the flow energy loss. In this study, the standard sea water properties at 20°C provided by the standards of sea water set out in ITTC were applied. Thus, the applied value of density was 1,024.8103 kg/m^3, and the applied value of viscosity was 0.001077 *Pa·s* (ITTC, p.8, 2011).

When calculating the flow energy loss, the pipe wall roughness included in the Equation (3) is very important because the friction loss coefficient is determined according to the pipe wall roughness, and thus, the friction loss coefficient affects the friction loss.

There are various data on the pipe wall roughness for pipes of various materials (BSI, 2000, Annex C, Table C.1; Casey, 1992, p.38-39, Table 3.1; Fried & Idelchik, 1989, p.11-13, Table 2-1; Miller, 1990, p.190, Table 8.1; Stephenson, 1984, p.7, Table 1.2). These data do not provide data on the pipe wall roughness for pipes used for a long time with seawater. Hence, a pipe wall roughness of 1.0 mm was applied, as proposed by Lee et al. (Lee et al., p.A-75, 2021).

The equivalent length was applied to evaluate the energy loss by pipe fittings. Numerous standards for equivalent length are available, and the equivalent length for pipe fittings described in NFPA 13 (Table 4) was applied, to secure the reliability of the equivalent length (NFPA, p.13-237, 2013).

4. CALCULATION PROCEDURE

In this study, the bilge pumping performance of a 180K class bulk carrier was evaluated. The bilge pumping performance was calculated using the actual arrangement of the bilge piping system for a No. 1 cargo hold of the sample vessel described in Section 2 and the flow energy loss calculation method described in Section 3.

In this study, the interval of the water level in the No. 1 cargo hold was chosen to be 5 mm to calculate the water speed at the bilge main, and the following procedure used by Lee et al. was applied for the calculation: (Lee et al., p.A-77, 2021)

(a) flow rate at the bilge main was assumed to be an appropriate value.
(b) The relevant suction head (*SH*) from the pumps' performance curve was calculated using the pumps' assumed flow rate.
(c) The flow energy loss at the bilge piping system (*dH*) was calculated on the basis of the flow rate at the bilge main.

Table 4: Equivalent schedule of the 40 steel pipe length chart (NFPA Code 13, p.13-237, Table 23.4.3.1.1).

Fittings and Valves Expressed in Equivalent Meter of Pipe															
Fittings and Valves	15 mm	20 mm	25 mm	32 mm	40 mm	50 mm	65 mm	80 mm	90 mm	100 mm	125 mm	150 mm	200 mm	250 mm	300 mm
45° elbow	-	0.3	0.3	0.3	0.6	0.6	0.9	0.9	0.9	1.2	1.5	2.1	2.7	3.4	4.0
90° standard elbow	0.3	0.6	0.6	0.9	1.2	1.5	1.8	2.1	2.4	3.0	3.7	4.3	5.5	6.7	8.2
90° long-turn elbow	0.2	0.3	0.6	0.6	0.6	0.9	1.2	1.5	1.5	1.8	2.4	2.7	4.0	4.9	5.5
Tee or cross (flow turned 90°)	0.9	1.2	1.5	1.8	2.4	3.0	3.7	4.6	5.2	6.1	7.6	9.1	10.7	15.2	18.3
Butterfly valve	-	-	-	-	-	1.8	2.1	3.0	-	3.7	2.7	3.0	3.7	5.8	6.4
Gate valve	-	-	-	-	-	0.3	0.3	0.3	0.3	0.6	0.6	0.9	1.2	1.5	1.8
Swing check	-	-	1.5	2.1	2.7	3.4	4.3	4.9	5.8	6.7	8.2	9.3	13.7	16.8	20.0

(d) The back pressure (*LH*) corresponding to the water level of the flooded compartment was calculated.

(e) If the calculated value of $SH + LH - dH$ was appropriate within the convergence condition, the process would progress to the next step; otherwise, a new value for the flow rate at the bilge main would be assumed, and steps (b) to (d) were to be iteratively undertaken.

(f) The water speed at the bilge main for each interval of the water level was calculated based on the calculated flow rate at the bilge main.

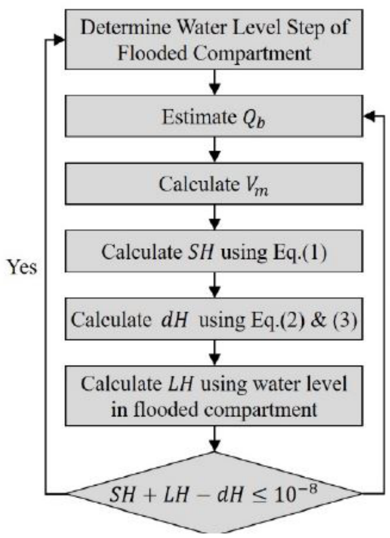

Figure 4. Calculation Procedure

Figure 4 shows the concept of the calculation method used in this study. When the bilge pumping system discharges seawater from the flooded compartment, the water level in the flooded compartment continuously changes due to seawater discharge.

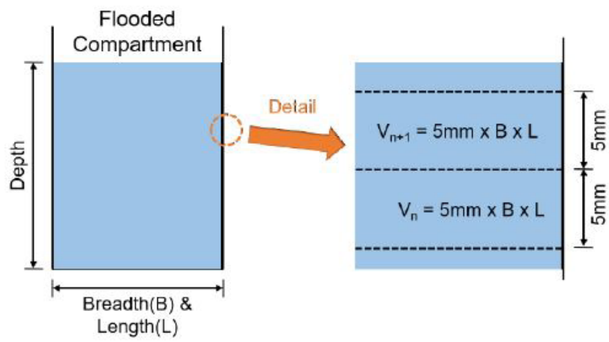

Figure 5. Concept of calculation

A change in the water level of the flooded compartment changes the flow rate and *SH* of the bilge pump, and a change in the flow rate in the bilge pump changes the flow energy loss of the bilge piping system.

Thus, discharging sea water from a flooded compartment using a bilge pumping system is a time-dependent problem. Furthermore, examining the bilge pumping performance of each vessel through time-dependent analysis requires significant much effort and time.

Therefore, it is necessary to examine the bilge pumping performance by replacing the time-dependent problem with the steady-state problem. To this end, in this study, we divided the flooded compartment into constant steps in the depth direction, as in the method applied by Lee et al. Assuming the steady state for each step, the flow rate in the bilge main was calculated for each step. (Lee et al., p.A-78-A-77, 2021)

When dividing the flooded compartment in the depth direction, the smaller the dividing interval, the more accurate the calculation results. However, if it is divided too finely, the calculation time increases; the appropriate intervals must be used. In this study, the calculation was performed by dividing the No. 1 cargo hold into 5 mm intervals. This 5 mm interval, which is 0.0225% of the 22,200 mm depth, was regarded to be small enough to yield reliable calculation results.

Equations (4) and (5) were applied to the convergence condition of the calculation. When Equation (5) was used as a convergence condition, the maximum flow rate of the onboard bilge pump was 396 m^3/h, and the flow energy loss of the bilge piping system when the flow rate was 396 m^3/h became much smaller than that of the water level in No. 1 cargo hold and SH, so convergence with Equation (4) was not available. In this case, the flow rate was fixed at 396 m^3/h, and Equation (5) was used to terminate the calculation of the related water levels.

$$\left| \frac{SH + LH - dH}{dH} \right| \leq 10^{-8} \tag{4}$$

$$\left| dH_{i-1} - dH_i \right| \leq 10^{-8} \tag{5}$$

5. RESULTS OF CALCULATION FOR THE ACTUAL ARRANGEMENT

Table 5 shows the change in water speed at the bilge main corresponding to the change in the water level of the No. 1 cargo hold, assuming that the No. 1 cargo hold is fully flooded, and the flooded water is discharged using actual bilge pumping arrangement.

The "Mean Speed" in Table 5 indicates the mean water speed at the bilge main while discharging flooded water from the flooded compartment.

As shown in Table 5, the actual arrangement did not satisfy the 2 m/s requirement at all water levels. In the authors' view, these calculation results were obtained because of the very small capacity of the bilge pump.

As shown in Table 1, the maximum flow rate of the bilge pump and the required capacity of the bilge pump showed a very small difference. Although the design of the bilge pumping system satisfies the rule requirements of the classification societies, the water speed at the bilge main is 1.56 m/s, which does not satisfy the 2 m/s requirement of SOLAS Reg.II-2/35-1.

Hence, "Dependent Criterion" should be applied while designing the bilge pumping system.

Table 5: Calculation results (Actual Arrangement, 300A-125A).

Tank Level	Flow Rate (m^3/h)	Water Speed at Bilge Main (m/s)	Pump Suc. Head (*SH*, m)	Flow Energy Loss (*dH*, m)	Static head by Water Level (*LH*, m)
0%	115.08	0.454	1.22	0.03	0.00
10%	200.04	0.789	1.44	0.08	2.22
20%	258.59	1.020	1.67	0.13	4.44
30%	306.19	1.207	1.90	0.19	6.66
40%	347.36	1.370	2.12	0.24	8.88
50%	384.15	1.515	2.35	0.29	11.10
60%	396.00	1.561	2.43	0.31	13.32
70%	396.00	1.561	2.43	0.31	15.54
80%	396.00	1.561	2.43	0.31	17.76
90%	396.00	1.561	2.43	0.31	19.98
100%	396.00	1.561	2.43	0.31	22.20
Mean Speed			1.319 m/s		

In addition, the water speed at the bilge main calculated according to the rule requirements of classification societies is 1.56 m/s, but the mean speed at the bilge main calculated by applying the "2 m/s Criterion" is 1.319 m/s. A difference of 0.241 m/s was observed, which may have been caused by the flow energy loss arising from the bilge piping system.

6. CALCULATION RESULTS FOR VARIOUS MODIFIED ARRANGEMENTS

As shown in Figure 1 and Table 3, the bilge pumping system of the sample vessel was composed of the bilge pump, main and common bilge pipes (Node 100-103), and branch bilge pipes (Node 103-112, 103-122).

As shown in Table 5, the actual arrangement did not satisfy the "2 m/s criterion" although the actual arrangement satisfied the rule requirements (internal diameter of bilge main and bilge pump capacity) of classification societies.

The reason the actual arrangement of the sample vessel did not satisfy the "2 m/s criterion" was twofold: the small pump capacity compared to the pipe size and the large pipe compared to the pump capacity.

Therefore, to find a bilge pumping arrangement that satisfies the "2 m/s criterion", calculations were performed for various cases.

The various cases were generated by combining (1) change in diameter of the main and common bilge pipes, (2) change in diameter of the branch bilge pipes, and (3) change in bilge pump capacity. The change of the bilge pump capacity was calculated while the *SH* was assumed to be the same, and the flow rate was increased by 10%. Table 6 shows the calculation results.

In addition, when the "Dependent Criterion" is applied to the actual arrangement of the sample vessel, the required capacity of the bilge pump is 507.7–515.8 m^3/h, which is similar to the case in which the flow rate of the bilge pump is increased to 130–140%.

200A & 250A piping is not satisfied as the bilge main according to the rule requirements of classification societies. However, considering that the reason the actual arrangement did not satisfy the "2 m/s criterion" is that the pipe size is large compared to the pump capacity, calculations were also performed for the cases in which 200A and 250A were used as the bilge main pipe.

Table 6: Calculation results for various modified arrangements.

Pump Capacity	Main & Common Pipes	Branch Pipes	Mean Speed
100% (Max. flow rate: 396.0 m^3/h)	200A	100A	1.589
		125A	**2.074**
		150A	**2.335**
		200A	**2.519**
	250A	100A	1.200
		125A	1.768
		150A	1.991
		200A	**2.109**
		250A	**2.134**
	300A	125A	1.319
		150A	1.470
		200A	1.544
		250A	1.556
		300A	1.559
	350A	150A	1.185
		200A	1.235
		250A	1.236
		300A	1.236
		350A	1.236
110% (Max. flow rate: 435.6 m^3/h)	200A	100A	1.585
		125A	**2.066**
		150A	**2.325**
		200A	**2.512**
	250A	100A	1.196
		125A	1.802
		150A	**2.100**
		200A	**2.259**
		250A	**2.294**
	300A	125A	1.376
		150A	1.579
		200A	1.682
		250A	1.701
		300A	1.707
	350A	150A	1.278
		200A	1.353
		250A	1.360
		300A	1.360
		350A	1.360
120% (Max. flow rate: 475.2 m^3/h)	200A	100A	1.583
		125A	**2.061**
		150A	**2.317**
		200A	**2.502**
	250A	100A	1.194
		125A	1.799
		150A	**2.183**
		200A	**2.391**
		250A	**2.437**
	300A	125A	1.410
		150A	1.676
		200A	1.813
		250A	1.840
		300A	1.849
	350A	150A	1.364
		200A	1.467
		250A	1.482
		300A	1.483
		350A	1.483

(*Continued*)

Table 6: Calculation results for various modified arrangements. (*Continued*)

Pump Capacity	Main & Common Pipes	Branch Pipes	Mean Speed
130% (Max. flow rate: 514.8 m^3/h)	200A	100A	1.581
		125A	**2.056**
		150A	**2.310**
		200A	**2.494**
	250A	100A	1.192
		125A	1.792
		150A	**2.237**
		200A	**2.502**
		250A	**2.561**
	300A	125A	1.420
		150A	1.760
		200A	1.937
		250A	1.974
		300A	1.986
	350A	150A	1.441
		200A	1.577
		250A	1.600
		300A	1.606
		350A	1.607
140% (Max. flow rate: 554.4 m^3/h)	200A	100A	1.579
		125A	**2.053**
		150A	**2.306**
		200A	**2.488**
	250A	100A	1.190
		125A	1.787
		150A	**2.259**
		200A	**2.592**
		250A	**2.666**
	300A	125A	1.415
		150A	1.830
		200A	**2.054**
		250A	**2.102**
		300A	**2.118**
	350A	150A	1.509
		200A	1.682
		250A	1.715
		300A	1.724
		350A	1.726
150% (Max. flow rate: 594.0 m^3/h)	200A	100A	1.578
		125A	**2.050**
		150A	**2.302**
		200A	**2.483**
	250A	100A	1.189
		125A	1.782
		150A	**2.254**
		200A	**2.659**
		250A	**2.750**
	300A	125A	1.410
		150A	1.886
		200A	**2.163**
		250A	**2.223**
		300A	**2.243**
	350A	150A	1.567
		200A	1.783
		250A	1.826
		300A	1.839
		350A	1.843
160% (Max. flow rate: 633.6 m^3/h)	200A	100A	1.577
		125A	**2.048**
		150A	**2.299**
		200A	**2.479**
	250A	100A	1.188
		125A	1.779
		150A	**2.247**
		200A	**2.701**
		250A	**2.812**
	300A	125A	1.406
		150A	1.925
		200A	**2.264**
		250A	**2.338**
		300A	**2.363**
	350A	150A	1.615
		200A	1.879
		250A	1.933
		300A	1.951
		350A	1.956

Table 6: Calculation results for various modified arrangements (*Continued*)

Pump Capacity	Main & Common Pipes	Branch Pipes	Mean Speed
170% (Max. flow rate: 673.2 m^3/h)	200A	100A	1.576
		125A	**2.046**
		150A	**2.296**
		200A	**2.476**
	250A	100A	1.187
		125A	1.776
		150A	**2.241**
		200A	**2.716**
		250A	**2.849**

Pump Capacity	Main & Common Pipes	Branch Pipes	Mean Speed
	300A	125A	1.403
		150A	1.947
		200A	**2.356**
		250A	**2.356**
		300A	**2.476**
	350A	150A	1.651
		200A	1.971
		250A	**2.037**
		300A	**2.059**
		350A	**2.066**

Table 7: Calculation results for modified arrangements (Modified Arrangement, 200A-125A, 100% flow rate)

Tank Level	Flow Rate (m^3/h)	Water Vel. at Bilge Main (m/s)	Pump Suc. Head (*SH*, m)	Flow Energy Loss (*dH*, m)	Static head by Water Level (*LH*, m)
0%	73.26	0.648	1.16	0.06	0.00
10%	127.43	1.128	1.25	0.19	2.22
20%	164.76	1.458	1.34	0.31	4.44
30%	195.11	1.727	1.43	0.43	6.66
40%	221.36	1.959	1.52	0.56	8.88
50%	244.82	2.167	1.61	0.68	11.10
60%	266.23	2.356	1.70	0.81	13.32
70%	286.05	2.532	1.80	0.93	15.54
80%	304.59	2.696	1.89	1.05	17.76
90%	322.06	2.851	1.98	1.18	19.98
100%	338.64	2.997	2.07	1.30	22.20
Mean Speed			2.074 m/s		

Table 6 shows the calculation results of various modified arrangements, and Table 7 shows the detailed calculation results of the specific modified arrangement (bilge main and common bilge pipe: 200A, branch bilge pipe: 125A, 100% flow rate of pump).

Referring to the results of Table 6 and Table 7, if the bilge pumping system is being designed considering the “2 m/s Criterion”, the design engineer may select the 200A-125A arrangement at 100% of the pump capacity.

An increase in the pump capacity may increase the pump volume, which may affect the machinery arrangement in the engine room. Furthermore, increasing the size of the bilge main and branch bilge pipes may affect the pipe installation practice. In addition, because all these aspects lead to increased costs, the design engineer must select the cheapest case.

However, because 200A and 250A pipes are not permitted as bilge mains, the design engineer should select a case in which the bilge main is 300A or above.

The design engineer should select the 300A-200A arrangement case at 140% of the pump capacity among cases using the 300A pipe as the bilge main.

The required capacity of the bilge pump calculated based on “Dependent Criterion” is 507.7-515.8 m^3/h, and the maximum flow rate of the 140% capacity is 554.4 m^3/h. The required capacity based on the “Dependent Criterion” is similar to the required capacity based on the “2 m/s criterion”.

7. DISCUSSION

The reason why the actual arrangement of the sample vessel did not satisfy the “2 m/s criterion” was twofold: the small pump capacity compared to the pipe size and the large pipe compared to the pump capacity. The calculations were performed for various modified arrangements based on the estimated reasons.

Table 6 shows the results of the calculation for various modified arrangements, and Table 7 shows the detailed calculation result for specific arrangements which satisfied the “2 m/s Criterion” with the smallest pipe size and with 100% pump capacity.

From Table 6 and Table 7, the “2 m/s criterion” can be satisfied by reducing the pipe size without increasing the pump capacity. Therefore, the cases that can satisfy the "2 m/s criterion" must be reviewed using a smaller pipe, although these cases with smaller pipes did not satisfy the requirements of SOLAS and classification societies.

In this step, the authors must consider which is the best way to analyse the bilge pumping performance: common sense or performance-based standards (PBS).

In the Goal Based Standard (GBS) structure, SOLAS sets high-level goals (GBS Tier 1 and 2), and classification societies acting as recognised organisations (ROs) should develop detailed rules requirements (GBS Tier 4) to meet the high-level goals. Hence, the rule requirements of classification societies should comply with the scope and intended purpose of the high-level goals.

The intended purpose of SOLAS Regulation II-2/35-1 is "to discharge accumulated water in a flooded compartment as quickly as possible to secure the ship's stability" (2 m/s requirements) and "A larger ship should use a larger bilge main pipe" (required internal diameter requirements). In the authors' view, the internal diameter requirements were developed based on common sense and experience.

According to the GBS structure, the rule requirements of classification societies regarding bilge pumping systems should comply with the intended purposes of SOLAS Regulation II-1/35-1. Hence, in the sample vessel case, the 200A and 250A pipes are not permitted as the bilge main.

However, if PBS is applied to the high-level goals of GBS (SOLAS Regulation II-1/35-1), it will be applied with different requirements than common sense.

PBS is a rulemaking principle for ship safety equipment and systems, and in the authors' view, the 200A pipe can be applied to the bilge main based on the PBS.

The basic concept of PBS is that it conducts tests to verify performance, identifies performance parameters of safety equipment and systems through tests, and applies the identified performance parameters to the design and installation of safety equipment and systems.

PBS is mainly applied to safety equipment and systems such as fire safety systems and aims to minimise the reduction in performance of safety equipment and systems due to unexpected parameters.

Based on the concept of PBS, even a pipe with an internal diameter smaller than that required by the rules of classification societies, if it satisfies the "2 m/s criterion", in the authors' view, should be permitted as the bilge main.

Furthermore, the 2 m/s requirement of SOLAS Regulation II-2/35-1 is the only performance requirement for bilge pumping performance. The required internal diameter is a supplementary requirement for the 2 m/s requirement. Therefore, to apply the concept of PBS, SOALS Regulation II-1/35-1.3.9, which stipulates the minimum required internal diameter, should be deleted.

Furthermore, if SOALS Regulation II-1/35-1.3.9 is deleted, the "internal diameter criterion" and "dependent criterion" except the "2 m/s criterion" in the three design criteria proposed by Lee et al. and "2 m/s criterion" should be applied as the main design criterion for the bilge pumping system.

8. CONCLUSION

In this study, the bilge pumping performance was reviewed for 180K class bulk carriers built in the early 2010s. Based on the current SOLAS Regulation II-1/35-1 and related rule requirements of classification societies, the authors found the following:

1. When the water speed was calculated at the bilge main using specifications and actual bilge pumping arrangement systems of 180K class bulk carriers, the water speed did not satisfy the 2 m/s requirement of SOLAS because the "dependent criterion" was not applied.
2. As a result of calculating the bilge pumping performance using the actual arrangement (bilge pumps and bilge piping system) assuming that the No. 1 cargo hold of the 180K class bulk carrier is fully flooded, in any case, the "2 m/s Criterion" was not satisfied.
3. According to the result of calculating the bilge pumping performance for various cases with modified arrangements (changing the size of bilge piping system and increasing the flow rate of the bilge pump by 10% with the *SH* fixed), authors found that the "2 m/s Criterion" was satisfied under the condition that the flow rate of the pump was increased by 40% and branch bilge pipes increased from 125A to 200A.
4. From a result of calculating the bilge pumping performance for various cases with modified arrangements, it was found that the "2 m/s Criterion" was satisfied under the condition that bilge main and common bilge pipes decreased from 300A to 200A with 100% flow rate of the pump, even though 200A is not satisfied with the required internal diameter.

The most important point from the above findings is that the "2 m/s criterion" is satisfied for a bilge main smaller than the required internal diameter specified in SOLAS Regulation II-1/35-1.

Hence, the above calculation results showed that there was a conflict between the 2 m/s requirement and the required internal diameter. To resolve this problem, authors have to select one requirement between them.

The basic intended purpose of the SOLAS Regulation II-2/35-1 is "to discharge accumulated water in a flooded compartment as quickly as possible to secure the ship's stability", and the 2 m/s requirement is the most important requirement.

Furthermore, the 2 m/s requirement of the SOLAS Regulation II-2/35-1 is the only performance requirement for bilge pumping performance, and the required internal diameter is a supplementary requirement for the 2 m/s requirement.

Therefore, to apply the concept of PBS and to avoid the conflict between the 2 m/s requirement and internal diameter requirement, SOALS Regulation II-1/35-1.3.9 should be deleted. Furthermore, it is proposed that the "2 m/s criterion" should be applied as the main design criterion for the bilge pumping system.

"**2 m/s Design Criterion**: The bilge pumping system should ensure that the average water speed at the bilge main is not less than 2 m/s during the discharge of the flooded water from the flooded compartment where it is expected to take the longest time to discharge all flooded water (most hydraulically remote compartment). In addition, when calculating the water speed at the bilge main during discharge of flooded water, the flow energy loss is calculated using Darcy–Weisbach equation and Colebrook–White's equation, and pipe wall roughness of 1.0 mm should be applied."

The deletion of SOLAS Regulation II-1/35-1.3.9 (required internal diameter) is correct in terms of hydraulic calculation and PBS, but it may not be deleted in terms of matters not considered in this paper such as corrosion, erosion, etc. In particular, the deletion of SOLAS Regulation II-1/35-1.3.9 is a technical and political issue and should be decided by IMO, so the proposals in this paper should be considered only in terms of hydraulic calculation and PBS.

9. DISCLAIMER

Opinions expressed in this paper are solely those of the authors.

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