PROPOSED DESIGN CRITERIA FOR A BILGE PUMPING SYSTEM FOR LARGE CONTAINER SHIPS

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SUMMARY

The IMO's Goal-Based Standards (GBS) in the Safety of Life at Sea Convention (SOLAS) sets the high-level goals (GBS Tier 1 and 2) and classification societies acting as recognized organizations (ROs) should develop detailed rules and regulations in order to meet the goals (GBS Tier 4). Even though the GBS requirements are applicable to new build construction standards of bulk carriers and oil tankers at present, given that IMO may develop goal-based standards for other safety areas, it will be meaningful to examine the bilge pumping system requirements in the context of principles of Goal-Based Standards. The bilge pumping system is one of the most important systems in ships but there is no requirement for its performance except for the 2 m/s speed of water requirement and the internal diameter of bilge main prescribed in SOLAS. The purpose of this study is to quantitatively evaluate bilge pumping performance of actual ships in service and to propose an alternative set of performance standards. The rules of Classification Societies were investigated, and the bilge pumping performance was quantitatively evaluated using specifications of a 14,000 TEU class container ship. As a result of the investigation, it was found that satisfying the 2 m/s requirement under many operating conditions was impossible, and the rules and regulations to determine the internal diameter of bilge main and the capacity of bilge pump did not meet intended purpose of the 2 m/s speed of water requirement. Finally, a set of design criteria are proposed to fulfil the intended purpose of the 2 m/s requirement of SOLAS.

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	required capacity of each bilge pump (m^3/h)
Re	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 IMO's Goal-Based Standards (GBS) in the Safety of Life at Sea Convention (SOLAS) sets the high-level goals (GBS Tier 1 and 2) and classification societies acting as recognized organizations (ROs) should develop detailed rules and regulations in order to meet the goals (GBS Tier 4). Even though the GBS requirements are applicable to new build construction standards of bulk carriers and oil tankers at present, given that IMO may develop goal-based standards for other safety areas, it will be meaningful to examine the bilge pumping system requirements in the context of principles of Goal-Based Standards.

The bilge system is intended to clear oil or water leakage and residues from machinery, cargo and other spaces as well as to provide an emergency pumping capability. It is one of the ship's primary machinery systems and is particularly important when the ship shall discharge accumulated water in a flooded compartment to overboard as soon as possible in order to restore the ship's stability at the time of flooding.

In the event of flooding, it is difficult to predict the extent of water ingress and to calculate how much seawater has been accumulated in a certain compartment.

In practice, the selection of ship's bilge pumps and the design of bilge piping system are entirely determined based on the 2 m/s requirements and the required internal diameter of bilge main both of which were introduced in SOLAS 1981 amendments.

However, the 2 m/s water speed requirement, when it was introduced in SOLAS 1981 amendment, was already a fairly old requirement. With the elapse of time, the ship sizes have been becoming larger, leading the associated bilge piping systems to have greater length and width than those when the 2 m/s requirement was introduced in

SOLAS. This means that the flow energy loss resulting from bilge piping systems may compromise the intended pumping performance of the bilge pumping system.

Flow energy loss may occur as a result of friction loss from pipe walls as well as change of fluid flow direction caused by pipe fitting arrangements such as valves, elbows, etc. This flow energy loss will lead to decrease of the actual pump suction head, thereby reducing the bilge pumping performance. The degree of decreasing pumping performance may become even bigger in modern large size ships installed with much longer bilge piping arrangements than conventional types of ships.

In this study, the aforementioned 2 m/s water speed requirements of SOLAS and corresponding rules of Classification Societies were investigated. And a comparative calculation with consideration of flow energy loss was carried out using design specifications of a large container ship to evaluate the ship's actual bilge pumping performance. It was found that the rules of Classification Societies would not deliver the required 2m/s speed of water requirements of SOLAS. This study therefore attempts to provide alternative design criteria of the bilge pumping system meeting the 2m/s flow speed requirement of SOLAS.

2. SOLAS REQUIREMENTS FOR BILGE PUMPING PERFORMANCE

The requirements of SOLAS (2017 amendments) relating to bilge pumping performance read as follows;

- *Regulation II-1/35-1.3.6: Each power bilge pump shall be capable of pumping water through the required main bilge pipe at a speed of not less than 2 m/s. Independent power bilge pumps situated in machinery spaces shall have direct suctions from these spaces, except that not more than two such suctions shall be required in any one space. Where two or more such suctions are provided, there shall be at least one on each side of the ship. The Administration may require independent power bilge pumps situated in other spaces to have separate direct suctions. Direct suctions shall be suitably arranged and those in a machinery space shall be of a diameter not less than that required for the bilge main.*
- *Regulation II-1/35-1.3.9: The diameter d of the bilge main shall be calculated according to the following formula. However, the actual internal diameter of the bilge main may be rounded off to the nearest standard size acceptable to the Administration:*

$$d_m = 1.68\sqrt{L_R(B + D_R)} + 25$$

It shows that SOLAS mandates a required water speed at the main bilge pipe only and provides a formula for calculating the internal diameter of the bilge main. In these requirements, the most important value is 2 m/s which is the only criteria for determining the required capacity of the bilge pumps. Therefore, a need has been identified for systematic reviews that will assist standard setting organizations to determine whether the flooded water in flooding compartment can be discharged to the outside of the vessel at a speed of 2 m/s, as is required by SOLAS. These reviews are more urgently needed for large size vessels that are expected to have a greater flow energy loss due to their longer bilge piping arrangements than conventional types of ships.

In general, a centrifugal pump is used as a bilge pump, and the discharge flow rate of pumps depends on the discharge and suction head according to the characteristics of a typical centrifugal pump. And, the water speed at bilge main changes in tandem with the change of flow rate. Therefore, the following 3 interpretations drawn from the 2 m/s requirement.

(A) Bilge pumping system shall satisfy the 2 m/s requirement for **almost all** operating ranges of the bilge pump (shall satisfy 2 m/s at point A in Figure 1);
(B) Bilge pumping system shall satisfy the 2 m/s requirement for **general** operating range of the bilge pump (shall satisfy 2 m/s at point B in Figure 1); or
(C) Bilge pumping system shall satisfy the 2 m/s requirement for **specific** operating range of the bilge pump (shall satisfy 2 m/s at point C in Figure 1).

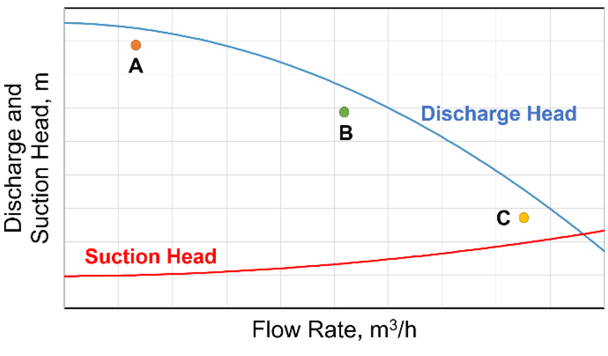

Figure 1: Performance curve of a typical centrifugal pump

Table 1: Rules of Classification Societies for Bilge Pumping Performance

Class	Required Internal Diameter of Bilge Main	Required Capacity of each Bilge Pumps
DNVGL (Rules for Classification: Ships)	- Formula: same as SOLAS - Allowance: The internal diameter of the main bilge suction line shall not be less than given by the following formula, to the nearest 5 mm (Pt.4, Ch.6, Sec.4, 8.4.1)	$Q_b = 5.75d_m^2 10^{-3}$ (Pt.4, Ch.6, Sec.4, 8.2.3)
LR (Rules and Regulations for the Classification of Ships)	- Formula: same as SOLAS - The diameter, d_m, of the main bilge line is to be not less than required by the following formula, to the nearest 5 mm, but in no case is the diameter to be less than that required for any branch bilge suction: (Pt.5, Ch.13, Sec.5, 5.1.1)	$Q_b = 5.75d_m^2 10^{-3}$ (Pt.5, Ch.13, Sec.6, 6.3.2)
ABS (Rules for Building and Classing Steel Vessels)	- Formula: same as SOLAS - The minimum internal diameter of the bilge suction pipes is to be determined by the following equations, to the nearest 6 mm (0.25 in.) of the available commercial sizes. (Pt.4, Ch.6, Sec.4, 5.3.1)	$Q_b = 5.66d_m^2 10^{-3}$ (Pt.4, Ch.6, Sec.4, 5.3.2)
KR (Rules for the Classification of Steel Ships)	- Formula: same as SOLAS - The standard pipes of internal diameter nearest to the calculated diameter may be used. However, in case where the diameter of such standard pipes is small of the calculated value by 13 mm or over, standard pipes of one grade higher diameter are to be used. (Pt.5, Ch.6, Sec.4, 404.1)	$Q_b = 5.66d_m^2 10^{-3}$ (Pt.5, Ch.6, Sec.4, 405.2)

In Figure 1, if the required bilge pump capacity of ship is 500 m^3/h and the capacity of selected pump have to satisfy the almost all operating rage of the bilge pump, the selected pump shall satisfy 500 m^3/h at “Point A”. And the maximum flow rate of this bilge pump would almost reach at least 2,000-3,000 m^3/h.

Further, if the ship needs to be installed with a pump capable of satisfying 500 m^3/h at “Point C”, the maximum flow rate of this pump would be 600-700 m^3/h only.
For these reasons, the capacity of a pump is too large in case of interpretation (A), whereas the capacity is too small if interpretation (C) is adopted. Therefore, interpretation (B) is deemed as the most reasonable choice.

3. RELEVANT RULES OF CLASSIFICATION SOCIETIES

The relevant rules of Classification Societies should be considered because all ocean-going ships subject to SOLAS shall be designed and constructed in accordance with the rules of Classification Societies. Table 1 shows the rules of a few Classification Societies.

In Table 1, the formula for the required capacity of bilge pump is derived from the 2 m/s requirement of SOLAS, as shown in formula (1).

$$Q_b(m^3/h) = A \times V = A \times 2(m/s) = \frac{\pi d_m^2}{4} \times 2(m/s) \times 3600/1000 \approx 5.66 \; or \; 5.75 d^2 10^{-3} \quad (1)$$

It should be noted that although the required capacity of the bilge pump is calculated based on 2 m/s, the actual internal diameter of the bilge main may be greater than the required internal diameter. If the capacity of the bilge pump and the size of bilge main are selected according to the rules of Classification Societies, it can be inferred that the water speed at the bilge main does not meet the 2 m/s requirement of SOLAS.

Using specifications of the 14,000 TEU class container ship used in the sample calculation performed in this study, the size of the bilge main, the required capacity of the bilge pump and the water speed at bilge main were calculated as follows.

In the Table 2, even when the bilge main of 300A pipe was selected of which the internal diameter is smaller than the required internal diameter (Case 1), the bilge pump capacity met the rules of the Classification Societies.

Since the water speed at the bilge main exceeded 2 m/s meeting the requirement of SOLAS, this case used a pipe with a smaller diameter than the required diameter (“d” as defined in SOLAS) which would result in more flow energy loss, which is not a desirable situation.

Table 2**:** Dimension and specification of sample vessel and its bilge pumping system
(The pipe dimension is based on KSA, Table 2)

$L_R \times B \times D_R$	350.0 × 48.0 × 29.0
Required internal diameter of bilge main (d_m)	300.8 mm

Accepted internal diameter of bilge main (Case 1)	300A Sch.40 (ID: 297.9 mm)
Accepted internal diameter of bilge main (Case 2)	350A Sch.40 (ID: 333.4 mm)
required capacity of bilge pump	512.1 or 520.3 m^3/h
maximum flow rate of onboard bilge pump	540 m^3/h
water speed at bilge main (Case 1)	2.15 m/s
water speed at bilge main (Case 2)	1.72 m/s

In case of selecting the 350A pipe of which the internal diameter is larger than the required internal diameter as in Case 2 in the above calculation example, it can be estimated that the flow energy loss is small and it is advantageous for the bilge pumping. However, the water speed at the bilge main pipe did not meet the 2 m/s requirement.

The reason why the 2 m/s requirement is not satisfied when a larger pipe is selected is that the internal diameter of bilge main and bilge pump capacity is reflected in the design of the bilge pumping system as independent variables, although both of them should be reflected in the design of the bilge pumping system as dependent variables.

It goes without saying that in order to satisfy the 2 m/s requirement of SOLAS, the required capacity of the bilge pump should be calculated by using the internal diameter of the actual bilge main. In addition, in order to reduce the flow energy loss in the bilge piping system, it is suggested that the actual bilge main should not be less than the required internal diameter of the bilge main.

However, the Class Rules are formulated in such a way that the internal diameter of the actual main bilge and the bilge pump capacity are addressed separately. They should be addressed as dependent variables not as independent variables.

4. FLOW ENERGY LOSS CALCULATION

Since the bilge piping system consists of not only the bilge main but also various branch bilge pipes, even if a bilge main of sufficient size and a bilge pump of sufficient capacity is selected, the 2 m/s requirement may not be satisfied due to the flow energy loss from branch bilge pipes. Therefore, the flow energy loss from the bilge piping system should be considered to keep the bilge pumping performance to the expected level.

Figure 2 shows the concept of bilge pumping performance. As shown in Figure 2, the combined energy from both the elevation head of the water level in the flooded compartment and the suction head of a pump is to be larger than the flow energy loss resulting from the bilge piping system to discharge water from the flooded compartment.

Hence, the pumping performance of the bilge pumping system should be verified by considering the influence of flow energy loss resulting from the bilge piping system. And, these effects should be dealt with on a ship by ship basis as all ships have different bilge piping systems.

In this study, a sample calculation was carried out using a 14,000 TEU class container ship to investigate the effect of flow energy losses resulting from the bilge piping system on pumping performance of the bilge pumping system. Therefore, it is important to evaluate the flow energy loss.

In this study, flow energy loss was calculated as per the Darcy-Weisbach equation, in formula (2) below. Regarding the use of the friction loss coefficient, Colebrook-White's equation in formula (3) below was applied, instead of the Moody chart (Casey, 1992, p.35-36).

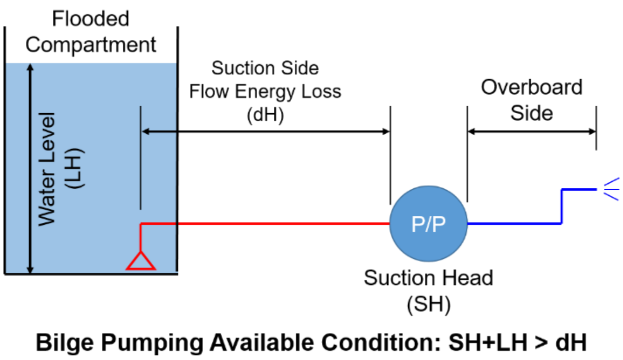

Figure 2: Concept of bilge pumping performance

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

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

In addition, the density and viscosity of sea water should be considered for calculation of flow energy loss. These parameters have different values depending on the sea water temperature and salinity. For this study, the standard sea water properties at 20°C in the standards of sea water set out in ITTC were applied. Thus, the applied value of density is 1,024.8103 kg/m^3, and the applied value of viscosity is 0.001077 $Pa \cdot s$ (ITTC, 2011, p.8).

The flow energy loss will increase when the diameter of pipe decreases or the length of pipe increases if the same flow rate is maintained. Also, the flow energy loss increases as the pipe wall roughness increases. In case of a seawater pipe, it is expected that with the elapse of time, pipe wall roughness will continue to increase due to corrosion.

As shown in formula (2) and (3), pipe wall roughness is a very important factor when calculating flow energy loss. Since the bilge piping system is exposed to seawater for a long period of time (5-20 years), corrosion due to seawater will occur, and it will increase pipe wall roughness inevitably. However, at present, there are no clear design criteria for pipe wall roughness that takes into account corrosion. Therefore, in this study, the pipe wall roughness of the bilge piping system was determined with reference to the existing data.

There are various data on the pipe wall roughness for various material pipes (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). And, these data do not provide data on the pipe wall roughness for pipes used for a long time with seawater. However, this data can be used to estimate pipe wall roughness that can be applied to the bilge piping system.

Among various data related to pipe wall roughness, Table 3 and Table 4 show data that can be applied to estimate pipe wall roughness of bilge piping system.

In Table 3, the pipe wall roughness is 0.05 mm and 0.15 mm for “steel pipe” and “galvanized iron pipe” respectively. However, these values are for new conditions and are difficult to apply directly to a bilge piping system of ships in service.

Table 3**:** Equivalent uniform roughness for pipes (BSI, 2000, Annex C, Table C.1)

Commercial pipe (new) material	Equivalent uniform roughness of the surface, mm
Glass, drawn brass, copper or lead	Smooth
Steel	0.05
Asphalted cast iron	0.12
Galvanized iron	0.15
Cast iron	0.25
Concrete	0.30 to 3.0
Riveted steel	1.0 to 10.0

Table 4: Roughness value, mm (Miller, 1990, p.190, Table 8.1)

2. Steel pipes	New smooth pipes	0.025
	Centrifugally applied enamels	0.025
	Mortar lined, good finish	0.05
	Mortar lined, average finish	0.10
	Light rust	0.25
	Heavy brush asphalts, enamels and tars	0.5
	Heavy rust	1.0
	Water mains with general tuberculations	1.2

In Table 4, the pipe wall roughness is 1.0 mm and 1.2 mm for “heavy rust” and “water mains with general tuberculatioins” respectively. These values can be applied as reference values to determine pipe wall roughness of the bilge piping system having corrosion due to seawater. However, considering that the water main is normally buried in such unreachable spaces as ducts and double bottom areas of short height and cannot be repaired but the bilge piping system can be repaired or replaced, if required. Hence, it is reasonable to apply 1.0 mm to the pipe wall roughness of the bilge piping system. Also, in the shipbuilding industry, it is a general practice to apply 0.5 mm to the pipe wall roughness for the seawater pipe.

For the purpose of this study, the wall roughness of the bilge piping system was applied as 1.0 mm, and the effect of the wall roughness was examined accordingly.

5. SAMPLE CALCULATION

In this study, the effect of flow loss on bilge pumping performance was investigated by using specifications of a 14,000 TEU class container ship.

The ship's specifications, the required diameter of bilge main and required bilge pump capacity are shown in Table 5.

Table 5: Dimension and specification of sample vessel and its bilge pumping system (The pipe dimension is based on KSA, Table 2)

L × B × D	350.0 × 48.0 × 29.0
Dimension of No.1 Cargo Hold (l × b × d)	30.0 × 48.0 × 29.0
Required internal diameter of bilge main	300.8 mm
Selected internal diameter of bilge main	300A Sch.40 (ID: 297.9 mm)
Required internal diameter of branch bilge suction pipe	128.3 mm
Selected size of branch bilge pipe	125A Sch.40 (ID: 126.6 mm)
Required capacity of each bilge pump capacity	520.25 m^3/h
No. of bilge pump	2 sets
Rated capacity of onboard bilge pump	530/190 m^3/h × 30/110m
Maximum discharge rate of onboard bilge pump	540 m^3/h
Inlet and outlet flange size of onboard bilge pump	250A × 250A
Length of bilge suction pipe for sample calculation	250 m

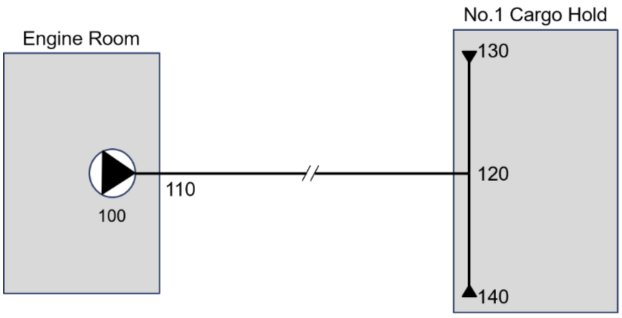

Figure 3: Schematic bilge piping diagram for No.1 cargo hold

The length of bilge piping system used for the sample calculation was determined considering actual piping arrangement. This calculation was carried out assuming that No.1 cargo hold in 14,000 TEU class container ship was flooded. The distance from bilge pumps (near E/R forward bulkhead) to bilge well of No.1 cargo hold (near to after bulkhead of No.1 cargo hold) is about 200m, however, we used 250 m in the calculation considering the equivalent length of fittings and valves. Also, it was assumed that there was no elevation difference between bilge wells in No.1 cargo hold and bilge pumps.

Further, the calculation was based on the condition that one bilge pump was being operated with various conditions of bilge piping arrangements. The size of bilge main and branch bilge pipe compliant with the Class rules were 300A and 125A, respectively. In addition, the calculation was performed in 350A case because the designer could choose 350A instead of 300A for the bilge main.
And, two kinds of arrangements are available for the pipe size between node number 110 to 120 in Figure 3. One arrangement is that the pipe between node number 110 and 120 is the main bilge. The 2nd arrangement is to treat it as a common bilge. In general, common bilge is a bilge pipe which two and more branch bilge pipes are connected.

In general, the size of the bilge pipe between engine room and No.1 cargo hold (node no. 110-120) is the same as the one required for the bilge main.

However, designer can choose 200A because the required branch bilge pipe size is 125A and the sectional area of the common bilge pipe between engine room and No.1 cargo hold (node no. 110-120) should not be less than the total sectional area of branch bilge pipes (125A X 2sets)

Hence, in this study, 4 cases were determined for the sample calculation and are described in Table 6. However, the purpose of this study was to examine the effect of flow energy loss on bilge pumping performance, and the branch bilge pipes inside No.1 Cargo Hold were relatively shorter than the bilge pipe between engine room and No.1 cargo hold. Hence, the branch bilge pipe inside No.1 cargo hold (node no. 120-130 & 120-140) was excluded from the sample calculation.

Table 6: Bilge piping arrangement for sample calculation

	Node	Node	Nominal Dia. (Sch.40)	Length of Pipe
Case 1	100	110	300A	20 m
	110	120	300A	230 m
Case 2	100	110	300A	20 m
	110	120	200A	230 m
Case 3	100	110	350A	20 m
	110	120	350A	230 m
Case 4	100	110	350A	20 m
	110	120	200A	230 m

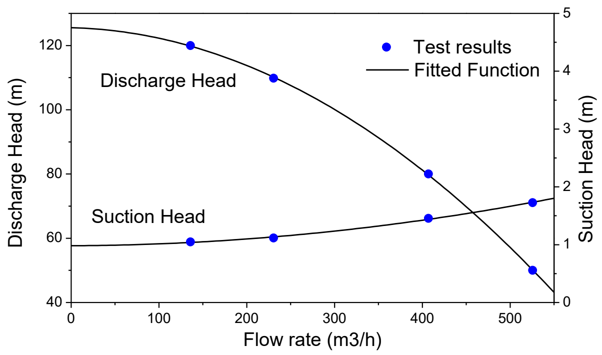

Figure 4: Performance curve of bilge pump

Also, the curve fitting function in Figure 4 was drawn based on the test report of bilge pumps installed on the vessel. Formula (4) is a fitting function formula for discharge head and Formula (5) is a fitting function for suction head. And, Formula (5) was used to calculate the suction head corresponding to the flow rate of the pump.

$$DH = -2.59827 \times 10^{-4}Q^2 - 0.00693Q + 125.56226 \; (R^2 = .99974) \tag{4}$$

$$SH = 2.60237 \times 10^{-6}Q^2 + 6.17454 \times 10^{-5}Q + 0.98229 \; (R^2 = .99237) \tag{5}$$

The flow energy loss that occurs in the bilge piping system depends on the flow rate and pipe wall roughness of bilge piping system. In this study, sample calculations were performed for 4 cases in Table 6 by applying 1.0 mm of pipe wall roughness under the condition that only one bilge pump was in operation.

Bilge pumping performance (water velocity at bilge main) depends on the water level in the flooded compartment (No. 1 cargo hold in this study). As shown in Figure 2, the higher the water level was in the flooded compartment, the higher the bilge pumping performance became, and the lower the water level, the lower the bilge pumping performance. Since the water level in the flooded compartment continuously changes over time, the water level should be divided into short sections, and the water velocity in the bilge main should be calculated for each section.

In this study, for the purpose of applying the Finite Difference Method, the interval of water level in No.1 cargo hold was chosen to be 10 mm to calculate water velocity at the bilge main, and the following procedure was applied for the calculation:

(1) flow rate at the bilge main was assumed to be a certain value.
(2) The relevant suction head (*SH*) from the pumps' performance curve was calculated by using the pumps' assumed flow rate.
(3) The flow energy loss at bilge piping system (*dH*) was calculated on the basis of the flow rate at the bilge main.
(4) The back pressure (*LH*) applicable to the ballast water level was calculated.
(5) 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 bilge main would be assumed, and steps (2) to (4) were to be undertaken iteratively.
(6) The water velocity at the bilge main for each interval of water level was calculated by the calculated flow rate at the bilge main.

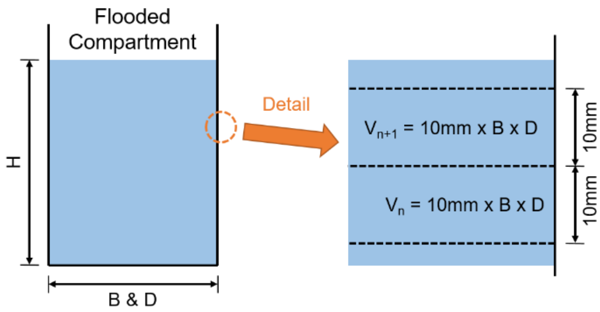

Figure 5: Concept of sample calculation

Figure 5 provides a concept based on which calculations for this study were carried out. As can be seen from Figure 2, the water level of the flooded compartment, which exerts influence on the bilge pumping performance, varies over time. Therefore, the calculation of bilge pumping performance is a time-dependent problem. To deal with it, this study applied the Finite Difference Method which requires dividing the flooded compartment into smaller sections to the direction of the compartment's depth. The smaller this "dividing" is, the more accurate the calculation becomes. The so divided sections should be small enough to be calculated as time-independent problems.

No.1 cargo hold of the sample ship was 29,000mm in depth and was thus divided with 10 mm interval.

This 10mm interval, which is 0.0345% of the 29,000mm depth, was regarded as small enough to yield reliable calculation results. Given that the purpose of this calculation was to compare the bilge pumping performance of the whole bilge system vis-à-vis that of the bilge main only, the 10mm interval was considered to be reasonable.

Formula (6) and formula (7) were applied to the convergence condition of the calculation. When formula (7) was used as a convergence condition, the maximum flow rate of the onboard bilge pump was 540 m³/h, and the flow energy loss of bilge piping system when the flow rate was 540 m³/h became much smaller than the water level in No.1 cargo hold and suction head, so convergence with the formula (6) was not available. In this case, the flow rate was fixed at 540 m³/h, and the formula (7) was used to terminate the calculation of the related water level.

$$\left|\frac{SH+LH-dH}{dH}\right| < 10^{-8} \quad (6)$$

$$|dH_{i-1} - dH_i| \leq 10^{-8} \quad (7)$$

6. RESULTS OF SAMPLE CALCULATIONS

The calculation results of 4 cases (Table 6) are shown in Tables 7, 8, 9, 10 and 11.

Table 7: Calculation results (Case 1, 300A-300A)

Tank Level	Flow Rate (m³/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%	253.19	1.01	1.16	1.16	0.00
10%	503.67	2.01	1.67	4.57	2.90
20%	540.00	2.15	1.77	5.25	5.80
30%	540.00	2.15	1.77	5.25	8.70
40%	540.00	2.15	1.77	5.25	11.60
50%	540.00	2.15	1.77	5.25	14.50
60%	540.00	2.15	1.77	5.25	17.40
70%	540.00	2.15	1.77	5.25	20.30
80%	540.00	2.15	1.77	5.25	23.20
90%	540.00	2.15	1.77	5.25	26.10
100%	540.00	2.15	1.77	5.25	29.00

Table 8: Calculation result (Case 2, 300A-200A)

Tank Level	Flow Rate (m³/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%	84.60	0.34	1.01	1.01	0.00
10%	168.98	0.67	1.07	3.97	2.90
20%	223.59	0.89	1.13	6.93	5.80
30%	267.29	1.07	1.19	9.89	8.70
40%	304.81	1.21	1.24	12.84	11.60
50%	338.20	1.35	1.30	15.80	14.50
60%	368.58	1.47	1.36	18.76	17.40
70%	396.65	1.58	1.42	21.72	20.30
80%	422.86	1.69	1.47	24.67	23.20
90%	447.54	1.78	1.53	27.63	26.10
100%	470.93	1.88	1.59	30.59	29.00

Table 9: Calculation result (Case 3, 350A-350A)

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%	368.59	1.17	1.36	1.36	0.00
10%	540.00	1.72	1.77	2.90	2.90
20%	540.00	1.72	1.77	2.90	5.80
30%	540.00	1.72	1.77	2.90	8.70
40%	540.00	1.72	1.77	2.90	11.60
50%	540.00	1.72	1.77	2.90	14.50
60%	540.00	1.72	1.77	2.90	17.40
70%	540.00	1.72	1.77	2.90	20.30
80%	540.00	1.72	1.77	2.90	23.20
90%	540.00	1.72	1.77	2.90	26.10
100%	540.00	1.72	1.77	2.90	29.00

Table 10: Calculation result (Case 4, 350A-200A)

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%	84.81	0.27	1.01	1.01	0.00
10%	169.39	0.54	1.07	3.97	2.90
20%	224.13	0.71	1.13	6.93	5.80
30%	267.94	0.85	1.19	9.89	8.70
40%	305.54	0.97	1.24	12.84	11.60
50%	339.01	1.08	1.30	15.80	14.50
60%	369.47	1.18	1.36	18.76	17.40
70%	397.60	1.27	1.42	21.72	20.30
80%	423.87	1.35	1.48	24.68	23.20
90%	448.61	1.43	1.53	27.63	26.10
100%	472.06	1.50	1.59	30.59	29.00

Table 11: Comparison of average water velocity

	Mean water velocity at bilge main while discharging flooded water from flooded compartment (No.1 Cargo Hold)
Case 1	2.09 m/s
Case 2	1.28 m/s
Case 3	1.71 m/s
Case 4	1.03 m/s

The results of the sample calculations show that the water speed at the bilge main did not meet the 2 m/s requirement when the low water level of the flooded compartment in all cases. Also, it can be seen that the water speed at the bilge main was heavily influenced by the size of the pipe between the engine room and the flooded compartment.
Case 1 was calculated to allow flooded water to be discharged in the fastest time, with an average water speed of 2.09 m/s at the bilge main, while case 3 was calculated with larger pipes with an average water speed of 1.71 m/s at the bilge main, which took more time than in Case 1.

This was due to the insufficient pumping capacity of bilge pump corresponding to the size of the pipes.

Hence, it can be seen that a bilge pump with sufficient pumping capacity should be installed on board a ship suitable for the selected size of the common bilge pipe and the size of the branch bilge pipe as well the size of the bilge main pipe.

Furthermore, even if the bilge main with a sufficient size had a sufficient pumping capacity were chosen to be installed to satisfy the 2.0 m/s requirement of SOLAS, it was noted that if the size of the common bilge pipes and branch bilge pipes were not appropriate, the actual water speed at the bilge main, could not meet 2 m/s due to flow energy loss, as demonstrated in case 2 and case 4.

In conclusion, it is practically impossible to satisfy the 2 m/s requirement of SOLAS in all operating conditions of bilge pumping systems. It should be noted that the purpose of the 2 m/s requirement of SOLAS is to discharge the flooded water in flooded compartment as soon as possible. Therefore, it can be seen that the design criteria for the bilge pumping systems considering the actual operating conditions of the bilge pumping system are needed.

In this study, it is proposed that the capacity of the bilge pump and the bilge piping systems should be designed in such a way that the average water speed at the bilge main is not less than 2 m/s, even in the compartments where it takes longest time for the bilge pumping system to discharge so-flooded water. To achieve this design objective, currently effective rules of Classification Societies should be revisited and amended accordingly.

7. CONCLUSIONS

In this study, concerns associated with the bilge pumping system were discussed using a 14,000 TEU class container ship as a test case.
The study was carried out bearing in mind the principles of IMO's Goal-Based Standards that the high-level goal of SOLAS (GBS Tier 1) should be met by detailed rules and regulations (GBS Tier 4).

Although, the 2 m/s requirement is identified as prescriptive requirements, the purpose of the requirement is "to discharge accumulated water in a flooded compartment as quickly as possible to secure ship's stability". According to our calculation results, the bilge pumping performance should be assessed from the viewpoint that pumping performance of the whole bilge piping system, not the bilge main only, should meet the intended purpose of the 2 m/s requirement. Hence, in our opinion, the 2 m/s requirement should be looked at as a functional requirement and one of the goals to be met by detailed rules under the Goal Based Standards.

Three different ways of interpreting the 2 m/s requirement of SOLAS, the inability of rules of Classification Societies to achieve the 2 m/s water speed, and the degradation of bilge pumping performance due to flow energy loss were all investigated using sample calculations for 4 cases. This approach has been applied to a 14,000 TEU Container ship design. As a result, the following conclusions were drawn.

(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.

(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.

(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.

8. DISCLAIMER

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

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