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Original Paper

Bilge pumping performance for cargo holds of large container ships

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Abstract: This study aims to improve the fire safety of container ships by examining the bilge pumping performance necessary to prevent the formation of free surfaces in cargo holds when a water spray system is introduced as an active protection system on hatch covers. The study calculates whether free surfaces would occur in a cargo hold equipped with a water spray system using the bilge pumping system installed on 24,000 TEU-class container ships. The calculation results indicate that the free surface could not be prevented in all cases when only one bilge pump was operated. Even with the operation of two bilge pumps, free surfaces were still observed in all cargo holds except for the No.1 cargo hold. Design modifications, such as increasing the size of the branch bilge pipe, are necessary to prevent free surfaces in the cargo holds. Therefore, it is strongly recommended that when installing a water spray system as an active protection system on hatch covers, the bilge pumping system's ability to prevent free surfaces in the cargo holds of each individual container ship be thoroughly examined.

Keywords: Container ship fire safety, Hatch cover protection, Water spray system, Bilge pumping performance, Free surface

1. Introduction

Fire accidents are among the most fatal incidents that occur on ships, prompting extensive research to mitigate their impact **[1][2]**.

According to the International Union of Marine Insurance (IUMI), between 2000 and 2015, 56 cargo fires on containerships resulted in an average cost of approximately $20 million per incident, totaling over $1.037 billion in damages (excluding hull damages). Hull damages account for an average of at least $6.5 million per cargo fire incident, with total costs exceeding $0.5 billion between 2000 and 2019 **[3]**.

Marshall Islands *et al.* and Bahamas *et al.* proposed measures to improve fire safety in container ship cargo areas, such as reviewing related requirements to reduce fire risks in cargo areas. Related matters have been discussed since the eighth session of the Sub-Committee on Ship Systems and Equipment (SSE Sub-Committee) **[4]-[6]**.

The European Maritime Safety Agency (EMSA) ordered the CARGOSAFE project, a formal safety assessment (FSA) study on fire safety in container ship cargo areas, and the CARGOSAFE report was submitted to the 107th session of the Maritime Safety Committee (MSC) **[7]**.

In the CARGOSAFE report, risk control options (RCOs) were categorized into four groups: “Prevention,” “Detection,” “Fire-fighting,” and “Containment”. A cost-effectiveness assessment (CEA) was conducted, leading to the recommendation of two RCOs for each category, as shown in **Table 1 [8]**.

In **Table 1**, “Containment” refers to preventing fires originating in the cargo hold of a container ship from spreading to the open deck area. A60 insulation was recommended as a passive protection RCO, while a water spray system was recommended as an active protection system.

At the 10th session of the SSE Sub-Committee, held in March 2024, the CARGOSAFE report and previously submitted agenda documents were reviewed. It was decided that active hatch cover protection would be discussed further at the 11th SSE Sub-Committee **[9]-[13]**.

Although the seawater flow rate to be supplied by the active protection system featuring a water spray system on the hatch covers has not yet been determined, it is anticipated that the existing SOLAS Regulation II-2/19.3.1.3 will apply.

This regulation currently applies to cargo holds storing class 1

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Table 1: RCO recommendations across all 3 ship sizes per layer of protection (Table 92 of CARGOSAFE Report)

Fire Mitigation Phase	Prevention	Detection	Firefighting	Containment
1st RCO	Improved Control of Lashing	Portable IR cameras for crew to enhance manual detection	Methods for unmanned fire fighting	Passive protection to protect from fire spread towards the deck
2nd RCO	Container Screening Tool	Heat detection looking at individual container temperature rise	Manual firefighting tools that increase reach	Active protection underneath hatch covers to protect from fire spread towards the deck

dangerous goods (explosive substances and articles). If the active protection system is introduced, this requirement is expected to be extended to all cargo holds.

SOLAS Regulation II-2/19.3.1.3 outlines not only the seawater flow rate for the water spray system but also the capacity of the bilge pumping system to effectively discharge the supplied seawater outside the ship. Before applying the water spray system to all cargo holds, the performance of the bilge pumping system must be reviewed in accordance with SOLAS Regulation II-2/19.3.1.3.

Lee *et al.* and Seo *et al.* conducted studies on the performance of bilge pumping systems. They found that, due to logical contradictions in the rule requirements of classification societies, the water speed requirement of 2 m/s in the main bilge pipe, as specified in SOLAS Regulation II-1/35-1, is not met in large container ships and bulk carriers **[14]-[16]**.

Given that the seawater flow rate specified in SOLAS Regulation II-2/19.3.1.3 is set at 5 L/min per square meter—a relatively high flow rate—the performance of bilge pumping systems in cargo holds requires careful review.

2. Regulations for Bilge Pumping System

The bilge pumping system, which is crucial to ship stability, is one of the most important safety systems on a vessel. The requirements for this system are outlined in SOLAS Regulation II-1/35-1, with the key provision being that the water speed in the bilge main should exceed 2 m/s. However, according to the research results of Lee et al. and Seo et al., there are cases where the water speed at the bilge main does not satisfy the 2 m/s requirement for large container ships and bulk carriers because of logical contradictions in the rule requirements of classification societies **[14]-[16]**.

The failure of the bilge pumping system to meet the 2 m/s requirement indicates that its performance is insufficient, preventing the effective discharge of seawater from lower compartments, such as cargo holds.

Therefore, before introducing the water spray system requirements specified in SOLAS Regulation II-2/19.3.1.3 as an active protection system on hatch covers, it is necessary to review the bilge pumping performance.

Table 2: SOLAS Regulation II-2/19.3.1.3

19.3.1.3 Means shall be provided for effectively cooling the designated underdeck cargo space by **at least 5 litres/min per square metre of the horizontal area of cargo spaces**, either by a fixed arrangement of spraying nozzles or flooding the cargo space with water. Hoses may be used for this purpose in small cargo spaces and in small areas of larger cargo spaces at the discretion of the Administration. However, **the drainage and pumping arrangements shall be such as to prevent the build-up of free surfaces**. The **drainage system shall be sized to remove no less than 125% of the combined capacity of both the water spraying system pumps and the required number of fire hose nozzles**. The drainage system valves shall be operable from outside the protected space at a position in the vicinity of the extinguishing system controls. Bilge wells shall be of sufficient holding capacity and shall be arranged at the side shell of the ship at a distance from each other of not more than 40 m in each watertight compartment. If this is not possible, the adverse effect upon stability of the added weight and free surface of water shall be taken into account to the extent deemed necessary by the Administration in its approval of the stability information.

Table 2 presents the specifications outlined in SOLAS Regulation II-2/19.3.1.3, detailing the required seawater flow rate for the water spray system and the performance criteria for the bilge pumping system. A detailed review is particularly necessary to ensure adequate bilge pumping performance to prevent the formation of free surfaces, especially in light of the research findings by Lee *et al.* and Seo *et al* **[14]-[16]**.

3. Bilge Pumping Performance

The bilge pumping performance can be determined by how quickly seawater is discharged from a flooded compartment to the outside of the ship. In line with this, SOLAS Regulation II-1/35-1 stipulates that the water speed at the bilge main must be at least 2 m/s.

Various methods exist for evaluating bilge pumping performance; however, in this study, the concept shown in Figure 1 was applied, following the approach used in the studies by Lee *et al.* and Seo *et al.* **[14]-[16]**.

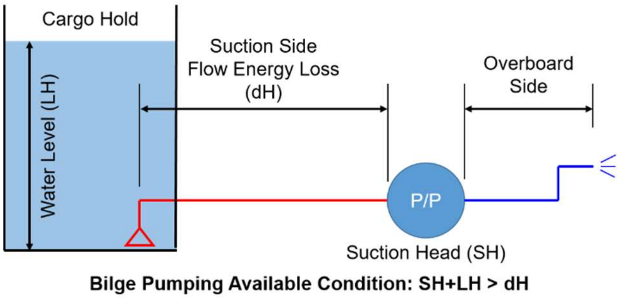

Figure 1: Schematic of bilge pumping system **[14]-[16]**

As illustrated in **Figure 1**, to effectively discharge seawater from the compartment to the outside of the ship, the combined suction head of the bilge pump and the head of the accumulated seawater, due to the water level in the compartment, must exceed the flow energy loss within the bilge piping system. Therefore, to assess bilge pumping performance, it is essential to evaluate the flow energy loss in the bilge piping system.

In this study, friction loss was assessed using the Darcy-Weisbach equation, as shown in **Equation (1)**, which is one of the various methods for evaluating flow energy loss **[17]-[19]**. The friction factor required for this calculation was determined using the Colebrook-White equation, as in **Equation (2)**, rather than relying on the Moody chart **[20][21]**.

$$\Delta P = f\left(\frac{L+L_E}{D}\right)\frac{\rho V^2}{2} \tag{1}$$

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

Here, ΔP represents flow energy loss (Pa), f is the friction loss coefficient, L and L_E denote the length of pipe (m) and equivalent length of valves and fittings (m), respectively, D is the internal diameter of pipe (m), ρ is the fluid density (kg/m^3), V is the velocity of the fluid in the pipe (m/s), and ε is pipe wall roughness (m). The pipe wall roughness, required to calculate the friction factor in Equation (2), was set to 1.0 mm, consistent with the values used in the studies by Lee *et al.* and Seo *et al.* **[14]-[16]**.

The flow energy loss from the pipe fittings and valves is calculated using the equivalent length method, as specified in NFPA Code 13 and shown in **Table 3**. However, **Table 3** provides equivalent lengths only for pipes up to 300 A, while 400 A pipes are used in the bilge pumping system of 24,000 TEU-class container ships. Because this study aims to compare the flow rate between cargo holds, the results are valid as long as the same conditions are applied across all cargo holds. Therefore, the equivalent length values for 300 A pipe fittings and valves are applied to the 400 A pipe fittings and valves **[22]**.

The density and viscosity of seawater are essential for evaluating flow energy loss, using **Equations (1)** and **(2)**, respectively. Although these conditions can vary, the study uses the physical properties of standard seawater at 20°C, as provided by the International Towing Tank Conference (ITTC). The applied density and viscosity are 1,024.8103 kg/m^3 and 0.001077 Pa·s, respectively **[23]**.

4. Bilge Pumping System of 24,000 TEU-class Container Ships

In this study, calculations were performed using the specifications of the bilge pumping system for cargo holds of 24,000 TEU-class container ships to determine whether the bilge pumping system meets the bilge pumping requirements of SOLAS Regulation II-2/19.3.1.3. A bilge pumping system with the same

Table 3: Equivalent schedule of the 40 steel pipe length chart (NFPA Code 13, p.13-237, Table 23.4.3.1.1)

Fittings and Valves	Fittings and Valves Expressed in Equivalent Meter of Pipe														
	15mm	20mm	25mm	32mm	40mm	50mm	65mm	80mm	90mm	100mm	125mm	150mm	200mm	250mm	300mm
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

specifications as those used in the study by Seo *et al.* was utilized **[16]**. The hull shape of the fore side of the container ship changes rapidly toward the bow, as shown in **Figure 2**, causing the width of the cargo holds to narrow. The volume and depth of each cargo hold are presented in **Table 4**.

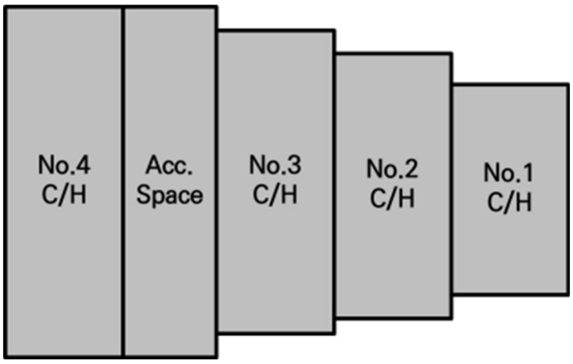

Figure 2: Schematic arrangement of cargo holds **[16]**

Table 4: Specifications of cargo holds **[16]**

Cargo Hold	Net Volume (m^3)	Depth (m)	Average Horizontal Area (m^2) (Volume/Depth)
No.1	41,526.4	31	1339.56
No.2	47,151.0	31	1521.00
No.3	51,099.2	31	1648.36
No.4	52,365.5	31	1689.21

Figure 3 shows a schematic of the bilge pumping system installed on 24,000 TEU-class container ships, and the detailed specifications for each cargo hold are shown in **Tables 5, 6, 7,** and **8**.

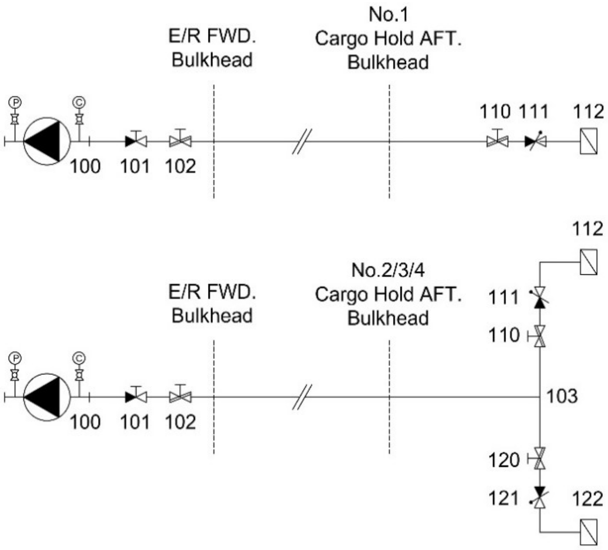

Figure 3: Schematic of bilge pumping system **[16]**

Table 5: Arrangement of bilge pumping system (No.1 C/H) **[16]**

Node	Node	ND (Sch.40)	Length of pipe (m)	Fittings and Valves
100	101	400A	1	Check Valve
101	102	400A	2	Butterfly Valve
102	110	400A	246.5	
110	111	200A	2	Butterfly Valve
111	112	200A	2	Check V/V, Elbow

Table 6: Arrangement of bilge pumping system (No.2 C/H) **[16]**

Node	Node	ND (Sch.40)	Length of pipe (m)	Fittings and Valves
100	101	400A	1	Check Valve
101	102	400A	2	Butterfly Valve
102	103	400A	218	
103	110	150A	10	Tee (branch)
110	111	150A	2	Butterfly Valve
111	112	150A	2	Check V/V, Elbow
103	120	150A	10	Tee (branch)
120	121	150A	2	Butterfly Valve
121	122	150A	2	Check V/V, Elbow

Table 7: Arrangement of bilge pumping system (No.3 C/H) **[16]**

Node	Node	ND (Sch.40)	Length of pipe (m)	Fittings and Valves
100	101	400A	1	Check Valve
101	102	400A	2	Butterfly Valve
102	103	400A	188	
103	110	150A	17.2	Tee (branch)
110	111	150A	2	Butterfly Valve
111	112	150A	2	Check V/V, Elbow
103	120	150A	17.2	Tee (branch)
120	121	150A	2	Butterfly Valve
121	122	150A	2	Check V/V, Elbow

Table 8: Arrangement of bilge pumping system (No.4 C/H) **[16]**

Node	Node	ND (Sch.40)	Length of pipe(m)	Fittings and Valves
100	101	400A	1	Check Valve
101	102	400A	2	Butterfly Valve
102	103	400A	141.5	
103	110	150A	19.7	Tee (branch)
110	111	150A	2	Butterfly Valve
111	112	150A	2	Check V/V, Elbow
103	120	150A	19.7	Tee (branch)
120	121	150A	2	Butterfly Valve
121	122	150A	2	Check V/V, Elbow

Figure 4 shows the performance curve of a bilge pump installed on a 24,000 TEU-class container ship. Two power bilge pumps were installed on the ship. The suction head of each bilge pump was calculated using **Equation (3)** through curve fitting of the performance curve.

Tables 9, 10, 11, and **12** show the research results of Seo et al., which indicates the calculation of the average speed while discharging all the seawater within the cargo hold, assuming that each cargo hold is fully filled with seawater **[16]**. The average water speed at the bilge main did not satisfy the 2 m/s requirement of SOLAS Regulation II-2/35-1, except for No.1 cargo hold. In addition, when the water level in the cargo hold is low, all cargo holds fail to satisfy the 2 m/s requirement.

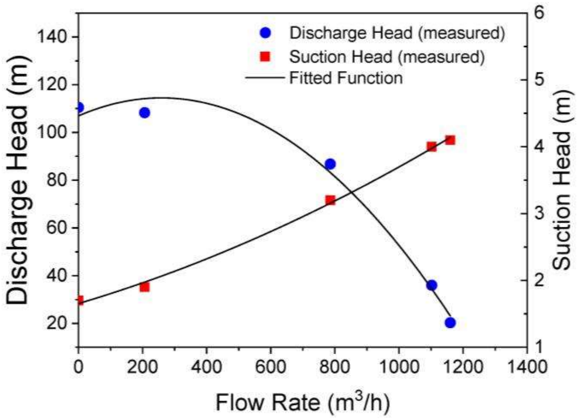

Figure 4: Bilge pump performance curve **[16]**

Table 9: Calculation results for No.1 cargo hold (actual arrangement, 400A-200A) **[16]**

Water Level	Flow Rate (m^3/h)	Water Velocity at Bilge Main (m/s)	Pump Suction Head (SH, m)	Flow Energy Loss (dH, m)	Static Head by Water Level (LH, m)
0%	321.63	0.758	2.18	2.18	0
10%	519.74	1.225	2.56	5.66	3.1
20%	657.88	1.55	2.86	9.06	6.2
30%	770.57	1.816	3.12	12.42	9.3
40%	868.18	2.046	3.35	15.75	12.4
50%	955.51	2.252	3.58	19.08	15.5
60%	1035.26	2.44	3.79	22.39	18.6
70%	1109.11	2.614	3.99	25.69	21.7
80%	1160.00	2.734	4.14	28.10	24.8
90%	1160.00	2.734	4.14	28.10	27.9
100%	1160.00	2.734	4.14	28.10	31.0
Mean Velocity (m/s)			2.121		

Table 10: Calculation results for No.2 cargo hold (actual arrangement, 400A-150A) **[16]**

Water Level	Flow Rate (m^3/h)	Water Velocity at Bilge Main (m/s)	Pump Suction Head (SH, m)	Flow Energy Loss (dH, m)	Static Head by Water Level (LH, m)
0%	258.98	0.610	2.06	2.06	0.00
10%	422.31	0.995	2.36	5.46	3.10
20%	536.10	1.263	2.59	8.79	6.20
30%	628.92	1.482	2.79	12.09	9.30
40%	709.30	1.672	2.97	15.37	12.40
50%	781.22	1.841	3.14	18.64	15.50
60%	846.89	1.996	3.30	21.90	18.60
70%	907.70	2.139	3.45	25.15	21.70
80%	964.59	2.273	3.60	28.40	24.80
90%	1018.24	2.400	3.74	31.64	27.90
100%	1069.15	2.520	3.88	34.88	31.00
Mean Velocity (m/s)			1.766		

$$SH = 6.20183 \times 10^{-7}Q^2 + 0.00142Q + 1.65441 \qquad (3)$$

Table 11: Calculation results for No.3 cargo hold (actual arrangement, 400A-150A) **[16]**

Water Level	Flow Rate (m^3/h)	Water Velocity at Bilge Main (m/s)	Pump Suction Head (SH, m)	Flow Energy Loss (dH, m)	Static Head by Water Level (LH, m)
0%	240.97	0.568	2.03	2.03	0.00
10%	393.98	0.928	2.31	5.41	3.10
20%	500.56	1.180	2.52	8.72	6.20
30%	587.49	1.384	2.70	12.00	9.30
40%	662.77	1.562	2.87	15.27	12.40
50%	730.13	1.721	3.02	18.52	15.50
60%	791.63	1.866	3.17	21.77	18.60
70%	848.58	2.000	3.31	25.01	21.70
80%	901.86	2.125	3.44	28.24	24.80
90%	952.10	2.244	3.57	31.47	27.90
100%	999.77	2.356	3.69	34.69	31.00
Mean Velocity (m/s)			1.650		

Table 12: Calculation results for No.4 cargo hold (actual arrangement, 400A-150A) **[16]**

Water Level	Flow Rate (m^3/h)	Water Velocity at Bilge Main (m/s)	Pump Suction Head (SH, m)	Flow Energy Loss (dH, m)	Static Head by Water Level (LH, m)
0%	237.95	0.561	2.03	2.03	0.00
10%	389.18	0.917	2.30	5.40	3.10
20%	494.52	1.165	2.51	8.71	6.20
30%	580.43	1.368	2.69	11.99	9.30
40%	654.84	1.543	2.85	15.25	12.40
50%	721.41	1.700	3.00	18.50	15.50
60%	782.19	1.843	3.14	21.74	18.60
70%	838.48	1.976	3.28	24.98	21.70
80%	891.14	2.100	3.41	28.21	24.80
90%	940.80	2.217	3.54	31.44	27.90
100%	987.91	2.328	3.66	34.66	31.00
Mean Velocity (m/s)			1.630		

5. Calculation and Review

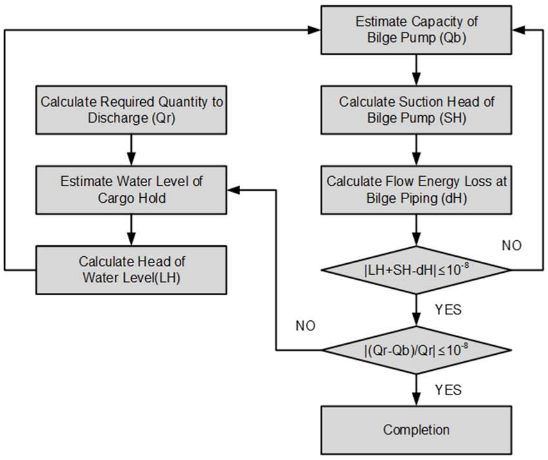

Figure 5: Calculation Procedure

The studies by Lee *et al.* and Seo *et al.* assumed that the cargo hold is filled with seawater and calculated the average water speed at the bilge main while discharging all seawater in the cargo hold, as it is not possible to predict how much seawater will flow into the cargo hold during flooding. The purpose of this study is to determine whether the bilge pumping system can prevent the formation of free surfaces in cargo holds when the water spray system is activated. Additionally, if a free surface occurs, this study aims to assess the level of seawater accumulated in the cargo holds. Therefore, the calculations were carried out according to the procedure shown in **Figure 5 [14]-[16]**.

The amount of seawater supplied to the cargo holds should be calculated in accordance with SOLAS Regulation II-2/19.3.1.3 to determine whether a free surface occurs during the operation of the bilge pumping system and to identify the water level when the free surface does occur. The amount of seawater supplied to the cargo hold is 125% of the combined capacity of the flow rate of 5 L/min per square meter of the horizontal area of the cargo holds and the required number of fire hose nozzles, in accordance with SOLAS Regulation II-2/19.3.1.3.

The amount of seawater supplied to the cargo holds by the water spray system varied depending on the horizontal area of the cargo holds, which varied with the depth according to the hull shape of the fore and aft sections of the container ship.

In this study, considering that the horizontal area of the cargo hold was not constant, the value obtained by dividing the total volume by the depth was applied as the average horizontal area. The value is the average horizontal area in **Table 4**.

The flow rate should be determined based on the number of fire hoses required. Because container ships generally carry dangerous goods, four jets are required for fire hoses. However, the flow rate of a single jet is not specified for the SOLAS and IMO instruments and the flow rate may vary for each container ship. In this study, by referring to IACS UI SC 163 Rev.2, the flow rate of one jet was determined as 23.5 m^3/h **[24]**.

Table 13: Required capacity of seawater when fire occurred in cargo holds

Cargo Hold	Average Horiz. Area (m^2)	Capacity of Water Spray System (m^3/h)	Capacity of 4 Jets (m^3/h)	125% of Combined Capacity (m^3/h)
1	1339.56	401.87	94.0	619.84
2	1521.00	456.30	94.0	687.88
3	1648.36	494.51	94.0	735.64
4	1689.21	506.76	94.0	750.95

Table 13 presents the combined capacity for each cargo hold of a 24,000 TEU-class container ship, considering the water spray system and the required number of fire hoses, in accordance with SOLAS Regulation II-2/19.3.1.3.

The calculation results of the accumulated water level for each cargo hold are listed in **Tables 14, 15, 16**, and **17**. In these cases, the required amount of seawater, as shown in **Table 13**, was supplied to the cargo hold, and the bilge pumping system was operated to discharge the seawater from the cargo hold to the outside of the ship.

Table 14: Calculation results for No.1 cargo hold

No. of Bilge Pumps	1	2	1	2
Size of Branch Bilge Pipe	200A	200A	250A	250A
Water Level for Free Surface (m)	5.27	0.00	1.52	0.00
Water Level for Free Surface (%)	17.00%	0.00%	4.91%	0.00%
Flow Rate of Each Pump (m^3/h)	619.84	321.63	619.84	468.14
Flow Rate at Bilge Main (m^3/h)	619.84	643.25	619.84	936.28
Water Speed at Bilge Main (m/s)	1.46	1.52	1.46	2.21

Table 15: Calculation results for No.2 cargo hold

No. of Bilge Pumps	1	2	1	2
Size of Branch Bilge Pipe	150A	150A	200A	200A
Water Level for Free Surface (m)	11.54	1.41	2.53	0.00
Water Level for Free Surface (%)	37.21%	4.56%	8.18%	0.00%
Flow Rate of Each Pump (m^3/h)	687.88	343.94	687.88	458.69
Flow Rate at Bilge Main (m^3/h)	687.88	687.88	687.88	917.39
Water Speed at Bilge Main (m/s)	1.62	1.62	1.62	2.16

Table 16: Calculation results for No.3 cargo hold

No. of Bilge Pumps	1	2	1	2
Size of Branch Bilge Pipe	150A	150A	200A	200A
Water Level for Free Surface (m)	15.77	2.46	3.49	0.00
Water Level for Free Surface (%)	50.86%	7.93%	11.26%	0.00%
Flow Rate of Each Pump (m^3/h)	735.64	367.82	735.64	446.23
Flow Rate at Bilge Main (m^3/h)	735.64	735.64	735.64	892.45
Water Speed at Bilge Main (m/s)	1.73	1.73	1.73	2.10

Table 17: Calculation results for No.4 cargo hold

No. of Bilge Pumps	1	2	1	2
Size of Branch Bilge Pipe	150A	150A	200A	200A
Water Level for Free Surface (m)	16.97	2.75	3.47	0.00
Water Level for Free Surface (%)	54.76%	8.88%	11.18%	0.00%
Flow Rate of Each Pump (m^3/h)	750.95	375.48	750.95	457.29
Flow Rate at Bilge Main (m^3/h)	750.95	750.95	750.95	914.58
Water Speed at Bilge Main (m/s)	1.77	1.77	1.77	2.16

In this study, calculations were performed separately for scenarios where one bilge pump was operating and where both bilge pumps were operating. These calculations were based on the installed branch bilge pipe as well as the branch bilge pipe of the next larger size.

Upon reviewing the calculation results, it was confirmed that the operation of a single bilge pump could not prevent the formation of a free surface in all cargo holds.

The occurrence of a free surface is depicted in **Figure 1**, where the sum of the water head (LH) due to the water level in the cargo hold and the pump suction head (SH) has the same value as the flow energy loss (dH) occurring in the bilge piping system. For instance, in the No.4 cargo hold, a free surface formed at 54.76% of the cargo hold depth; however, when the water level was lower than 54.76%, dH exceeded the sum of LH and SH, indicating that the bilge pump could not discharge the seawater supplied to the cargo hold (via the water spray system and number of jets) to the outside of the ship.

Additionally, even when two bilge pumps were operated, the formation of a free surface could not be prevented in the case of the currently installed branch bilge pipe (150 A), except in the No.1 cargo hold. To address this issue, two bilge pumps should be operated, and a branch bilge pipe of larger diameter than the one currently installed should be used, in accordance with the rule requirements of ship classification societies, to prevent the formation of a free surface.

While the prevention of free surfaces, as required by SOLAS Regulation II-2/19.3.1.3, is intended to prevent accidents caused by sloshing, it is important to note that in most cases, the cargo holds of container ships are always loaded with containers, reducing the likelihood of accidents such as hull damage caused by sloshing.

Therefore, it is necessary to evaluate whether allowing a free surface up to a certain water level is acceptable or if it is more reasonable to prevent free surfaces through design modifications to the bilge pumping system. Considering the calculation results, because the size of the branch bilge pipe—part of the bilge pumping system—needs to be increased by only one step, it is reasonable to uphold the free surface prevention requirement with minimal design modifications for 24,000 TEU-class container ships.

Furthermore, similar cases are anticipated for container ships of other sizes, where it is believed that free surface prevention can also be achieved with minor design modifications, such as increasing the size of the main, common, or branch bilge pipes.

However, bilge pumping performance is affected by flow energy loss. This study did not include data on flow energy loss related to the strainer fitted on the pump inlet, nor did it account for the mud box at the end of the branch bilge pipe. Future studies would incorporate these factors to provide a more comprehensive assessment of bilge pumping performance.

6. Conclusion

In this study, a review of the free surfaces in cargo holds was conducted using the bilge pumping system installed on 24,000 TEU-class container ships, along with the introduction of a water spray system in accordance with SOLAS Regulation II-2/19.3.1.3. This regulation serves as an active protection system for hatch covers to enhance the fire safety of container ships. The findings of this study are as follows.

(1) Two bilge pumps should be operated when operating the water spray system because a free surface cannot be prevented when only one bilge pump is in operation.

(2) Even when two bilge pumps were operated, a free surface occurred in cargo holds No. 2, No. 3, and No. 4 with the currently installed bilge pumping system. To prevent this free surface, design modifications, such as increasing the size of the branch bilge pipe, were required.

(3) When the free surface occurred, the water speed at the bilge main did not satisfy the 2 m/s requirement of SOLAS Regulation II-1/35-1.

Considering the calculation results, this study found that when a water spray system is installed on the hatch cover as an active protection system in accordance with SOLAS Regulation II-2/19.3.1.3, it is necessary to evaluate whether the bilge pumping system can effectively prevent the formation of a free surface in the cargo holds of each container ship.

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Author Contributions

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