



Experimental Analysis of the Effect of Air-Injection Pressure System Configuration on The LNG Resistance

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ABSTRACT

Ballast-free systems (BFS) provide an ecological alternative to conventional ballast water systems but increase ship resistance due to additional wetted surfaces and discharge outlets. Limited studies have experimentally quantified the drag reduction potential of air lubrication in BFS configurations for LNG vessels. This study investigates the integration of air-injection pressure systems to mitigate this resistance penalty. Experimental tests were conducted on a 1:80 scale model of an LNG vessel, evaluating various configurations of air injection at 0.5 bar and water pump operation. The results show that while BFS alone increased total resistance by an average of 2.67%, the optimized configuration BFS+0.5B+B_Config—which combines air injection from all water ballast tanks (WBTs) with water pumping only to the fore WBTs—effectively counteracted this effect. This configuration achieved an average resistance reduction of 4.6%, peaking at 6.81% at a Froude number of 0.19. These findings validate the practical integration of air lubrication in BFS-equipped LNG vessels, offering a pathway to enhanced hydrodynamic efficiency and improved environmental sustainability in maritime transport.

1. Introduction

LNG vessels play a crucial role in the transportation of liquefied natural gas across the globe. LNG vessels play a crucial role in the transportation of liquefied natural gas across the globe. These vessels utilize specialized containment systems, such as membrane and Moss-type tanks, to safely transport LNG under cryogenic conditions. Ship resistance experienced by LNG vessels significantly affects fuel consumption and environmental impact. This means that the higher the resistance; the more power is needed from the propulsion engine to develop the required service speed and to transport the forecasted tonnage of cargo within the anticipated voyage duration. Correspondingly higher generated power increases the emissions as the maritime sector represents 80% of all cargo shipment, and the figure represents the important role of the sector to international trade and

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transportation as shown in the study by Wang *et al.*, [1]. The International Maritime Organization (IMO) has set ambitious goals for reducing GHG emissions in maritime transport, targeting net-zero emissions by 2050 according to Anantharaman *et al.*, [2], Di Vaio *et al.*, [3], and Yılbaşı [4]. Resistance components in ships are broadly categorized into frictional and residual resistance. Frictional resistance arises from the viscous effects of water on the hull surface, while residual resistance includes wave-making and wave-breaking components.

Various methodologies applying computational fluid dynamics (CFD), experimental testing, and empirical regression models, have been employed to reduce ship resistance as employed by Kadir *et al.*, [5]. Among these, air lubrication drag reduction (ALDR) has emerged as an effective approach. ALDR techniques, including microbubble drag reduction (MBDR) and air layer drag reduction (ALDR), minimize frictional resistance by introducing air into the boundary layer, effectively separating the hull surface from water contact as shown in Figure 1 and discussed in the works of An *et al.* [6], Caprace *et al.* [7], Huang *et al.*, [8], and Qin *et al.*, [9].

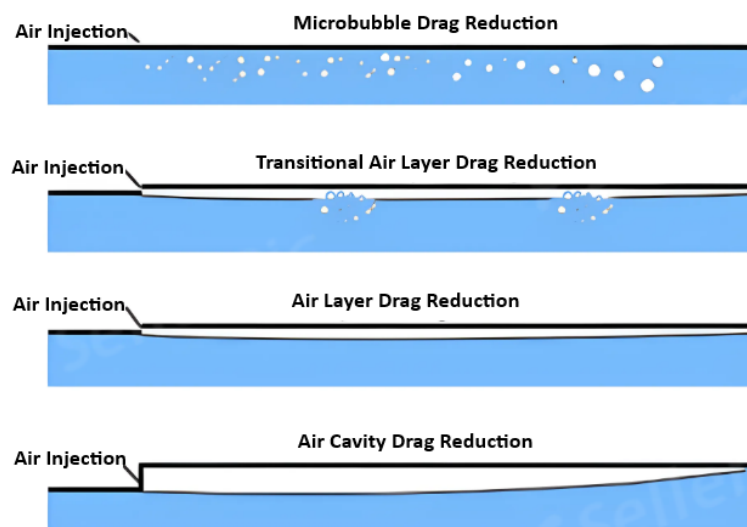


Fig. 1. Modes of lubrication drag reduction

BFS systems have been introduced to address ecological challenges associated with traditional ballast systems, such as the spread of invasive species. However, BFS configurations have been shown to increase ship resistance, leading to higher operational costs. Studies on BFS have identified significant resistance increments due to hydrodynamic flow alterations caused by the ballast system. For example, research by Godey *et al.*, [10] indicates that BFS designs incorporating longitudinal ballast trunks and continuous water flushing result in increased frictional and residual resistance by 30% to 35% compared to traditional setups. Nevertheless, integrating air lubrication systems with BFS can counteract these drawbacks. Experimental studies as shown in Table 1 by Kadir *et al.*, [11] show that optimized air injection at 0.5 bar can reduce hull resistance by up to 29.79% in certain configurations.

Table 1

Previous result of experimental studies by Kadir *et al.* [11]

Fr	R _{BARE} [N]	R _{BFS} [N]	Relative increase (%)	R _{BFS+0.5B} [N]	Relative increase (%)	R _{BFS+1.0B} [N]	Relative increase (%)	R _{BFS+1.5B} [N]	Relative increase (%)
0.17	4.70	5.16	9.76	4.25	-9.74	4.90	4.08	5.39	14.58
0.18	5.28	5.57	5.58	3.42	-35.22	4.53	-14.18	5.31	0.60
0.19	5.63	6.11	8.54	3.30	-41.39	4.90	-12.97	5.64	0.18
0.20	6.15	7.13	15.98	3.90	-36.56	5.78	-5.98	5.81	-5.49
0.21	6.94	7.98	14.90	4.80	-30.87	6.40	-7.82	7.00	0.82
0.22	8.15	9.17	12.55	6.11	-24.99	6.81	-16.39	7.93	-2.64
Average		11.22		-29.79		-8.88		1.34	

Air injection methodologies vary, including systems utilizing nozzles, porous plates, and hydrofoils. In their review, Vidović *et al.*, [12] reviewed some notable implementations, such as Mitsubishi's MALS and Silverstream Technologies. They demonstrate the practical viability of these systems in reducing resistance and improving fuel efficiency as shown in Figure 2 and Figure 3 from the work of Fotopoulos and Margaris [13].

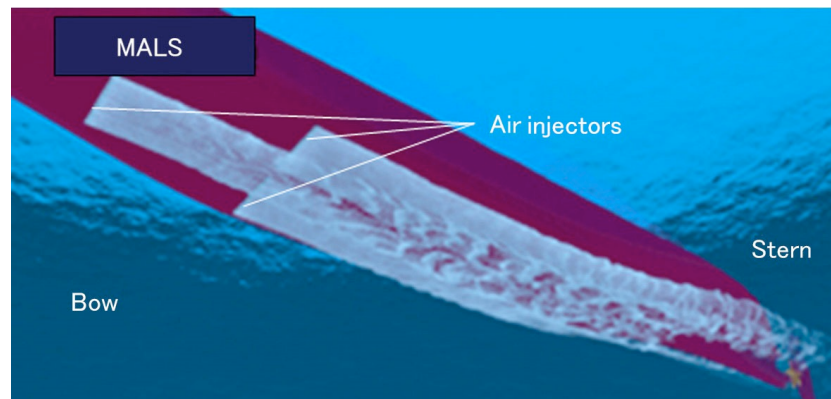


Fig. 2. MALS application at fore part of a ship

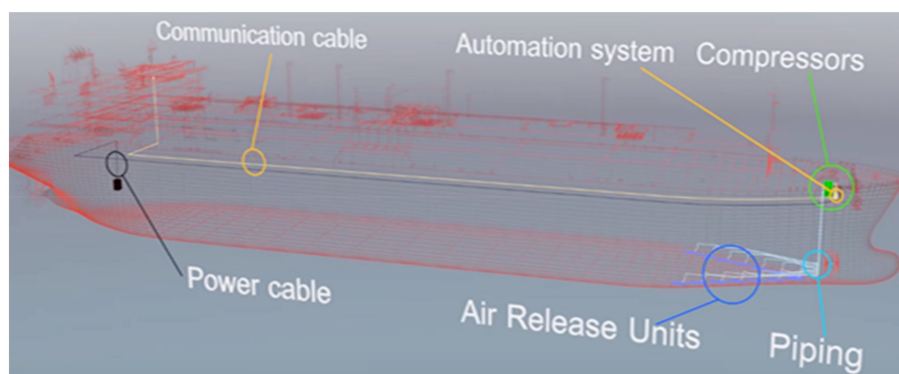


Fig. 3. Silverstream Technologies application at fore part of a ship

However, challenges remain in optimizing air distribution, pressure settings, and system configurations to achieve consistent performance across different vessel types and operating conditions. This study builds upon these findings by experimentally validating the performance of air-

injection pressure systems in BFS-equipped LNG vessels. By addressing resistance-related challenges, this research aims to enhance the energy efficiency and environmental sustainability of maritime operations.

2. Methodology

2.1 Experimental Setup

For The research was conducted at the Marine Technology Centre (MTC), Universiti Teknologi Malaysia (UTM), using a 1:80 scale model of the Tenaga Class LNG vessel with the specification as specified in Table 2.

Table 2
Main specification of Tenaga Class LNG vessel

Main Characteristics	Symbol	Full scale	Model (MTL 063)
Length overall [m]	LOA	280.62	3.508
Length at waterline [m]	LWL	268.414	3.355
Length between perpendiculars [m]	LPP	266.000	3.325
Breadth at waterline [m]	B	41.600	0.520
Draught [m]	T	11.130	0.139
Normal ballast water draught [m]	T	9.755	0.122
Block coefficient	CB	0.746	0.746
Water density at 25°C [kg/m ³]	ρ	1025.000	1000.000
Water kinetic viscosity [m ² /s]	ν	9.67x10 ⁻⁷	9.26x10 ⁻⁷
Gravitational acceleration [m ² /s ²]	g	9.810	9.810
Scale factor	λ	1	80

The model represented key features of BFS, and integrated air lubrication systems as shown in Figure 4 and Figure 5. The towing tank, with dimensions of 120 m × 4 m × 2.5 m, facilitated controlled experiments, including calm water resistance tests. The experimental setup was comprised of several key components. An air injection system was used to introduce air at a pressure of 0.5 bar in order to evaluate its effectiveness in reducing frictional resistance. The Ballast-Free System (BFS) was tested in various configurations, which involved variations in injection locations and water flow dynamics controlled by a pump. All measurements, including resistance, sinkage, and trim, were recorded using a Data Acquisition and Analysis System (DAAS).

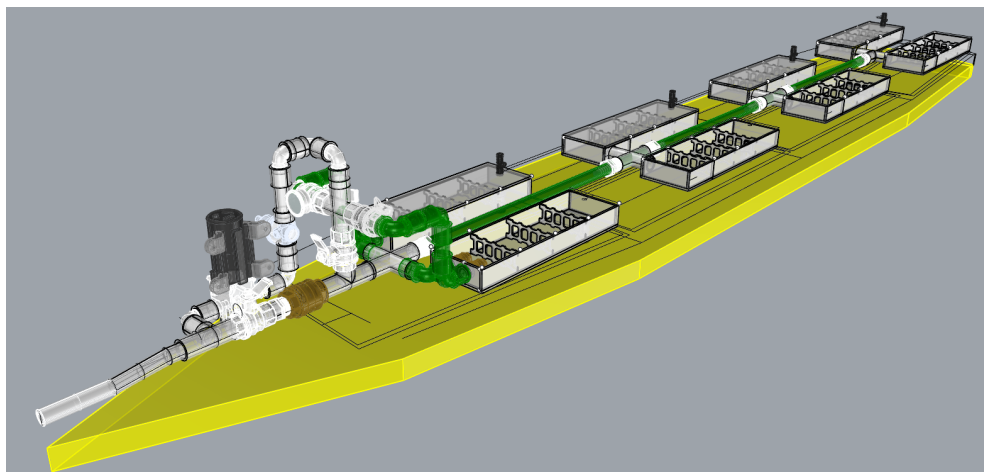


Fig. 4. Overview of BFS system



Fig. 5. Perspective view of MTL 063 equipped with BFS system

2.2 Testing Protocol

The towing tests followed ITTC guidelines to ensure dynamic similarity and reliable scaling. Froude numbers ranging from 0.15 to 0.21 as shown in Table 3 were tested to represent typical operating conditions. The experimental procedure was conducted in a systematic sequence. It began by testing the bare hull to establish a baseline measurement for resistance. Following this, the Ballast-Free System (BFS) was evaluated on its own without any air injection to isolate its effect on the hull's performance. The final phase involved a comprehensive assessment of the BFS combined with various air-injection configurations, as illustrated in Figure 6. The flexibility of the flow setup permitted the isolation of specific lines and the selection of different configurations for these tests.

Table 3
Test protocol

Test Group	Condition	Air Injection Pressure (bar)	Pump Capacity (%)	Loc. Subset	Fr _m (-)	Details
C1	Bare	0.0	0%	-	0.15	- Bare hull condition without BFS system
				-	0.17	
				-	0.19	
				-	0.21	
C2	Bare+0.5B	0.5	0%	-	0.15	- Bare hull condition without BFS system - Inject 0.5 compressed air from outlet of all WBTs
				-	0.17	
				-	0.19	
				-	0.21	
C3	BFS	0.0	17%	-	0.15	- BFS system without air injection - With minimum water pump application to activate BFS
				-	0.17	
				-	0.19	
				-	0.21	
C4	BFS+0.5B	0.5	17%	-	0.15	- BFS system with 0.5 bar air injection - With minimum water pump application to activate BFS
				-	0.17	
				-	0.19	
				-	0.21	
C5	BFS+0.5B+A_Config	0.5	33%	A	0.15	- BFS system with 0.5 bar air injection and water pump application to all WBTs
				A	0.17	
				A	0.19	
				A	0.21	
C6	BFS+0.5B+B_Config	0.5	33%	B	0.15	- BFS system with 0.5 bar air injection from outlet of all WBTs but water pump application to fore WBT1s (WBT1P & WBT1S) only
				B	0.17	
				B	0.19	
				B	0.21	

Note

Subset A: Air injection & pressured water for all WBTs

Subset B: Air injection for all WBTs & pressured water for WBT1s only

WBT: Water Ballast Tank

WBTs: all WBT1P, WBT1S, WBT2P, WBT2S, WBT3P, WBT3S, WBT4P and WBT4S

WBT1s: WBT1P and WBT1S

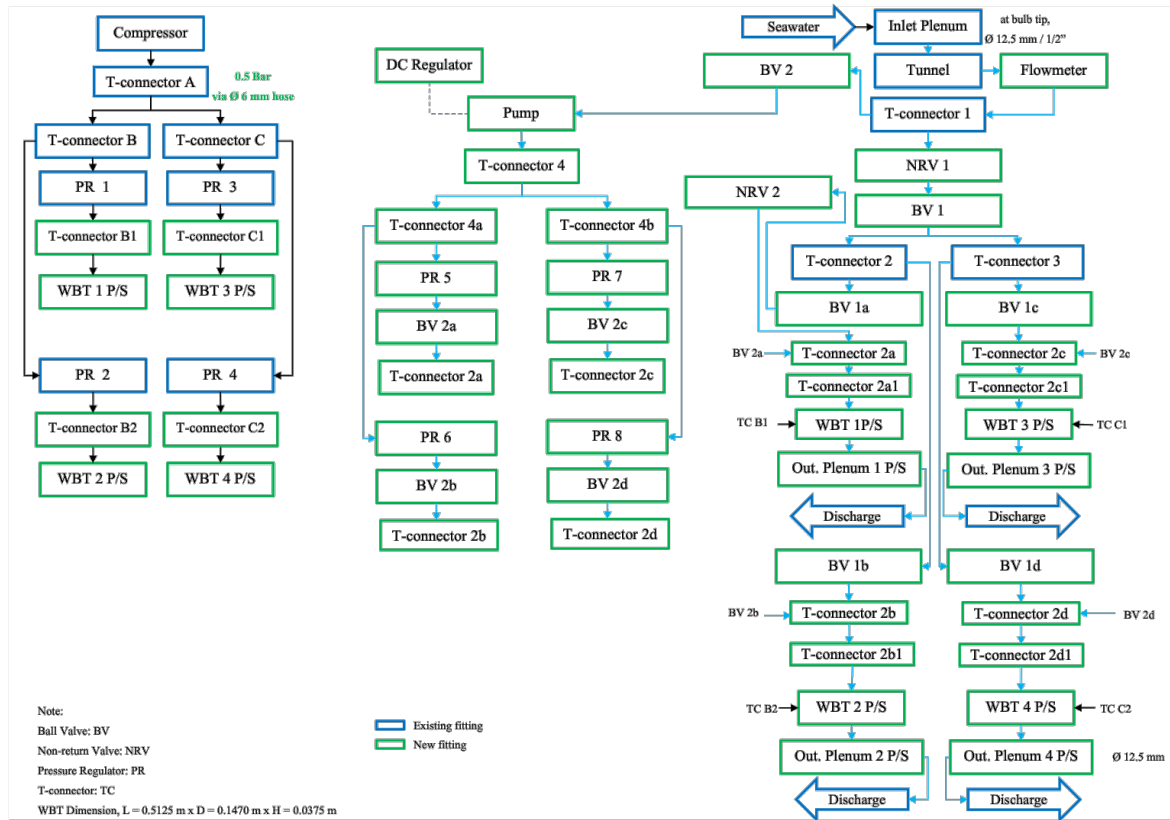


Fig. 6. Overview of flow setup

2.3 Data Analysis

The total resistance was subcategorized into frictional and residual components using ITTC 1957 procedures. Extrapolation methods were applied to derive full-scale resistance values. Comparisons were made between experimental data and theoretical predictions to validate results.

3. Results

3.1 Total Resistance Analysis

The general trend as shown in Table 4 and Figure 7 observed is that as the hull speed increases, the resistance also increases regardless any type of the system configuration. The experiment demonstrated that BFS configurations alone increased total resistance by average of 2.67% due to the added wetted surface area and water discharge outlets. However, the integration of air injection at 0.5 bar significantly mitigated this effect. In comparison with previous bare hull condition by Kadir *et al.*, [5], all relevant cases of configurations including bare condition (C1) show better performance in the hull efficiency.

Table 1

Total resistance of vessel for each condition and relative increase from bare hull

Fr	R _{Bare} Group:C1 (N)	R _{Bare+0.5B} Group:C2 (N)	Relative increase (%)	R _{BFS} Group:C3 (N)	Relative increase (%)	R _{BFS+0.5B} Group:C4 (N)	Relative increase (%)	R _{BFS+0.5B+A_Config} Group:C5 (N)	Relative increase (%)	R _{BFS+0.5B+B_Config} Group:C6 (N)	Relative increase (%)
0.15	3.495	3.023	-13.50	3.587	2.63	3.376	-3.39	3.701	5.92	3.311	-5.27
0.17	4.426	3.718	-16.00	4.674	5.61	4.195	-5.23	4.557	2.96	4.185	-5.45
0.19	5.518	4.558	-17.39	5.521	0.06	5.184	-6.05	5.561	0.77	5.142	-6.81
0.21	6.627	5.934	-10.46	6.785	2.38	6.368	-3.90	6.701	1.13	6.568	-0.89
Average			-14.34		2.67		-4.64		2.69		-4.60

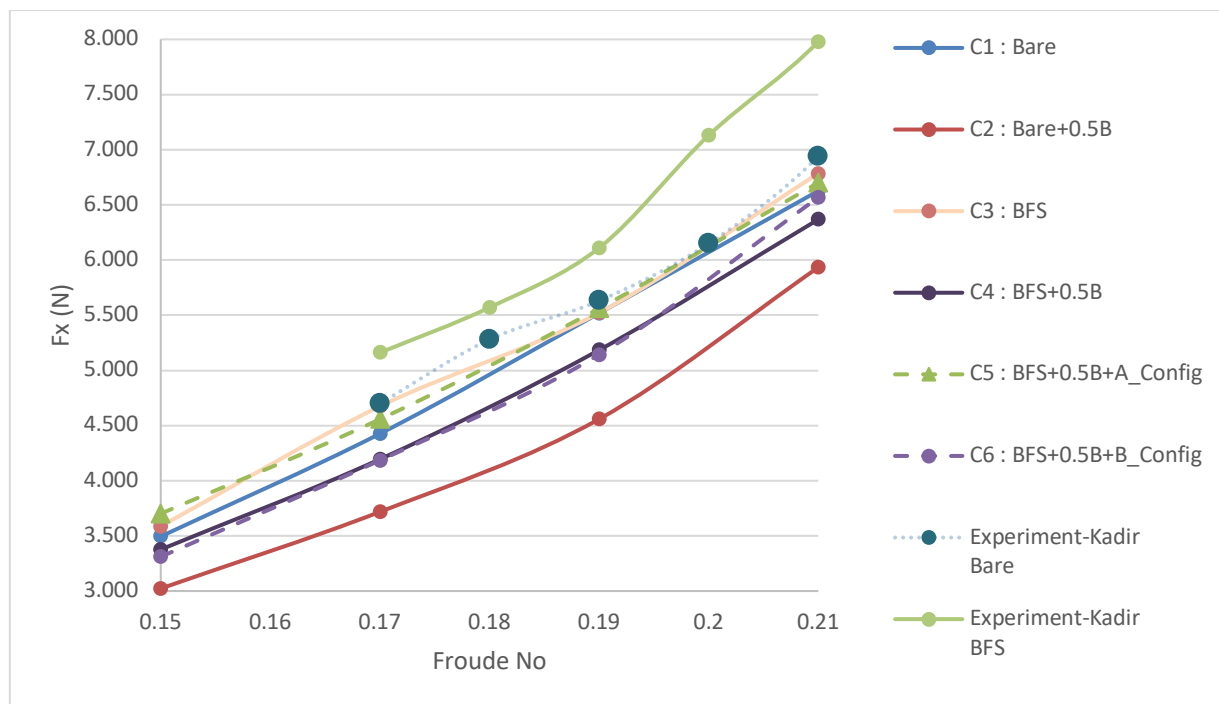


Fig. 7. Resistance curves for each condition

The configuration of Bare+0.5B (C2) offers the most efficient trend in total hull resistance reduction with average value of 14.34% and achieves 17.39% resistance reduction at $Fr=0.19$. Unlike condition of C3 till C6, this arrangement of air injection system has no added wetted surface area that can contribute to resistance increment. The result shows that the air lubrication drag reduction manages to form microbubbles and change the turbulent boundary layer on the hull surface.

In line with previous studies by Babadi and Ghassemi [14]; Godey *et al.*, [10]; Kadir *et al.*, [5]; Kotinis [15], the pure ballast free system (C3) increases the total hull resistance of the vessel due to additional wetted surface area immersed BFS system including piping configuration, water ballast tanks and the pressure resistance addition due to the outlet openings at the bottom of the hull. In average, this configuration increases the total hull resistance with average of 2.67% and significantly

affects at $Fr=0.17$ with 5.61% increase against negligible value if only 0.06% at $Fr=0.19$. Comparatively, a one-sided experiment by Kadir *et al.*, [5] found that the hull resistance significantly increased by average of 11.22% and 27.23% for two-sided CFD simulation. The much smaller difference in resistance increase observed in the current experiment also suggests that design improvements, including layouts, can make BFS solutions less costly. With these enhancements, BFS inherently increases resistance as compared to a hull naked because there are adding components. Such effects must be compensated by appropriate air-injection or other similar methods. The study therefore justifies call for additional experimental and computational research to refine BFS configurations for actual maritime operations.

The condition of the pure ballast free system was improved with application of air injection at 0.5 bar or known as condition C4. This condition integrates the applied concept in C2 and increases the hull performance with average reduction of 4.64%. Significant differences in result between C2 (average of 14.34%) and C4 are due to the additional wetted surface area. Again, the hull the highest total hull resistance reduction 6.05% occurs at $Fr=0.19$. Despite achieving lower resistance reduction percentage compared to Kadir *et al.*, [5] due to different pump and piping arrangement, this condition arrangement manages to overcome the drawback due to implementation of BFS system. C4 demonstrates the potential for combining BFS with air lubrication but highlights the need for optimized designs to minimize the added resistance from BFS components.

The application of pump to enhance the seawater flow in the system as well as varies the water pressure is investigated in the condition C5 with the optimum pump capacity of 33%. In average, the pump application to all WBTs increases the total hull resistance up to 2.69% and the increments occur worst at lower Froude number range of 0.15 (5.92%) and 0.17 (2.96). The pump application has the least undesirable impact on the hull resistance at $Fr=0.19$ with value of 0.77%. This result shows that there is excessive water pressure that led to total hull resistance increment.

In varying the pumping arrangement of the vessel as in the condition C6, the pump is applied only on fore WBTs of WBT1P and WBT1S. This arrangement significantly improves the hull efficiency with average of 4.60% resistance reduction. The most desirable resistance reduction occurs at $Fr=0.19$ with value of 6.81% and this is considered as the optimum air-injection pressure ballast free system. Noteworthy that this configuration gives advantages at lower Froude number range equal or less than 0.19 whilst only contributes 0.89% of reduction at $Fr=0.21$. Observed that C4 and C6 have similar pattern and resistance values throughout the test despite the difference between these conditions is only the presence of the pump at the fore WBTs.

3.2 Resistance Reduction Trends

The air injection at 0.5 bar was most effective at Froude number 0.19, where resistance reduction peaked at 6.81%. This aligns with prior numerical studies, confirming the efficiency of air lubrication in BFS systems. Further, the use of air injection localized to specific ballast tanks (C6) demonstrated a higher impact compared to uniform air distribution across all tanks.

3.3 Component-wise Resistance Breakdown

The study decomposed total resistance into frictional and residual components. BFS alone increased frictional resistance due to extended wetted surface areas, while residual resistance rose from hydrodynamic disruptions at water discharge outlets. Air injection effectively reduced both components, with frictional resistance seeing the most significant improvement through boundary layer air separation as shown in Figure 8.

In general, the frictional resistance is the dominant contributor of the total hull resistance with average of 82 – 85 % but it reduces as the vessel speed increases for Froude number range of 0.15 till 0.19 but increases towards $Fr=0.21$ except for C1 and C5. The patterns show that $Fr=0.19$ is the most optimum vessel speed regardless any type of the system configuration.

The frictional resistance trends of C2, C3 and C4 are in accordance with previously discussed in 3.1 and discussed previous study by Kadir *et al.*, [11] as the effective air lubrication drag reduction system of C2 without any additional wetted surface led to resistance reduction. The resistance trend of C3 condition proves that added wetted surface contribute to resistance increment whilst optimization by air injection in C4 manages to overcome BFS weaknesses.

In comparison between condition C5 and C6, the result shows that excessive water pressure has been applied on the vessel as the condition of C5 contribute to the resistance addition versus the effective C6 condition that manages to reduce the hull resistance. With the introduction of pump, the C6 condition has better resistance reduction compared to C4 within Froude number range equal or less than 0.19.

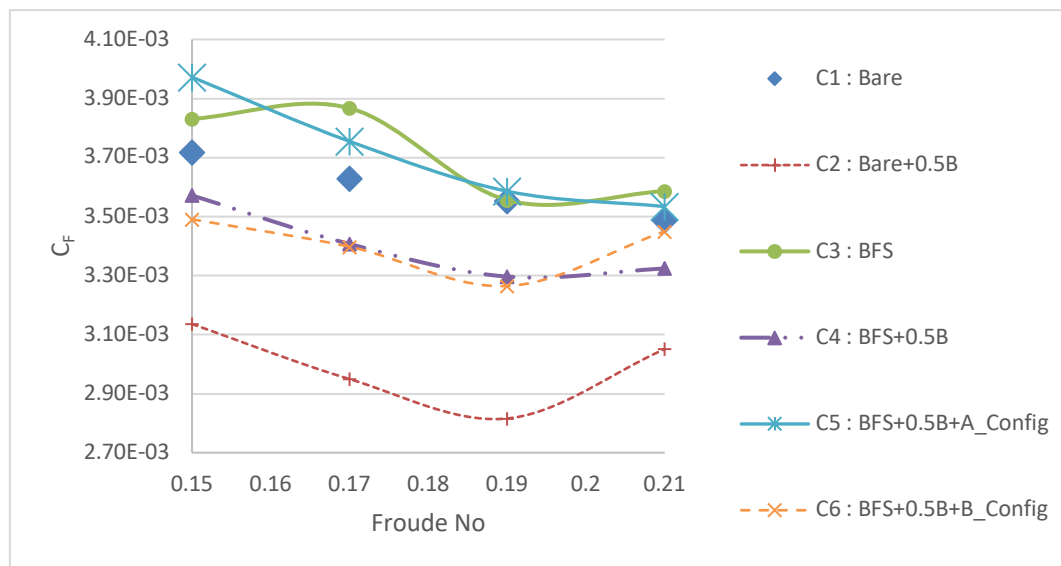


Fig. 8. Frictional resistance coefficient curves for each condition

3.4 Influence of Water Pump on BFS

The use of a pump to enhance seawater flow in the BFS slightly increased resistance especially at lower speeds. This is attributed to the energy utilized to counterpoint the pressure created by the pumping technique, and the resultant flow impact on the ballast-free system.

At higher speeds, the pump-assisted configurations showed less significant resistance increases, suggesting that the adverse effects of added pressure are mitigated by higher water flow velocities.

Configurations targeting specific WBTs, such as BFS+0.5B+B_Config, effectively addressed the challenges of pump-induced resistance. By limiting the application of the pump to fore WBTs, this setup balanced the benefits of enhanced flow control with minimized resistance penalties, achieving an average reduction of 4.6%.

This study suggests that there is a need for improving the utilization of the pump head and flow of the distribution to make the system more efficient. The studies show that only the utilization of pump require strict management to control pressure which otherwise undermines the effectiveness of air lubrication system and creates unfavourable configuration like in BFS+0.5B+A_Config.

3.5 Practical Implications

The study highlights the importance of precise control of air-injection pressures, strategic placement of nozzles to enhance drag reduction and integration of water pumps to improve BFS water flow dynamics. Future implementations should consider computational fluid dynamics (CFD) modelling to refine these findings further and extend applications to different vessel types and operating conditions.

4. Conclusions

This study provides a comprehensive experimental analysis of air-injection systems for resistance reduction in ballast-free LNG vessel configurations. The key findings demonstrate that while the implementation of a BFS inherently increases hull resistance due to added wetted surface area and discharge outlets, this drawback can be significantly mitigated through optimized air lubrication.

The most effective configuration, BFS+0.5B+B_Config, which employs strategic air injection and localized water pumping, achieved an average resistance reduction of 4.6%. This result confirms that targeted air distribution is more effective than uniform application across all tanks. The research successfully bridges a gap in the literature by delivering quantitative, experimental evidence on the synergy between BFS and air lubrication technology.

The outcomes of this study offer direct practical implications for the design of eco-efficient vessels and outline a clear path for future work. Subsequent efforts should focus on validating these results at full scale through pilot projects, utilizing Computational Fluid Dynamics (CFD) to further optimize air injection parameters such as pressure and nozzle design for different hull forms, and developing advanced pump and flow management systems to minimize ancillary energy consumption. In summary, this research establishes a scientifically-grounded method for mitigating resistance in BFS-equipped vessels, contributing meaningfully to the development of more hydrodynamic and environmentally sustainable maritime operations.

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