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Assessment of the Effectiveness of Air Bubbler Systems in Reducing Hull-Ice Interaction Loads

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ABSTRACT

Icebreakers have been using air bubbler systems for many years. These systems provide a reduction in the ice-hull friction interaction by inducing water agitation through the rising of air bubbles. Currently, there is little empirical evidence to indicate their effectiveness in lowering the ice-hull friction values. Direct modeling of the ice-hull interaction with an air bubbler system could provide valuable insight into the effectiveness of this technology. Evidence obtained from testing on the CCGS Henry Larsen in full-scale demonstrates that air bubbler technology has operational and empirically verifiable advantages. Along with the anecdotal operational advantages of the air bubbler systems, there is a need for reliable empirical evidence demonstrating the frictional reduction and the subsequent improvement in efficiency that these systems provide. This research is aimed at addressing shortcomings in understanding of air bubbler systems and their effect on the ice-hull interaction by performing a series of model-scale testing using a custom test apparatus. The apparatus is capable of simulating various ice and ship operating conditions by using several ice pressures, interaction speeds (ship speeds), and different flow rates of the air bubbler system. Testing was performed using brash ice with commercially available ice cubes to maintain consistent test conditions. This paper provides a detailed description of the test program and test results to quantify the effectiveness of air bubbler systems. It was found that at given test conditions, there was about a 65% reduction in longitudinal force translated to the friction board indicating a significant reduction in drag forces due to the bubbler system. This type of air bubbler technology could provide significant advantages in terms of the friction reduction and fuel savings for future icebreaker development.

KEY WORDS: Air bubbler; Ice-surface interaction; Model-scale; Brash ice; Friction board

INTRODUCTION

Since the late 1960s, air bubbler systems have been used on icebreakers to reduce ice-hull friction (Wilkman, 2011; Juurmaa, 1978). These systems function by releasing air through ports along the ship's hull below the ice belt, creating agitation in the water that minimizes friction between the ice and the hull (Wang et al., 2023; Wilkman, 2011; Juurmaa, 1978). Advancing icebreaker technology and improving our understanding of ice-hull friction interactions require innovative testing methods. This paper presents the results of an experiment utilizing a newly developed testing apparatus. The system incorporates a friction board, six load cells, and five flex links that constrain all degrees of freedom. The friction board's surface is coated with a specialized paint designed to achieve an ice-hull friction coefficient of 0.05 (Browne & Wang, 2023; Lau, 2015; Spencer & Jones, 2001). The apparatus can simulate key operational conditions, including ship speed, pack ice pressure, and air bubbler flow rate. Further details on the apparatus design are available in a companion paper (Osmond et al., 2025). The primary objective of this experiment was to assess the effectiveness of an air bubbler system in reducing ice-hull interaction. By analyzing the effects and collecting numerical data, this study provides valuable insights that can contribute to future icebreaker design improvements.

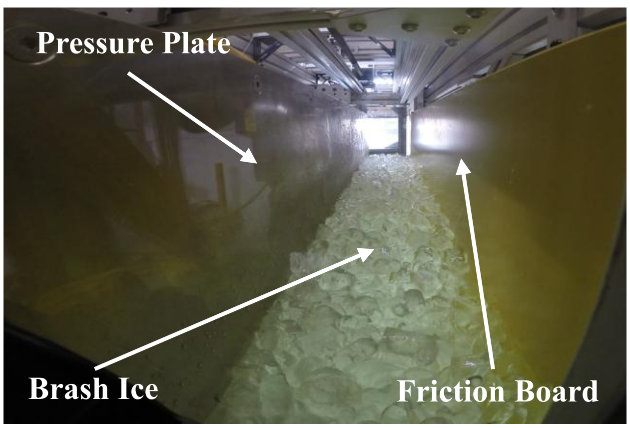

Figure 1. Inside ice box top-down view

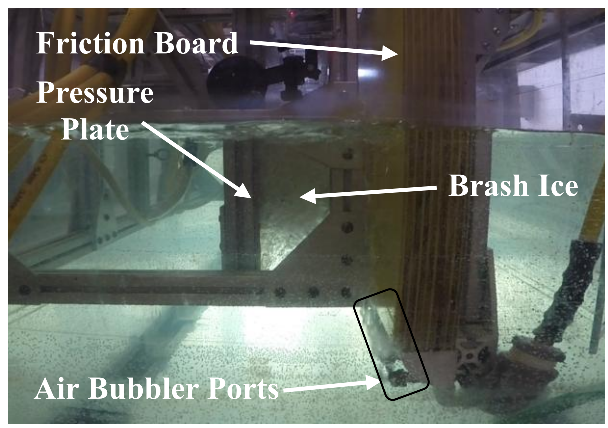

Figure 2. Ice box side view

For this set of experiments, brash ice testing was conducted with and without the bubbler system active. Ice cubes were used as a stand-in for brash ice to maintain a consistent size and composition, as shown in Figure 1. When the bubbler system was active, the airflow rate was set to 500 L/min, based on the design of the apparatus's air bubbler system. The system featured 31 ports located beneath the friction board, as illustrated in Figure 2. Tests were performed at four different speeds using a moving ice container, referred to in this paper as the "ice box". The test speeds were 10 mm/s, 58 mm/s, 116 mm/s, and 174 mm/s. A constant ice box speed was maintained throughout each test to ensure steady-state conditions for comparison. To simulate constant pack ice pressure, pneumatic pistons at the rear of the ice box actuated a plate that forced the brash ice against the friction board as the ice box moved along the tank. The applied ice pressures averaged 163 Pa, 370 Pa, and 600 Pa, representing low, medium, and high-pressure conditions, respectively. These pressures were estimated based on the pneumatic pressure supplied to the actuating pistons, with each pneumatic pressure setting corresponding to a specific applied force. The resulting ice pressure was then calculated by dividing the applied force by the estimated contact area between the ice and the friction board. Further details on the apparatus design are provided in a companion paper (Osmond, et al., 2025).

TEST RESULTS AND ANALYSIS

This paper primarily focuses on data recorded by load cell Fx_{6A}, which measured the drag force of the ice on the friction board. Under the testing conditions previously discussed, 78 brash ice tests and 24 open water tests were performed. Data processing was conducted using measurements taken when the ice box was positioned between 200 mm and 800 mm. This ensured that data was recorded at the same point in each test run, helping to mitigate any undesirable loading characteristics introduced by the apparatus. A mean value taken from the open water tests was removed from the brash ice test data to assess the effects of ice loading on the friction board. For each test run, the Data Acquisition System (DAS) recorded data for 20 seconds before the movement of the ice box. A mean value was then calculated for each load cell, and these values were used as a tare. This ensured that the recorded values accurately reflected the true ice forces within the system. After processing, a mean value was taken over the duration of each test, allowing for comparisons between different test conditions. For more information on the design of the apparatus, refer to the companion paper (Osmond et al., 2025).

Effect Of Ice Box Speed on Recorded Drag Force

Figure 3 presented the forces recorded by load cell Fx_{6A} for all tests conducted at different ice box speeds in brash ice, categorized by whether the bubbler system was active or inactive. The results demonstrated that ice box speed alone had minimal influence on the recorded force. In both cases, with the bubbler system on or off, the trend lines exhibited only a slight change in slope, indicating that variations in ice box speed did not significantly affect the frictional force exerted by the ice on the friction board. A minor decrease in recorded force was observed as ice box speed increased. Additionally, Figure 3 highlighted a substantial reduction in force when the bubbler system was activated, as evidenced by the separation between the two trend lines. This finding suggested that the operation of the bubbler system effectively reduced the measured frictional force of the ice on the friction board, reinforcing its potential applicability in full-scale icebreaker designs.

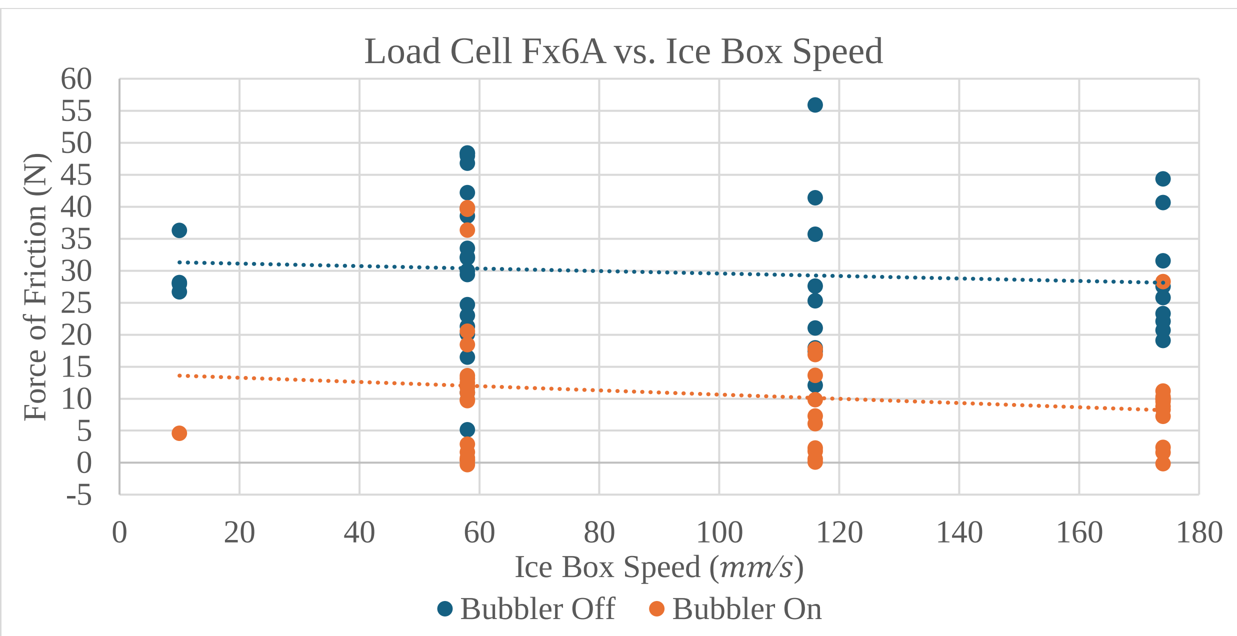

Figure 3. Load cell Fx_{6A} vs. ice box speed, across all brash ice tests

Effect of Pressure and Air Bubbler on the Frictional Force

Table 1 presents the values obtained from testing at each speed with an average between the bubbler being on and off. For each test speed, an average was calculated between the cases with the air bubbler system on (484 L/min) and off, isolating the effect of ice pressure. The results indicate that as the ice box speed increased, the difference in force due to higher ice pressure became less pronounced. This was likely due to hydrodynamic effects caused by the increased ice box speed, which may have induced ice movement within the box. In this scenario, the pressure plate advanced to maintain ice pressure on the friction board. However, during this process, some ice pressure may have been lost, reducing the frictional force recorded by load cell Fx_{6A}. This effect was more significant at lower ice pressures, as the pneumatic pistons required additional time to respond to maintain the ice pressure. The phenomenon was further exacerbated when the air bubbler system was active, as the increased agitation caused additional ice movement within the box. This represents a limitation of the apparatus design as implemented in this test series. Despite this potential effect, ice pressure had a substantial impact on the measured force in load cell Fx_{6A}. Table 1 shows that at every speed, there was a general increase in recorded force, with an average increase of 64% when transitioning from both low to high and medium to high ice pressure conditions.

Table 1. Effects of ice pressure on load cell Fx_{6A}

Speed (mm/s)	Frictional force in load cell Fx_{6A} (N)			Frictional force Increase (%)		
	Low pressure	Medium pressure	High pressure	Low-Medium	Medium-High	Low-High
10	-	16.08	-	-	-	-
58	8.98	22.17	38.75	147	75	332
116	8.31	17.18	27.97	107	63	237
174	15.76	16.74	22.11	6	32	40
Average	11.02	18.04	29.61	64	64	169

Figure 4 illustrates the effect of ice pressure on the friction board and the corresponding frictional force recorded by load cell Fx_{6A} across all brash ice tests. As shown, in both cases whether the bubbler system was active or inactive there was a general increase in force recorded by load cell Fx_{6A} as ice pressure increased. This trend aligned with expectations, as an increase in the normal force exerted by the ice on the friction board resulted in a corresponding increase in the measured ice frictional force. Similar to Figure 3, Figure 4 also demonstrated that when the bubbler system was active, there was a significant reduction in the recorded force in Fx_{6A}. Notably, at low ice pressure with the bubbler system on, the recorded force in Fx_{6A} was minimal or nearly zero, suggesting that the bubbler system largely or entirely counteracted the drag force of the ice on the friction board. Additionally, at medium ice pressure, there were instances where the recorded force in Fx_{6A} remained very low or zero when the bubbler was active. This phenomenon may have occurred due to the relatively low ice pressure in comparison to the high bubbler flow rate, which could have effectively negated the drag force.

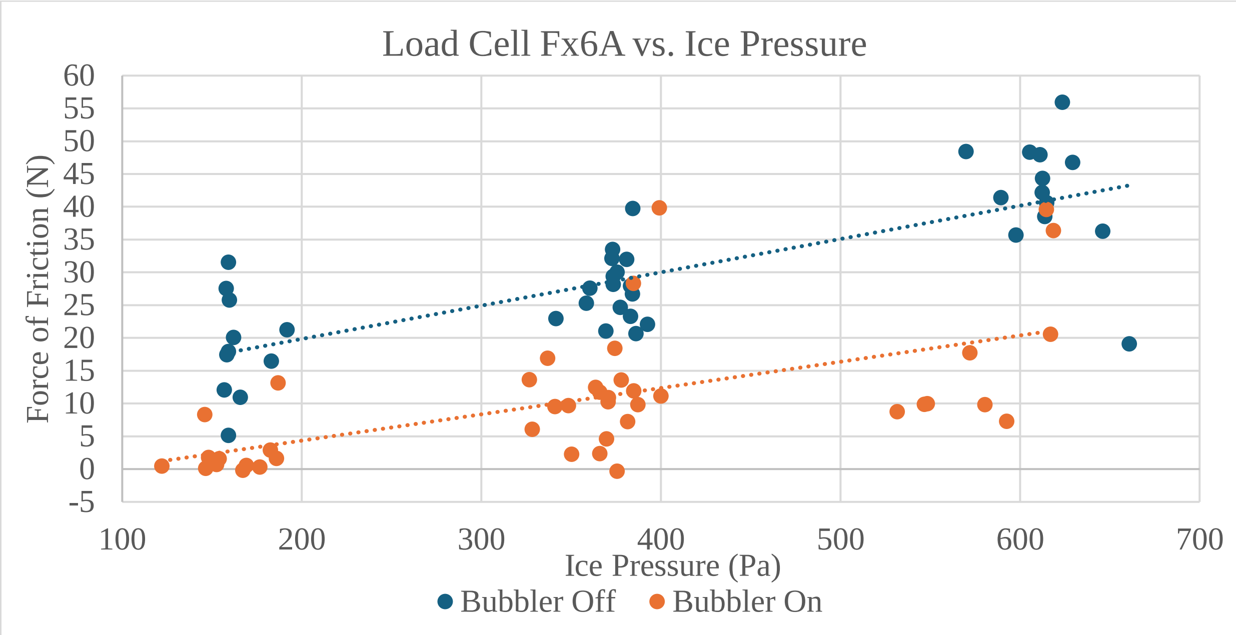

Figure 4. Load cell Fx_{6A} vs. normal ice pressure across all brash ice tests

The effect of the air bubbler system was observed in Table 2, where the total average indicated a 65% reduction in force recorded by load cell Fx_{6A} when the bubbler was active. Regardless of ice pressure, the presence of the bubbler consistently resulted in a significant decrease in drag force. The reduction in measured force ranged from 29% to 95%, demonstrating the substantial influence of the bubbler system on the friction board surface. Due to the limited number of tests conducted, no data such as potential outliers were excluded from the evaluation. Additionally, only a single test was performed at a speed of 10 mm/s with the bubbler on at medium pressure. Further testing at this speed would be necessary to develop a more comprehensive data set.

Table 2. Effects of air bubbler on force in load cell Fx_{6A}, for all testing scenarios

Speed (mm/s)	Ice Pressure (Pa)	Force in Load Cell Fx_{6A} (N)			Force Reduction (%)
		Air Bubbler (OFF)	Air Bubbler (ON)	Delta	
58	170	14.77	3.18	11.59	78
116	156	15.81	0.81	15.00	95
174	157	28.30	3.23	25.07	89
10	378	27.59	4.57	23.01	83
58	374	30.53	13.80	16.73	55
116	347	24.64	9.71	14.92	61
174	378	22.01	11.48	10.53	48
58	610	45.35	32.16	13.19	29
116	593	44.33	11.60	32.73	74

174	586	34.68	9.53	25.15	73
Average	375	28.80	10.01	18.79	65

Figure 5 illustrates the effect of the air bubbler system on the drag force recorded by load cell Fx_{6A}. Regardless of ice pressure, activation of the air bubbler system resulted in a decrease in recorded force. This effect was clearly demonstrated by the decreasing slope in all trend lines of different pressure levels. Based on the trend lines in Figure 5, the recorded force at low ice pressure was approximately 88% lower when the air bubbler was active (484 L/min) compared to when it was off. At medium ice pressure, the drag force recorded was 62% lower with the bubbler on, while at high ice pressure, the force was reduced by 56%. These results indicate that the air bubbler system had a greater effect on reducing ice drag force at lower simulated pack ice pressures. This suggests that a similar amount of force was mitigated when the air bubbler was activated, regardless of ice pressure. This trend was further demonstrated in Figure 5, where all trend lines exhibited similar slopes.

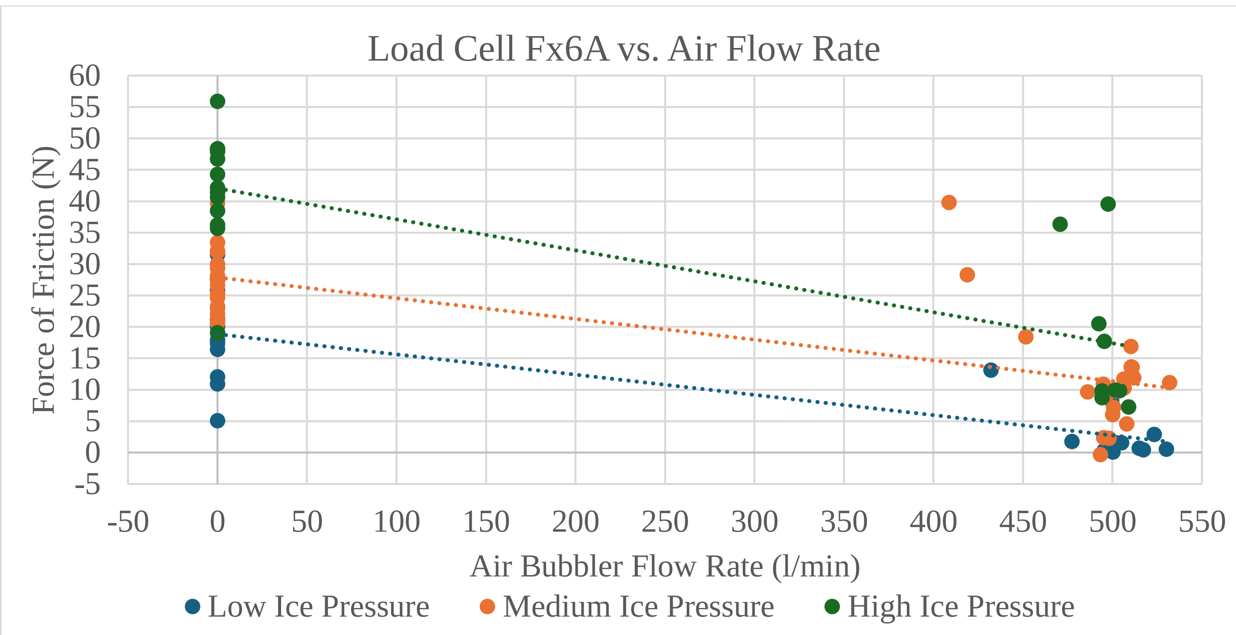

Figure 5. Load cell Fx_{6A} vs. air flow rate across all speed

DISCUSSION

The test data obtained from this experiment provided valuable insight into the operation and effectiveness of an air bubbler system. The results demonstrated that the air bubbler contributed to a reduction in the drag force of ice on the friction board. Assuming a consistent ice-to-surface interaction area across all tests, two primary mechanisms may have contributed to this reduction in drag force. First, if the same pneumatic piston pressure corresponded to the same normal force of the ice on the friction board, any observed changes in frictional force would be attributed to variations in the coefficient of friction (μ), as demonstrated in (1). Based on this premise, it could be inferred that the air bubbler system functioned as a form of lubrication, reducing frictional force by altering the surface-to-surface interaction characteristics (Browne & Wang, 2023).

$$\mu = \frac{F_F}{F_N} = \frac{P_F}{P_N} = \frac{P_F \cdot A_{Nom}}{P_N \cdot A_{Nom}} \quad (1)$$

Another possible explanation is that the air bubbler system reduced the normal force of the ice on the friction board. According to this theory, the coefficient of kinetic friction between the friction board and the ice remained unchanged, but the normal force exerted by the ice decreased. As air was released from the bubbler system, it rose due to buoyancy, generating an upward water current along the friction board. Upon reaching the water's surface, this current displaced the ice away from the friction board, effectively reducing the normal force. During testing, when the bubbler system was active, a rotating current was observed within the moving ice in the box, further supporting this hypothesis.

If it was assumed that the air bubbler system effectively reduced the normal force of the ice on the friction board, the design of this apparatus would not allow for an accurate measurement of this effect. This limitation arises because ice pressure was calculated based on the pneumatic piston pressure, which actuated the pressure plate in the ice box to apply force to the ice. In this scenario, the bubbler-induced water currents could have displaced the ice away from the friction board, redirecting the force. Additionally, it is possible that the water current generated by the air bubbler system directly exerted force on the pressure plate, further reducing the surface pressure between the ice and the friction board. This theory is further supported by the observation that the air bubbler system consistently reduced the drag force recorded by load cell Fx_{6A} by a similar magnitude across different ice pressure settings.

An interesting phenomenon observed during testing which could have had a direct impact on the recorded drag force in load cell Fx_{6A}, is when the bubbler is activated the ice is agitated by the rising air and water current. This agitation is likely to affects the interaction area of the ice and the friction board. A reduction in the interaction area could have altered the surface-to-surface characteristics, directly contributing to the observed decrease in measured drag force.

CONCLUSION

This paper provides valuable insights and empirical data regarding the effectiveness of an air bubbler system in brash ice, obtained through experiments using a novel testing apparatus. The apparatus was capable of simulating ship speed (ice box speed), ice pressure, and incorporating an air bubbler system. It featured a dynamometer with load cells in conjunction with flex links to measure forces in all axes, while simultaneously constraining all degrees of freedom.

In the experiments conducted, four ice box speeds and three ice pressures were tested, with the air bubbler system either activated or deactivated. The data showed that ice box speed had little effect on the frictional force recorded by load cell Fx_{6A}. However, increasing ice pressure led to a notable increase in frictional force, with an average increase of 64% between medium to low and high to medium ice pressures, which was in line with expected trends. The air bubbler system was found to significantly reduce the recorded frictional force. On average, the system lowered the measured force by 65% across all tests, suggesting that it could be an effective tool for icebreakers operating in brash ice under pressure conditions. Notably, the system had a more pronounced effect at lower ice pressures, where the frictional force reduction ranged from 56% at high ice pressure to 88% at low ice pressures.

The development of new testing equipment has proven crucial in advancing our understanding of ice-hull interactions for icebreakers. This study served as a preliminary investigation into the effectiveness of air bubbler systems, and based on the results, these systems show promise in reducing drag forces during ice-surface interactions. However, further testing is needed to explore the mechanisms behind these systems in greater detail. Future research should consider testing with precise pressure control, multiple air bubbler flow rates and using various friction board surface materials to gain a more comprehensive understanding.

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