Iceberg Towing in Newly Formed Ice

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ABSTRACT

The paper presents results of experimental iceberg towing operations performed in ice fields during the early stages of ice formation. Experiments were conducted in October 2017 in the area of Franz Josef Land with the diesel icebreaker “Novorossiysk” as a part of the “Kara-Summer-2017” expedition organized by Rosneft Oil Company in cooperation with the Arctic and Antarctic Research Institute (AARI) and participation of Arctic Research Centre.

This paper describes techniques and scope of the carried out iceberg towing experiments. Limitations of iceberg drift direction change under different ice conditions are determined and discussed. The technological features of towing operations within negative air temperatures and the presence of sea ice are also highlighted. Based on experiments, optimal tactics for towing icebergs of different sizes under conditions of early ice formation with the means of icebreaking fleet are proposed. Besides, description for one day non-stop experiment of iceberg towing for 50 miles in ice conditions of the British Channel is given. The main practical application of the experiment is possibility of iceberg towing in arctic conditions during autumn ice formation period (10.09.2017-19.10.2017) from the area of exploration drilling.

KEY WORDS: Iceberg; towing; defense; water; Artic; Kara; Barents; ice

INTRODUCTION

Iceberg towing experiments in ice conditions performed during “Kara-Summer-2017” expedition as far as authors know are unique and first in the world real-scale tests with monitoring of all parameters.

Numerical simulations and ice basin modeling (Eik, Marchenko, 2010; Yulmetov et al., 2016; Yulmetov, Loset, 2017) show fundamental possibility of iceberg towing in ice conditions, as well as its’ significant difficulties. It is noted that the lack of information about actual behavior of iceberg and towing system under the influence of ice cover seriously complicates interpretation of the obtained results. This work describes experiments on iceberg towing under conditions of newly formed ice as well as ice effects and thus gives unique data for further research.

Rosneft Oil Company in cooperation with Russian Arctic and Antarctic Research Institute together with Arctic Research Centre tested iceberg towing technology in the autumn periods of 2016-2017. Field real scale experiments on icebergs were performed with various technical means. A description of conducted studies and results discussion of iceberg towing in ice-free waters is given in article Icebergs towing experiments in the Barents and Kara seas in 2016-2017 (Kornishin K.A., et al 2019), this paper covers iceberg towing experiments in sea conditions of early ice formation as part of the “Kara-Summer-2017” expedition.

This scientific expedition was carried out in 2017 onboard the diesel icebreaker “Novorossiysk” (Russian Federation) (Fig. 1).

Fig. 1. “Novorossiysk” icebreaker

The choice of a maneuverable and powerful diesel icebreaker made it possible to work on towing icebergs in a wide range of ice conditions, including breaking out icebergs frozen in ice fields. The vessel was equipped with the necessary deck equipment: towing and mooring winches, hydraulic cranes of various capacities located in the fore and aft parts of the vessel. Main technical characteristics of the vessel are presented in the Table 1.

Table 1. Main technical characteristics of the “Novorossiysk” icebreaker

№.	Characteristic	Value
1	Ship class	KM*Icebreaker6(2)AUTI-ICS FF2EPP ECO HELIDECK
2	Project	21900M
3	Full-load displacement, t	14334
4	Maximum length, m	119,79
5	Maximum width, m	27,5
6	Hull height, m	12,4
7	Ballast draft, m	6,8
8	Full load draft, m	8,5
9	Maximum speed, kt	17,0
10	Eco travel speed, kt	14,5
11	Deadweight, t	5142
12	Type of main engine	Diesel
13	Number of main engines, pcs	4
14	Power of main engines, kW	6960
15	Total generator power, kW	27840
16	Propulsion system	Pods
17	Number of propulsers	2
18	Crew capacity	29

The relationship between total power of the vessel's pod propulsion system and the tow force is very important for planning and carrying out iceberg towing operations. For the “Novorossiysk” icebreaker, this dependence (derived from experimental data) has a power law (Fig. 2):

$$T = 1{,}56 * P^{0{,}72} \quad (1)$$

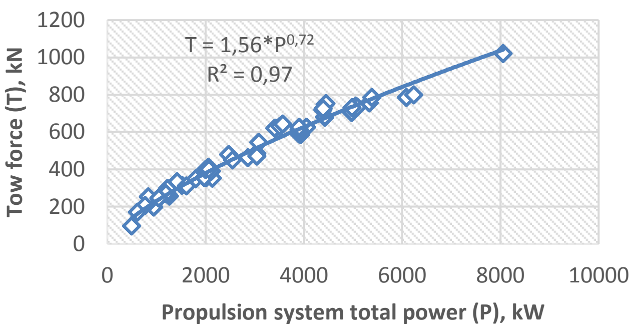

Fig. 2. Tow force on propulsion system total power dependence for the “Novorossiysk” icebreaker (all iceberg towing speeds)

For the case of iceberg towing at speeds exceeding 1 m/s, a power dependence can be proposed with coefficients slightly different from (1):

$$T = 1{,}38 * P^{0{,}73} \quad (2)$$

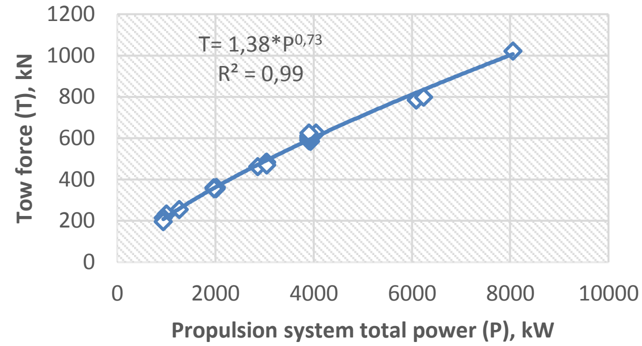

Fig. 2. Tow force on propulsion system total power dependence for the “Novorossiysk” icebreaker (iceberg towing speeds > 1 m/s)

EXPERIMENTS DESCRIPTION

During "Kara-Summer-2017" expedition in the first half of October 2017 4 icebergs towing experiments (continuous numbering out of all towing experiments) were carried out within sea ice fields. The overall dimensions of the icebergs towed are given in the Table 2 with a detailed description of the experiments given below.

Table 2. Weight and-dimensional characteristics of icebergs towed in ice

#	Ice conditions/ characteristic thickness, cm	Length, m	Width, m	Height, m	Mass, 10^3 tons
12	Pancake ice/ 10	51,0	38,0	18,2	41,0
13	Pancake ice/ 10-15	32,0	18,0	5,6	6,2
14	Frozen gray ice/ 15-20	100,8	58,1	18,7	303,5
17	Pancake ice+ Ice fields/ 10	44,5	21,8	9,4	18,9

Experiment #12. Towing with a rope (October 8, 2017)

Iceberg towing was performed with a 1200 m length rope.
The area of experiment was the Kara Sea, near Frantz Josef Land.
Total duration of the experiment: 4 h 31 min (06:15 - 10:46 UTC).
Towing duration: 3 h 27 min (07:18 - 10:45 UTC).
The iceberg selected for towing is shown in Fig. 3. Iceberg parameters are given in Table 3.

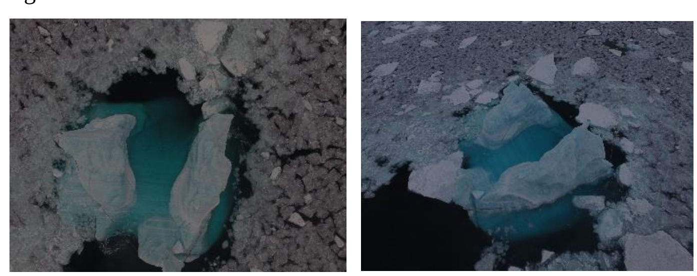

Fig. 3. Iceberg #12 – top view (left), side view (right)

The experiment was conducted in a pancake ice of 8–10 concentration with a characteristic thickness of 10 cm. The initial iceberg drift velocity was 0.2 m/s southbound.
The iceberg was towed at different power regimes of the vessel with a

change of course by 90°, when the rope was loosened during the vessel's course change, the iceberg turned in the loop of the rope (Fig. 4).

Fig. 4. Iceberg #12 after course change by 90°. Rope raise-up

The distance covered by the vessel during towing was 12.2 km. The trajectories of the vessel and iceberg are shown in Fig. 5, it also indicates sections of the iceberg movement (regimes) with minimal acceleration, for which the influence of inertial forces can be neglected. The wind speed did not exceed 5 m/s, which made it possible to neglect its influence of the wind when calculating the power characteristics of the regimes.

The parameters of the iceberg movement on the modes are shown in Table 3.

Table 3. Iceberg movement parameters on regimes

Regime #	Time	Ice conditions	Iceberg velocity V, m	Towing force F, kN	K = F/V^2
1	7:39:07	Ice	1,02	356	344
2	8:02:30	Free water	1,22	471	316
3	8:50:30	Ice	1,41	785	396

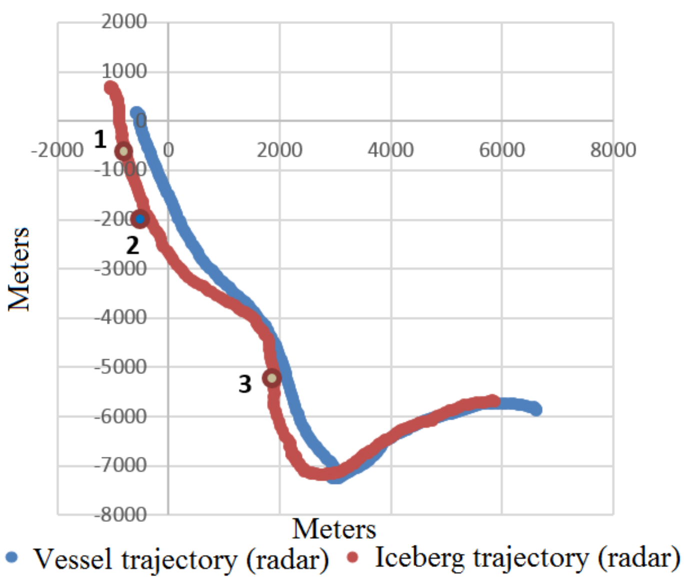

Fig. 5. Experiment #12. Vessel and iceberg trajectories. Dots 1, 2, 3 - regimes

For its linear dimensions, this iceberg is characterized by a rather low drag coefficient (in the range of 300–400 kN s^2/m^2), that may be due to its small draft due to severe destruction. For the regime #2 resistance force coincides with the drag force, whereas for the 1 and 3 regimes, characterized by iceberg movement through ice (Fig. 6), the force of interaction between the pancake ice and iceberg additionally appears; and the resistance coefficient rises by 10-25%.

Thus, when towing iceberg with linear dimensions up to 50 m in unconsolidated pancake ice, for practical calculations the additional resistance to movement due to interaction with ice is insignificant and can be estimated by a factor of 1.25 in the expression for drag force.

Fig. 6. Iceberg #12 interacting with pancake ice

Experiment #13. Towing with a rope (October 8, 2017)

Iceberg towing was performed with a 1200 m length rope.
The area of experiment was the Kara Sea, near Frantz Josef Land.
Total duration of the experiment: 2 h 43 min (12:27 – 15:10 UTC).
Towing duration: 2 h 14 min (12:49 - 15:03 UTC).
The iceberg selected for towing is shown in Fig. 7. Iceberg parameters are given in Table 4.

Fig. 7. Iceberg #13 side view

The experiment was conducted in a pancake ice of 9–10 concentration with a characteristic thickness about 10-15 cm. Ice floes were up to 3 m in diameter, with several layers, obviously transitional form to the next gradation. Before towing the iceberg was practically immobile (speed about 0.05 m/s).

The iceberg was towed at different vessel power modes, with most of the towing being carried out at night (Fig. 8). The distance covered by the vessel during towing was 7.4 km.

Fig. 8. Iceberg #13 towing in night

The vessel and iceberg trajectories are shown in Fig. 9, it also indicates the sections of iceberg movement (regimes) with minimal acceleration, for which the influence of inertial forces can be neglected. The maximum wind speed was 8 m/s (on average - up to 5 m / s), which allowed, taking into account the small size of the iceberg, to neglect the effect of wind on drag force during towing.

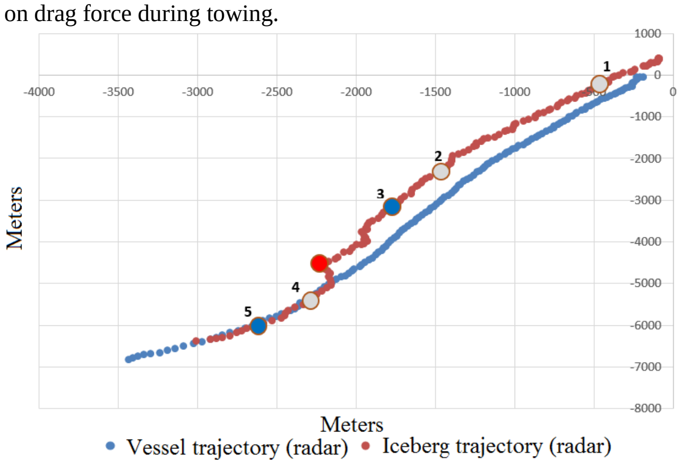

Fig. 9. Experiment #13. Vessel and iceberg trajectories.
Dots 1, 2, 3, 4, 5 - regimes

Table 5. Iceberg movement parameters on regimes

Regime #	Time	Ice conditions	Icebeg velocity V, m	Towing force F, kN	K = F/V²
1	13:07:08	Ice	0,72	206	394
2	13:55:30	Ice	0,97	268	285
3	14:09:30	Free water	1,01	311	303
4	14:42:30	Ice	1,19	555	389
5	14:55:30	Free water	1,29	625	374

The dependence of the drag force on the iceberg velocity is shown in Fig. 10; a quadratic dependence of tow force on towing speed is obtained. The drag coefficient varies from 285 to 395 kN*s²/m², regardless of the ice conditions.

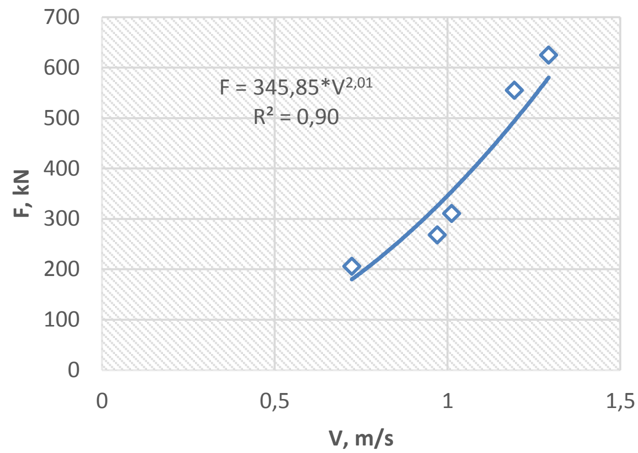

Fig. 10. Iceberg #13 dependence of resistance force on its towing speed

When interacting with the ice field located ahead of the vessel (red circle in Fig. 9), the iceberg quickly entered the vessel's wake, which indirectly indicates a significant effect of the field on the lateral iceberg displacements with a slight effect on the resistance to movement.
Thus, the presence of pancake ice (including beginning of freezing) slightly affects the process of towing small icebergs (weighing up to 10 thousand tons and of less than 30-35 m length). An iceberg enters the wake channel without significant changes in towing force.

Experiment #14. Towing with a rope (October 9, 2017)

Iceberg towing was performed with a 1200 m length rope.
The area of experiment was the Barents Sea, near Frantz Josef Land, the "Famous" glacier.
Total duration of the experiment: 7 h 00 min (05:15 - 12:15 UTC).
Towing duration: 4 h 09 min (05:47 - 09:56 UTC).
The iceberg selected for towing is shown in Fig. 11. Iceberg parameters are given in Table 6.

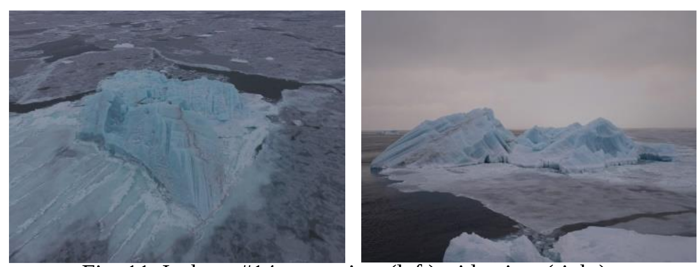

Fig. 11. Iceberg #14 – top view (left), side view (right)

The experiment was carried out in a frozen gray ice of 9/10 concentration with a characteristic thickness about 15-20 cm. The initial iceberg velocity coincided with the surrounding ice field speed and was 0.6 m/s in the south-west direction. The wind speed varied in the range of 8-12 m/s, while the wind direction coincided with the direction of the drift speed and the direction of towing (back wind). 36 minutes after the start of towing with a force of 630 kN, the iceberg speed reached 0.8 m/s and the iceberg, without getting into the channel of the icebreaker, began to interact with the ice field (Fig. 12). Iceberg crushed the initial part of the field, but could not destroy it.

Fig. 12. Iceberg #14 interacting with ice field

With further movement (Fig. 13), iceberg, ice field velocity and the vessel speed coincided, and no dependence on the applied tow load was observed (Fig. 14). The change in the field/iceberg velocity is associated with a complex movement of ice fields in the vicinity of the iceberg caused by the vessel's and iceberg's channel laying during rope laying and allotting, as well as not fully concentrated ice.

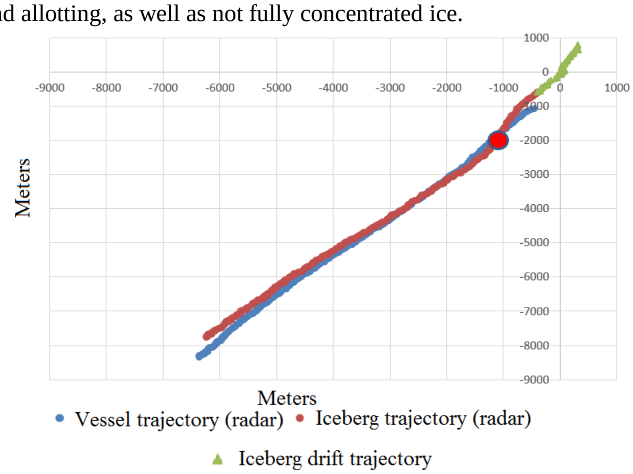

Fig. 13. Experiment #14. Vessel and iceberg trajectories. Red circle – iceberg/ice filed contact

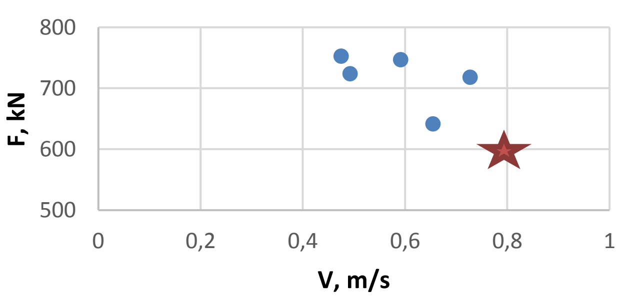

Fig. 14. Iceberg #14 dependence of tow force on speed. Star indicates the iceberg regime characteristics when moving without icefield contact

Thus, the success of the physical impact on icebergs in the case of frozen ice fields is determined by the fact whether or not the iceberg got into the channel behind the icebreaker. Even in the simplest iceberg towing case - towing in the direction of free movement of the iceberg, operation success for large icebergs is not guaranteed - ice fields block the canal, which makes further icebergs management impossible; the movement of the ship-iceberg system is determined by ice drift.

Experiment #17. Towing with a rope (October 13-14, 2017)

One day long iceberg towing was performed with a 1200 m length rope. The area of experiment was the British channel, near Frantz Josef Land,
Total duration of the experiment: 24 h 00 min (13.10.2017 10:00–14.10.2017 10:12 UTC).
Towing duration: 22 h 53 min (13.10.2017 11:07–14.10.2017 10:00 UTC).
This extra-long experiment was needed in order to show practical possibility of iceberg removal to the maximum distance from the offshore oil and gas field facilities under conditions of early ice formation.
The iceberg selected for towing is shown in Fig. 15.

Fig. 15. Iceberg #17 side views

The extra-long iceberg towing route and the area of other towings in ice conditions is shown in Fig. 16.

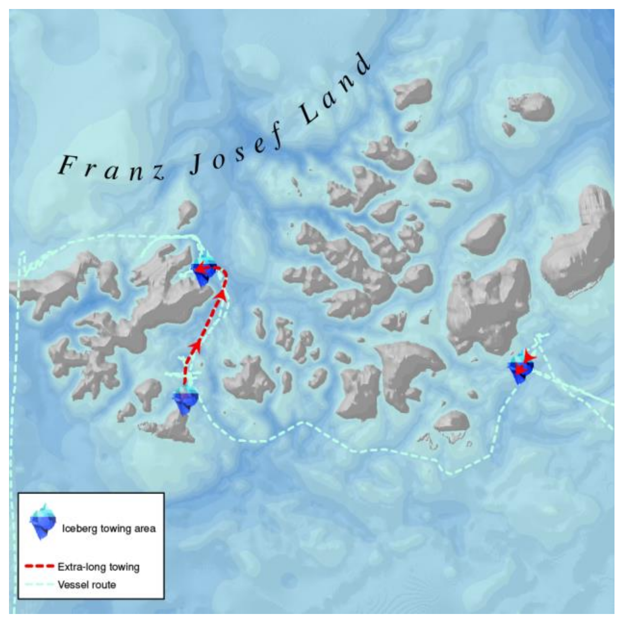

Fig. 16. Extra-long iceberg towing route near Franz Josef Land

The iceberg was towed under one load (about 600 kN) with a change of direction when entering "Geographers" Bay. The distance traveled by the vessel during towing (Fig. 17) was 91 km. When going north, the vessel crossed several fields of pancake ice of various concentrations with a characteristic thickness of 10-15 cm. The wind was less than 5 m/s and had almost no effect on towing.

Fig. 17. Iceberg #17 towing process

The average speed when towing was 1.1 m/s, with the allocated time intervals at which deviations were recorded within 10-15% of its value. The following regimes can be distinguished, characterized by constant values of relative velocities (relative to water, taking into account the current) of icebergs and forces (Table 6).

Table 6. Separated towing regimes during day long iceberg towing

	Time	Iceberg relative velocity, m/s	F, kN
1	17:08:30	1,21	607
2	18:36:30	1,29	594
3	19:24:30	1,10	588
4	21:04:30	1,16	592
5	22:04:30	1,11	603
6	22:32:30	1,12	598
7	22:56:30	1,10	612
8	1:36:30	1,01	613
9	3:00:40	1,12	624
10	8:16:30	0,98	605

1. Time interval from 5:00 p.m. to 7:00 pm is characterized by a speed increase in compared to the average speed, which may be due to a change in the position of the iceberg in a rope loop.

2. From 1:00 to 4:00 a.m. the iceberg interacted with ice fields, which led to a slower movement.

3. The speed reduction around 8:00 was due to the entrance in the "Geographers" Bay, where there could be unaccounted local currents.

At the same time, it is impossible not to note the trend towards a decrease in towing speed when advancing the vessel to the north, which may be due both to a certain change in ice conditions and to the vessel's "fatigue" during long towing of an iceberg (problems with winch and machinery).

TECHNOLOGICAL ASPECTS OF TOWING IN EARLY ICE

The iceberg towing process in the ice in comparison with towing in open water is characterized by a number of technological complications:

1. Freezing of the towing rope/net to the deck at stable negative temperatures.

This effect significantly reduces the rope/net deployment time, as well as the deck crew safety. To reduce this effect during the series of towing trials, the rope was left at night in the sea water, that prevented its icing on the deck. It was also found out that surrounding sea ice did not damage the rope (Fig. 18).

Fig. 18. On-deck rope icing

2. Catching the end of the rope in ice conditions when it is lifted to the deck after a vessel has gone around the iceberg.

The movement of ice makes the process of fishing operations much more difficult, makes it necessary for the vessel to maneuver in the ice and to flush the ice in the vicinity of the rope (Fig. 19). When using modern icebreakers (such as Russian 21900M project), these operations are challenging and overall possible, but when using older icebreakers, catching the end of the rope can be a significant problem.

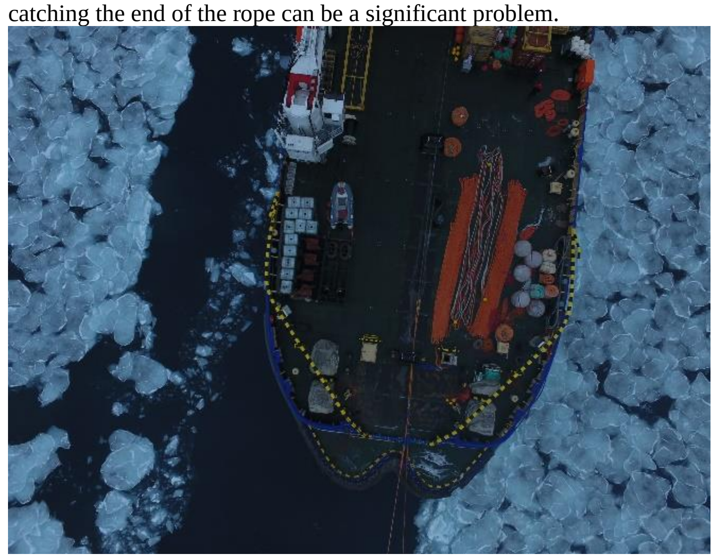

Fig. 19. Ice conditions during iceberg towing

3. Radar error when determining iceberg coordinates.

Rutter Sigma S6 radar with ice navigator installed at the vessel determined the distance between the stern and iceberg with an error of 200-300 meters. When towing in open water, this error was significantly less. This effect should be studied in the future research.

CONCLUSION

1. When towing icebergs in conditions of early ice formation, it is necessary to use a maneuverable and powerful icebreaker, which should:

- perform iceberg breaking out from the ice field;
- ensure that the end of the rope is lifted onboard (including pulling the end of the rope out of the ice);
- lay a channel of considerable width;
- towing icebergs at high speeds (more than 1 m/s) to forestall the channel deformation process and its close up;
- overcome ice fields without losing speed.

2. Towing of up to 50 meters length icebergs in pancake (non-frozen) ice up to 10 cm thick is practically confirmed. At the same time, the drag force increases slightly, within 10-25%. The iceberg itself falls into the icebreaker's wake canal, the role of its lateral movements is significantly reduced compared to towing in ice-free water. The presence of pancake ice somewhat reduces the amplitude of long-period oscillations discussed in paper Icebergs towing experiments in the Barents and Kara seas in 2016-2017 (Kornishin K.A., et al 2019), while constant collisions with ice floes lead to the development of short-period oscillations in towing system.

3. When towing icebergs in conditions of frozen gray ice about 15–20 cm thick, it is essential the iceberg gets into the icebreaker canal, which is determined by the speed of the vessel-iceberg system, the width of the iceberg and oscillating movements of the iceberg in the beginning of towing. For large icebergs (about 100 m long), an iceberg collision with a field was experimentally observed, which made impossible further towing. For small icebergs (30–50 meters), iceberg collision with an ice field was observed with further iceberg following in the icebreaker wake canal; at the same time the walls of the icebreaker canal do not allow iceberg long-period oscillations to develop.

4. The possibility of extra-long iceberg towing under conditions of early ice formation is demonstrated; at the same time, the distance covered during this day-long towing was 50 nautical miles, including crossing various fields of early ice. The average speed when towing a 45 m length and about 20 thousand tons iceberg with a force of 600 kN was 1.1 m/s; at the same time, the instant towing speed varied in a range of 1-1.3 m/s.

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