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POLISH MARITIME RESEARCH 3 (127) 2025 Vol. 32; pp. 4-12
10.2478/pomr-2025-0031

AIR CUSHION ICEBREAKING PLATFORMS: INNOVATIVE APPROACHES TO ICE DESTRUCTION AND PARAMETER OPTIMISATION

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ABSTRACT

This article discusses innovative approaches to icebreaking and the optimisation parameters of Air Cushion Icebreaking Platforms (AC IBP). The study is conducted in the context of the need to ensure year-round navigation on northern rivers and potentially support Arctic expeditions. The primary method of icebreaking involves creating an air cavity under the ice, causing it to break under its own weight. This research employs both theoretical mathematical models and experimental data to determine the optimal parameters of AC IBP, such as the length and width of the air cushion, cushion pressure, and the power of the lifting complex. The results demonstrate the high efficiency of AC IBP in breaking ice up to 400 mm thick, exceeding design specifications. Optimising the AC IBP parameters helps to achieve minimal energy consumption with maximum efficiency. Experimental tests confirm the reliability of the design and compliance with project specifications. Further research aims to improve the AC IBP design and expand its operational conditions.

Keywords: air cushion, flexible skirt, icebreaking platform, icebreaking tests, lifting complex

INTRODUCTION

The development of icebreaking technologies is crucial for ensuring year-round navigation in northern seas, as well as for supporting Arctic expeditions and mineral resource extraction. Despite their versatility and power, traditional icebreakers have several drawbacks, including high energy consumption and significant operating costs [1]. Therefore, there is a need to search for alternative icebreaking technologies [2-4].

One of these promising technologies is an Air Cushion Icebreaking Platform (AC IBP). These devices are characterised by low energy consumption, as well as relatively low construction costs and operational expenses. AC IBPs can effectively operate as parts of tugboats and transport vessels, as well as small icebreakers, breaking ice up to 1.5 m thick at speeds of up to 5–6 km/h (1.39-1.67 m/s). They are used for creating ice channels, freeing ships that are stuck in the ice, and other tasks related to icebreaking in the waters of factories and ports.

Icebreaking by air cushion vehicles can be accomplished in two ways: by pressure and by moving at critical speeds leading to resonance [5-7]. This article discusses the results of research into the design calculations of an AC IBP, based on mathematical models and experimental data and applied to the method of icebreaking by pressure.

The main principle of this icebreaking method is that the ice breaks under its own weight, rather than from the significant forces exerted by the vessel. When an AC IBP moves at a low speed, an air cavity forms beneath the ice cover, causing the water below to no longer support it. Once the air cavity reaches a certain size, depending on the physical and mechanical properties (including the thickness) of the ice, the ice begins to break under the influence of gravity [8, 9].

For the successful creation of such icebreaking platforms, it is necessary to combine the knowledge, experience, and information from previous research into studying the following scientific and design areas:

– theory, design, and calculations for traditional amphibious air cushion vehicles [10-13];
– design and calculation of flexible skirts for hovercrafts [12, 13];
– stability calculations for traditional vessels and hovercrafts [14, 15];
– theory and calculations of resistance for air cushion vehicles in various operating conditions, including ice conditions [16-18];
– physical properties of ice and the mechanics of its destruction [19, 20];
– planning experimental research and its analysis [21-23].

The main focus of the research is on determining the optimal parameters and characteristics of an AC IBP for efficient ice cover breaking with minimal energy consumption.

The aim of this research is to develop, design, and optimise Air Cushion Icebreaking Platforms for efficient ice cover breaking with minimal energy consumption [24-26]. To achieve this goal, it is necessary to study the interaction of an AC IBP with the ice, develop mathematical models and calculation algorithms for optimal parameters, and conduct experimental testing to verify the models.

The research objectives are as follows:

▪ Studying the interaction between an AC IBP and ice:
– analysis of the icebreaking mechanism under the influence of an AC IBP;
– determination of the parameters affecting the efficiency of icebreaking (ice thickness, air cushion pressure, speed of movement, etc.).

▪ Development of mathematical models and calculation algorithms:
– creation of a mathematical model for calculating the air cushion pressure required for icebreaking;
– development of an optimisation algorithm for the main parameters of an AC IBP (length and width of the air cushion, power of the lifting complex, etc.).

▪ Design and construction of an AC IBP:
– designing the structure of an AC IBP by considering the optimal parameters obtained;
– creating a prototype of an AC IBP and its components, including the lifting complex and flexible skirt.

▪ Conducting experimental tests:
– testing AC IBPs in real ice conditions;
– analysing test results to verify mathematical models and calculation algorithms.

▪ Analysis of the obtained results:
– comparing theoretical calculations with experimental data;
– identifying the advantages and limitations of AC IBPs;
– recommendations for further research and development.

The idea of using air cushion vehicles (ACV) for icebreaking emerged soon after the invention of such vessels. Initial research in this field was conducted at that time [27, 28] and the first mathematical models for using ACVs as icebreakers were developed [27, 28]. In the 1980s, there was a surge of interest in this topic in the USSR. Early studies were conducted on breaking ice cover using an ACV [8, 9], the stability of air cushion icebreaking platforms [14, 15], and calculating resistance when these platforms move in icy conditions [16]. During these years, a series of operational tests was carried out on AC IBPs [21]. After a long hiatus, publications on AC IBPs began to reappear in the late 1990s, including those related to energy systems for these vessels.

In the following 10–15 years, there were publications on model testing of AC IBPs [22] and other research in this area [3, 6, 17]. Due to the intensification of Arctic research in the 2010s, interest in this topic increased and new publications appeared, exploring the subject of AC IBPs and the physics of icebreaking in greater depth [4, 7, 18, 20, 23]. Around the same time, research on AC IBPs began in Ukraine. The results of these studies were presented in a series of reports at international conferences [24-26, 29].

Our research focuses on improving the calculations and design of AC IBPs, taking into account more modern equipment, energy devices, and materials. This involves the basic dependencies which, in previous publications, showed some contradictions between the equations and graphs; the overall design of AC IBPs; the choice of flexible skirt type; the design and calculation of flexible skirts; and the design of the lifting complex as a whole.

METHODS AND MATERIALS

THEORETICAL FOUNDATIONS AND METHODOLOGY

Icebreaking using an Air Cushion Icebreaking Platform occurs through the creation of an air cavity under the ice. When the AC IBP approaches the edge of the ice cover, a depression forms in the water beneath the platform. If the depth of this depression exceeds the thickness of the ice, an air cavity forms under the ice, eliminating the buoyant forces of the ice (Fig. 1). As a result, the ice is cantilevered over a certain section and begins to break under its own weight.

The key parameters affecting the efficiency of icebreaking by AC IBPs are:

– **Ice thickness** (h_{ice}): the thicker the ice, the more pressure is needed in the air cushion to break it.
– **Air cushion pressure** (P_{AC}): a lifting complex with air blowers is used to create the necessary pressure.
– **Speed of AC IBP movement**: the optimal speed depends on the parameters of the ice cover and the characteristics of the AC IBP.

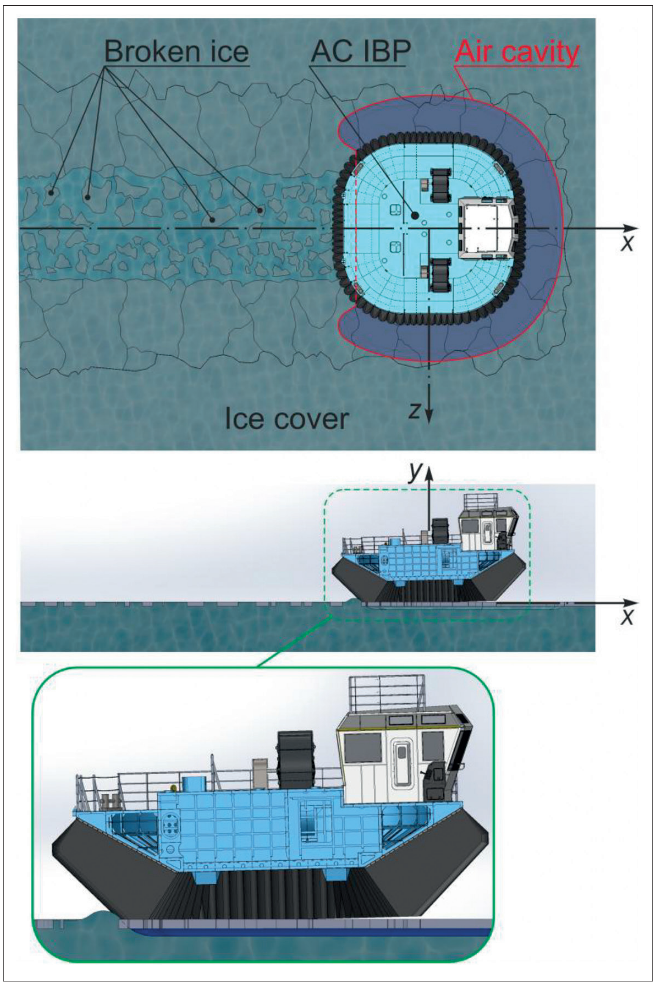

Fig. 1. Icebreaking scheme

To calculate the pressure in the air cushion required for breaking the ice cover, P_{AC} (kPa), the following equation is used:

$$P_{AC} = \frac{K_P \cdot h_{ice}^2}{r^2} \cdot \left(1 + \frac{r^2}{S_{AC} \cdot k_1 \frac{L_{AC}}{B_{AC}}}\right), \quad (1)$$

where K_P is the specific energy for ice cover destruction (for movement with the formation of an ice channel, it is recommended to use 1300 ±100 kPa); h_{ice} is the ice thickness (m); $\sqrt{\frac{E_{ice} h_{ice}^3}{12 \cdot (1-\mu_{ice}^2 \cdot \rho_w \cdot g)}}$ is the characteristic linear size during ice plate bending (m); E_{ice} is the modulus of elasticity of the ice plate (Pa) (taken to be $5 \cdot 10^9$ Pa); $\mu_{ice} = 0.33$ is Poisson's ratio for ice; ρ_w is the density of water (kg/m^3); $g = 9.81$ is the acceleration of free fall (m/s^2); S_{AC} is the area of the air cushion (m^2); k_1 is the coefficient of the influence of the air cushion elongation; and L_{AC} and B_{AC} are the length and width of the air cushion (m), respectively.

To calculate the air flow rate from the air cushion, Q_{AC} (m^3/s), the following formula is used:

$$Q_{AC} = \Pi_{AC} h_{eff}{}^2 \sqrt{\frac{2P_{AC} \cdot 10^3}{\rho_{air}}}, \quad (2)$$

where Π_{AC} is the perimeter of the air cushion (m); h_{eff} is the effective gap between the lower edge of the flexible skirt and the supporting surface (m); and ρ_{air} is the density of air (kg/m^3).

To calculate the drive power of the blower, N_1 (kW), the following formula is used:

$$N_1 = \frac{(P_{AC} + \Delta P) Q_{AC}}{\eta}, \quad (3)$$

where ΔP is the pressure loss in the air ducts of the lifting complex (kPa) and η is the efficiency of the blower.

Pressure losses in the air ducts of the lifting complex are determined by the formula:

$$\Delta P = k_{\Delta P} \cdot P_{AC}, \quad (4)$$

where $k_{\Delta P}$ is the pressure loss coefficient in the air duct (in the first approximation, it can be taken to be in the range 0.2–0.3).

The coefficient of the effect of air cushion elongation, k_1, is determined by interpolation, based on the key points indicated in Table 1 [9, 20].

Tab. 1. On determining the influence coefficient of the air cushion elongation

L/B	k_1
0.80	1.0
1.00	0.8
1.20	1.1

To automate the calculation of coefficient k_1, key points can be interpolated into the following function:

$$k_1 = 6.25\left(\frac{L_{AC}}{B_{AC}}\right)^2 - 12.25\frac{L_{AC}}{B_{AC}} + 6.8 \quad (5)$$

The optimisation of AC IBP parameters was conducted with the aim of minimising power consumption. The algorithm includes the following steps:

– Varying the parameters L_{AC} and h_{ice};
– Calculating the lifting power consumption N_1 for various combinations of parameters;
– Determining the optimal air cushion length L_{opt} and other parameters that ensure minimal power consumption.

Example of an optimisation calculation

For an ice thickness $h_{ice} = 0.25$ m, a range of air cushion lengths L_{AC} from 5 to 14 m was considered. The effective clearance h_{eff} was assumed to be 0.010 m and 0.008 m. The calculation results are shown as graphs of the dependence of blower power and air cushion pressure on the length of the air cushion (Figs. 2 and 3).

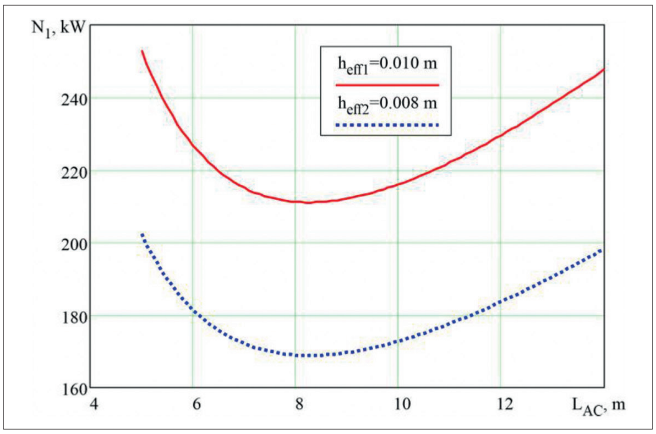

Fig. 2. Blower power depending on air cushion length

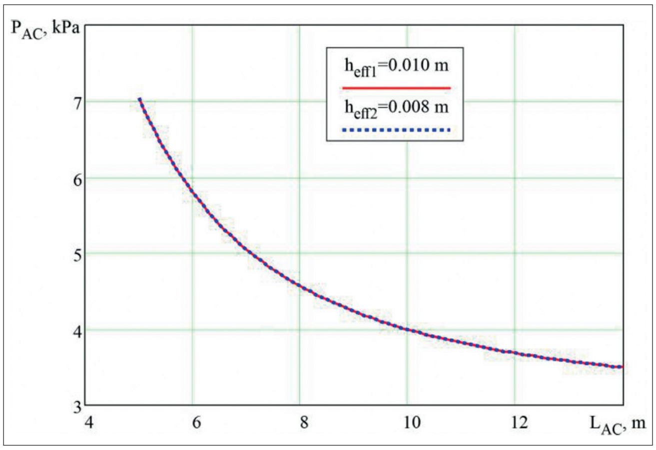

Fig. 3. Air cushion pressure depending on cushion length

CALCULATION AND OPTIMISATION OF KEY PARAMETERS OF AN AC IBP

To achieve optimal characteristics of Air Cushion Icebreaking Platforms, the optimisation of key parameters, such as the length and width of the air cushion, as well as the power of the lifting complex, was conducted. The main goal is to minimise the power consumed while maintaining high icebreaking efficiency.

Variable parameters:
- Length of the air cushion (L_{AC}): for small vessels, this can be varied in the range 5-14 m;
- Ice thickness (h_{ice}): analysed for various values, e.g. 0.25 m.

Optimisation calculation process:
- Calculation of air cushion pressure (the pressure required for icebreaking):

$$P_{AC} = \frac{K_P \cdot h_{ice}^2}{r^2} \cdot \left(1 + \frac{r^2}{S_{AC} \cdot k_1 \frac{L_{AC}}{B_{AC}}}\right) \quad (6)$$

- Calculation of air consumption (air consumption from the air cushion):

$$Q_{AC} = \Pi_{AC} h_{eff}^2 \sqrt{\frac{2P_{AC} \cdot 10^3}{\rho_{air}}} \quad (7)$$

- Calculation of blower power (the blower drive power):

$$N_1 = \frac{(P_{AC} + \Delta P) Q_{AC}}{\eta} \quad (8)$$

- Optimisation of parameters: by varying the parameters L_{AC} and h_{ice}, the optimal length of the air cushion L_{opt} was determined, which ensures minimal power consumption. The determination of the optimal air cushion length L_{opt} (m) was obtained by solving Eq. (9):

$$dN(L) = 0 \quad (9)$$

where $dN(L) = \frac{dN_1(L)}{dL}$ is the function of the derivative of the consumed power, with respect to the length of the air cushion.

The results of the optimisation calculations:
- Optimal air cushion length: according to the calculations, the optimal length of the air cushion for the given conditions is L_{opt} = 8.26 m;
- Minimum required power: for the optimal air cushion length, the minimum required power of the lifting complex is calculated to be 165 kW, for an effective gap of 8 mm, and 210 kW, for an effective gap of 10 mm.

The icebreaking platform for these specified operating conditions is shown in Fig. 4.

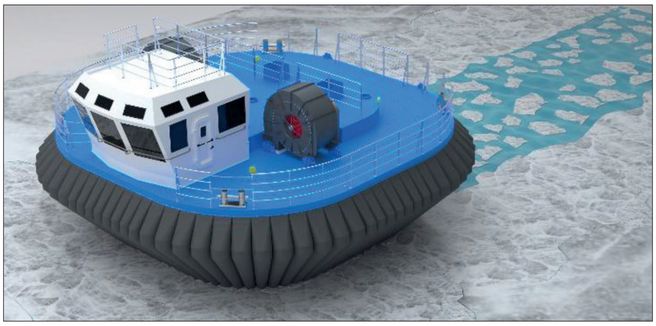
Fig. 4. Air Cushion Icebreaking Platform AC IBP (general view)

The algorithm described above (for $L_{AC}/B_{AC} = 1$) allowed us to determine the dependence of the length of the optimal air cushion on the thickness of the broken ice (Fig. 5), as well as the dependence of the minimum power required for the lifting complex on the thickness of the broken ice (Fig. 6). Similarly, the optimal pressures in the air cushion, which depend on the thickness of the ice being broken, were determined (Fig. 7).

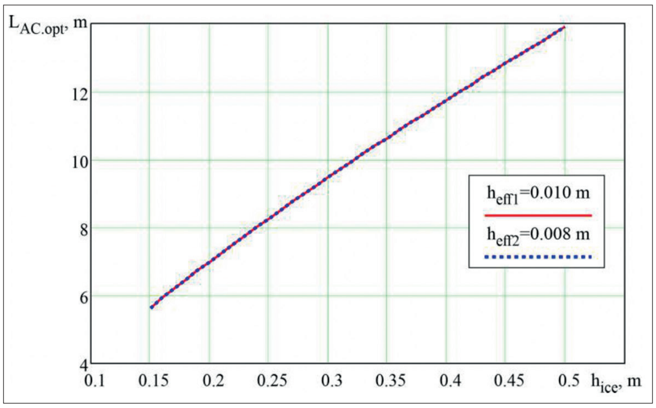

Fig. 5. Optimal air cushion length as a function of ice thickness

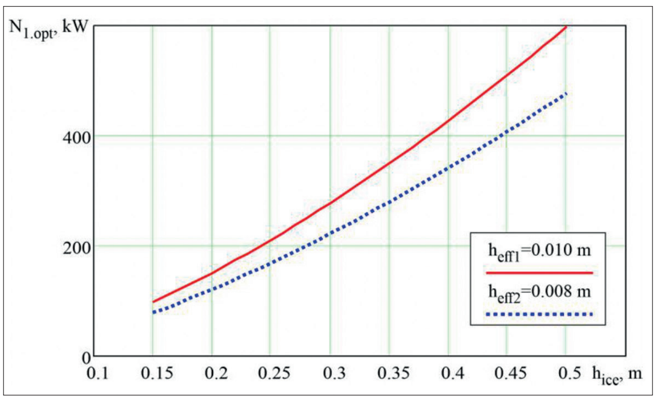

Fig. 6. Minimum required lifting power as a function of ice thickness

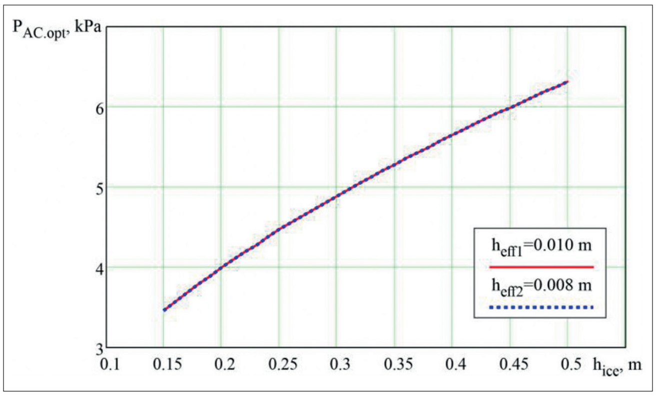

Fig. 7. Optimal air cushion pressure as a function of ice thickness

The design of an AC IBP includes several key components that ensure its operability and efficiency in icebreaking:

- ▪ Lifting Complex (LC):
- – Air blowers: devices that provide the necessary pressure in the air cushion;
- – Flexible Skirt (FS) of the AC IBP: a chamber-type flexible skirt with segmented elements installed around the perimeter of the air cushion (FS prevents air leakage and ensures the maintenance of the necessary pressure under the icebreaking platform).
- ▪ Hull of the AC IBP:
- – This includes two engine compartments and service rooms. The hull is equipped with two watertight bulkheads;

vThe upper deck houses the cabin for operators and crew.

Operational parameters of AC IBP:

- – Temperature range: it is recommended that the operation takes place at temperatures not lower than -35 °C;
- – Displacement: the full displacement for our project was 33 tons;
- – Speed: the operational towing speed was U_S = 2 knots (1.03 m/s).

AC IBP design requires aerodynamic and strength calculations, to ensure the reliability and efficiency of the structure.

The aerodynamic calculations include:

- – calculation and analysis of the air velocity and pressure distribution inside the air cushion and in the air duct channels;
- – determination of the optimal parameters of the lifting complex.

The main strength calculations include:

- – strength calculations of the hull and superstructure of the AC IBP;
- – strength calculations of the flexible skirt and its segmented elements.

Based on these calculations, an AC IBP was designed and built for the specified operating conditions. Its main technical specifications were as follows: air cushion length and width – 8.0 m; clearance – 1.35 m; air cushion area – 58.63 m^2; air cushion pressure – 5520 Pa.

DESIGN, CONSTRUCTION, AND TESTING

In this research, the team comprised engineers from a Ukrainian design bureau and academic researchers from Ukraine. They jointly executed the platform's design and construction, alongside colleagues at an engineering university in China.

The main stages of the design and construction included:

- ▪ Development of project documentation:
- – creation of drawings and diagrams of the AC IBP structure;
- – determination of technical specifications and operational parameters.
- ▪ Prototype creation:
- – construction of the AC IBP at a shipyard in China;
- – installation of a lifting complex, flexible skirt, and other key components.
- ▪ Factory testing:
- – verification of the functionality of all systems and components of the AC IBP;
- – testing of the lifting complex and flexible skirt at the factory site.

Icebreaking tests were conducted using the AC IBP in April 2021 [29]. The purpose of the testing was to study the operational parameters of the AC IBP and the features of the interaction between the icebreaking platform and the ice.

The main stages of the testing included:

- ▪ Preparation for the tests:
- – analysis of the test water area and measurement of the ice thickness at different locations;
- – selection of the test route;
- – transportation of the AC IBP to the test site;
- – assembly and preparation of the AC IBP for icebreaking tests.
- ▪ Testing process:
- – icebreaking tests were conducted for an ice thickness of 400 mm, which exceeded the design specifications (250 mm);
- – the measurement of ice strength in uniaxial compression (3–6 MPa) and bending (0.4–1.5 MPa);
- – evaluation of the ice's elastic modulus (0.8-1.2 GPa).
- ▪ Test results:
- – the AC IBP demonstrated full compliance with the design specifications;
- – icebreaking was effective in all operational scenarios, meeting stability and strength requirements;

vthe identified features of the interaction between the AC IBP and the ice will be taken into account in future design work.

The tests demonstrated that the AC IBP is highly effective in breaking ice and can be operated in a wide range of temperatures and conditions. The main conclusions from the test results are as follows:

- ▪ Icebreaking efficiency:
- – the AC IBP broke ice with a thickness of 400 mm, which exceeded the design specifications;
- – the correctness of the mathematical models used in the design and optimisation of the AC IBP was confirmed,

allowing the creation of an operational lifting complex and its flexible skirt.

- Compliance with design characteristics:
  – the AC IBP fully met the stated technical specifications;
  – the necessary stability and structural strength were ensured.
- Recommendations for further research:
  – it is necessary to continue studying the interaction of AC IBP with ice of various thicknesses and strengths, as well as the different sizes of icebreaking platforms;
  – further research should be conducted, in order to optimise the parameters of the lifting complex and the flexible skirt, and to improve the efficiency of the icebreaking platforms.

RESULTS AND DISCUSSION

ANALYSIS OF CALCULATIONS AND TEST RESULTS

The results of the calculations and experimental testing of the Air Cushion Icebreaking Platform (AC IBP) demonstrated high efficiency and compliance with the design specifications. During the tests, data were obtained that confirmed the theoretical models and calculations, and the key parameters affecting the efficiency of icebreaking were identified.

Comparison of theoretical calculations and experimental data:

– **Air cushion pressure**: The calculated air cushion pressure P_{AC} required for icebreaking aligns with the data obtained during the tests, confirming the correctness of the mathematical models used;

– **Optimal air cushion length**: The optimal air cushion length L_{opt} determined by calculations corresponds to the length used in the prototype, confirming the effectiveness of icebreaking;

– **Power consumption**: Calculations of the minimum power required for the lifting complex showed that the actual power consumption values match the calculated data.

Influence of parameters on the efficiency of an AC IBP:

– **Ice thickness**: Increasing ice thickness requires higher air cushion pressure and, consequently, more power from the lifting complex to break it; optimising these parameters allows maximum efficiency with minimal energy consumption to be achieved;

– **Length and width of the air cushion**: Increasing the length and width of the air cushion to certain dimensions reduces the minimum required pressure, leading to lower energy consumption; however, excessively large dimensions can increase air consumption, necessitating more powerful blowers;

– **Speed of movement**: The optimal speed of an AC IBP depends on the ice thickness and air cushion parameters; test results showed that, at a speed of 2 knots (1.03 m/s), the icebreaking efficiency was maximised.

ADVANTAGES AND LIMITATIONS

Advantages of AC IBP:

– **Low energy consumption**: An AC IBP requires significantly less energy compared to traditional icebreakers, due to the use of an air cushion;

– **Low construction cost**: Designing and constructing an AC IBP is cheaper than building traditional icebreakers;

– **Versatility**: An AC IBP can be used for various tasks, including creating ice channels, freeing vessels which are trapped in ice, and breaking ice in port and plant waters.

Limitations of AC IBPs:

– **Dependence on ice thickness**: The efficiency of AC IBP decreases when breaking very thick ice (more than 0.5 m); in such cases, additional equipment or reinforcement of the lifting complex may be required;

– **Limited operational conditions**: An AC IBP is most effective under certain temperature and weather conditions; for example, extremely low temperatures or high wind speeds can pose challenges to operations.

RECOMMENDATIONS FOR FURTHER RESEARCH

– **Study of the interaction of an AC IBP with different types of ice**: It is recommended that additional research is conducted to determine the parameters for icebreaking with varying thicknesses and strengths.

– **Optimisation of the lifting complex**: Further development of new designs for the lifting complex and flexible skirt is necessary to enhance the efficiency of AC IBPs.

– **Expansion of operating conditions**: Further research is needed to explore possibilities for improving the design of AC IBPs, allowing icebreaking platforms to operate in a wider range of weather and temperature conditions.

CONCLUSIONS

The results of this research and the tests conducted confirm the high efficiency of Air Cushion Icebreaking Platforms for breaking ice cover. The main conclusions drawn from the work are as follows:

- Efficiency of AC IBP:
  – AC IBPs demonstrated high efficiency in breaking ice cover up to 400 mm thick, exceeding design specifications;
  – the operability of the lifting complex and the flexible skirt, which provides the necessary pressure in the air cushion, has been confirmed.
- Optimisation of the parameters:
  – the mathematical models and calculation algorithms developed during the research allowed the determination of the optimal parameters of AC IBPs, including the length and width of the air cushion, as well as the power of the lifting complex;
  – for the given operating parameters, the optimal length of the air cushion L_{opt} is 8.26 m, ensuring minimal energy

consumption with maximum icebreaking efficiency.

- Strength and stability of the structure:
  - AC IBP fully complies with the stated technical characteristics and requirements for strength and stability in all operational scenarios;
  - he conducted aerodynamic and strength calculations confirmed the reliability of the AC IBP design.
- Operational parameters:
  - AC IBPs can effectively operate at temperatures down to -35 °C and under conditions of moderate wind and waves.
  - the operational towing speed is 2 knots (1.03 m/s), which is optimal for icebreaking.

Based on the research and testing conducted, recommendations for the further development of AC IBP technologies can be made:

- Study of the interaction of AC IBPs with various types of ice:
  - additional research is required to determine the parameters for breaking ice of different thicknesses and strengths;
  - further studies are needed to examine the impact of snow cover, and other factors, on icebreaking efficiency.
- Optimisation of the lifting complex:
  - further development of new designs for the lifting complex and flexible skirt are necessary, to improve the efficiency of AC IBPs;
  - it is essential to explore the possibilities of using various materials in the flexible skirt to enhance its characteristics.
- Expansion of operating conditions:
  - research is needed to determine the possibilities for improving the AC IBP design for operation in a wider range of weather and temperature conditions;
  - the further development of methods and technologies is required to enhance the stability of AC IBP under extreme weather conditions.
- Automation and control:
  - the implementation of automatic control systems is necessary to increase the accuracy and efficiency of AC IBP operations;
  - the development of intelligent monitoring and diagnostic systems is needed for timely detection and the elimination of malfunctions.

In conclusion, it should be noted that Air Cushion Icebreaking Platforms represent a promising direction in the development of icebreaking technologies. Their use significantly reduces energy consumption for ice cover breaking and improves operational characteristics, compared to traditional icebreakers.

The conducted research and testing have confirmed the possibility of optimising AC IBP parameters to achieve the best results. Further development of AC IBP technologies will contribute to ensuring year-round navigation and supporting Arctic expeditions in the context of global climate change.

ACKNOWLEDGMENTS

The authors are grateful to the Zhejiang International Maritime College for providing financial assistance for the publication of this article – The Zhoushan public welfare science and technology projects (2022C31041).

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