Ice adhesion to hydrotechnical structures

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Abstract. Mitigating ice adhesion on offshore and port structures is crucial for ensuring their safety and operational efficiency in cold climates. Ice adhesion, the molecular attraction between ice and a surface, can lead to increased structural loads, reduced stability, and restricted functionality. This work provides an overview of the different concepts, including the nature of ice adhesion, its consequences on structures, and effective strategies to minimize it. The strategies include surface coatings, surface roughness modifications, heating systems, de-icing and anti-icing systems, structural design considerations, and regular maintenance. These approaches aim to reduce ice adhesion, facilitate ice shedding, and enhance the resilience of offshore and port structures. By implementing these strategies, the integrity and performance of these critical infrastructures can be maintained, ensuring safe operations and supporting transportation and energy production in cold regions.

1 Introduction

Offshore and port structures operating in cold climates face unique challenges due to ice formation and accumulation. Ice adhesion, the molecular attraction between ice and a surface, can significantly impact the safety, integrity, and functionality of these structures. Understanding the nature of ice adhesion, its consequences, and effective strategies to reduce it are crucial for designing, operating, and maintaining these critical infrastructures.

Ice adhesion is a fundamental property in which the attractive forces between ice and a surface lead to the formation of a bond. The strength of this bond depends on factors such as temperature, surface properties, and intermolecular forces [1-2]. Adhesion forces can vary, typically ranging from a few pascals (Pa) to several hundreds kilopascals (kPa), quantifying the resistance of ice to detachment from a surface.

The adhesion of ice to offshore and port structures presents a range of challenges. One major concern is the increased structural loads caused by ice accumulation [3-5]. The weight of ice, influenced by its thickness, density, and coverage, can add substantial loads to structures, potentially exceeding their design limits and compromising their integrity. The altered aerodynamic or hydrodynamic characteristics resulting from ice adhesion can also impact the stability of these structures, leading to potential instabilities and structural failures.

Moreover, ice adhesion can induce vibration and resonance within the structures. As ice forms irregular shapes and unevenly distributes its weight, vibrations can arise, potentially

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causing fatigue damage and accelerated wear. The adhesion of ice can also restrict the functionality of offshore and port structures by obstructing critical components, impeding maintenance activities, and hindering access for inspection.

To address these challenges, various strategies are employed to reduce ice adhesion on these structures. One approach involves the application of specialized coatings or paints with low surface energy properties. Ice-repellent coatings hinder ice adhesion by reducing the contact area between ice and the surface, enabling easy ice removal. These coatings can be engineered to have hydrophobic or superhydrophobic properties, preventing water and ice from adhering to the surface.

Heating systems are also employed to reduce ice adhesion [6-8]. By raising the surface temperature, these systems either melt ice formations or prevent their formation altogether. Electrical resistance heating, hot water circulation, or embedded heating elements are some common methods utilized to control ice accumulation on critical surfaces.

Another strategy focuses on modifying the surface roughness of structures. Smoother surfaces are generally associated with lower ice adhesion, while controlled micro or nano-scale roughness can facilitate ice shedding. Techniques such as surface treatments, shot blasting, laser texturing, or hydrophobic patterns are used to optimize surface roughness for minimizing ice adhesion [9-11].

De-icing and anti-icing systems are additional strategies used to manage ice adhesion. De-icing systems remove ice from structures after its formation, while anti-icing systems prevent ice formation in the first place. These systems utilize methods such as heating elements, heated cables, or pneumatic systems to facilitate ice removal or prevent ice formation.

Effective structural design considerations can further minimize ice adhesion. Structures can be designed with optimized slope angles, streamlined shapes, and minimized ledges or protrusions that facilitate ice shedding and prevent ice accumulation.

Regular monitoring and maintenance play a vital role in addressing ice adhesion on offshore and port structures. Prompt removal of ice formations, continuous inspection of critical components, and timely assessment of ice conditions are crucial to ensure the integrity and safe operation of these structures in cold environments.

By implementing effective strategies to reduce ice adhesion, offshore and port structures can operate more reliably and safely in icy conditions. Enhanced safety leads to uninterrupted transportation, improved energy production, and sustained infrastructure support in cold regions.

2 Analysis

Adhesion refers to the molecular attraction or sticking together of different substances. It is the force that holds two dissimilar materials in contact with each other. Adhesion is a fundamental property in various aspects of science and technology, including physics, chemistry, biology, and engineering.

In the context of physics and chemistry, adhesion is the attraction between molecules of different substances. It is caused by intermolecular forces such as van der Waals forces, electrostatic interactions, or hydrogen bonding. These forces allow substances to stick together at their interface, forming a bond.

In engineering and materials science, adhesion is essential for the performance of adhesives, coatings, paints, and many other materials. It determines the strength and durability of bonds between materials, influencing factors such as adhesion strength, cohesion, surface tension, and wettability.
The adhesion of ice to marine and offshore structures can pose several dangers and challenges. Some of the key concerns include:

Increased structural loads: Ice accumulation on offshore structures, such as oil platforms or wind turbines, can significantly increase the weight and load on the structures. This additional weight can lead to structural deformation or damage, potentially compromising the integrity of the platform or its components.

Reduced structural stability: Ice adhesion can alter the aerodynamic or hydrodynamic characteristics of offshore structures, affecting their stability in harsh weather conditions. Ice formations can change the center of gravity, increase drag, or disrupt the flow patterns around the structure, potentially leading to instability and structural failure.

Vibration and resonance: Ice accretion on offshore structures can induce vibrations and resonant effects due to the irregular shape and weight distribution of the ice. These vibrations can lead to fatigue damage, accelerated wear, and potential structural failure if not adequately accounted for in the design and maintenance of the structure.

Impact and crushing forces: When ice breaks loose or falls from an offshore structure, it can create significant impact forces upon impact with the water surface or other components of the structure. These forces can cause damage to the structure or its surrounding equipment.

Restricted functionality: Ice adhesion can impair the functionality of offshore structures by blocking access to critical components, such as sensors, valves, or equipment. It can also hinder maintenance and inspection activities, making it challenging to identify and address potential issues promptly.

Ice adhesion to structures can lead to an increase in ice load primarily due to the added weight and changes in aerodynamic or hydrodynamic characteristics caused by the ice accumulation.

Weight of ice: When ice accumulates on a structure, it adds significant weight to the overall load the structure must bear. The weight of the ice can increase the overall load on the structure, potentially exceeding its design limits. The weight of the ice itself can vary depending on factors such as ice density, thickness, and the extent of ice coverage.

Shape and profile changes: Ice formations on structures can alter their shape and profile, leading to changes in aerodynamic or hydrodynamic characteristics. Irregular ice formations can increase the surface area exposed to wind or water flow, resulting in higher drag forces. The altered shape can also affect the distribution of forces on the structure, potentially leading to concentrated loads in specific areas.

Wind and current effects: Ice adhering to structures can modify the flow patterns of wind and water around the structure. The presence of ice can disrupt the smooth flow of wind or water, increasing turbulence and generating additional forces on the structure. These forces can include drag, lift, and lateral forces, further adding to the overall ice load.

Ice accretion: Ice accumulation is not always uniform, and it can occur unevenly on different parts of a structure. This uneven distribution of ice can create unbalanced loads, inducing asymmetric forces on the structure. The combination of varying ice thickness and distribution can lead to localized stress concentrations, potentially affecting the structural integrity.

The increased ice load resulting from ice adhesion can place additional stress on the structure, potentially exceeding design limits and compromising its stability. Proper consideration of ice loads and appropriate design measures, such as ice-resistant coatings and structural reinforcement, are necessary to ensure the safety and integrity of offshore structures in icy environments.
Ice adhesion is influenced by temperature, and understanding this relationship is crucial when dealing with ice formation on structures. Generally, the adhesion strength between ice and a surface tends to increase with decreasing temperature. At temperatures below the freezing point, when a surface comes into contact with water or moisture, the water molecules can freeze, forming ice. Lower temperatures facilitate the freezing process and promote the initial bond formation between the ice and the surface. As the ice crystals grow and interlock with surface irregularities, the adhesion strength increases. Water viscosity: As the temperature decreases, water viscosity increases. Higher viscosity means that water molecules move more slowly and have a higher chance of forming strong intermolecular bonds with the surface molecules. This enhanced bonding contributes to increased adhesion between ice and the surface. Intermolecular forces: The strength of intermolecular forces, such as hydrogen bonding, van der Waals forces, and electrostatic interactions, becomes more pronounced at lower temperatures. These forces play a significant role in the adhesion between ice and a surface. Lower temperatures enhance the effectiveness of these forces, resulting in stronger ice adhesion. Ice crystal structure: Ice forms a crystal lattice structure consisting of ordered water molecules. At lower temperatures, the ice crystal structure becomes more stable and compact. The compact ice structure has a higher density and stronger molecular bonds, leading to increased adhesion strength. It is worth noting that there are other factors besides temperature that can influence ice adhesion, such as surface roughness, surface energy, and presence of impurities. These factors can interact with temperature effects to determine the overall adhesion characteristics.

The adhesion strength between ice and a specific material can vary depending on the material's surface properties. Here are some general observations regarding ice adhesion for different materials, along with approximate adhesion strength ranges:

- Metals typically have good ice adhesion due to their high surface energy and the potential for intermolecular interactions with ice. The adhesion strength can vary depending on the specific metal and its surface condition. For example, stainless steel can have ice adhesion strengths typically ranging from 10 kPa to 1 MPa.

- The adhesion of ice to polymers can vary widely depending on the polymer type, surface roughness, and surface energy. In general, polymers with lower surface energies tend to have reduced ice adhesion. For example, low-density polyethylene (LDPE) can have ice adhesion strengths ranging from 1 to 10 kPa, while high-density polyethylene (HDPE) can have ice adhesion strengths in the range of 3 to 15 kPa.

- Glass and ceramic materials generally exhibit relatively high ice adhesion due to their high surface energy and potential for intermolecular interactions. The adhesion strength can vary depending on the specific composition and surface condition. Glass can have ice adhesion strengths ranging from 10 to 300 kPa, while ceramics can have adhesion strengths in a similar range.

- Surfaces or coatings designed to have low surface energy can significantly reduce ice adhesion. Examples include certain fluoropolymer coatings, such as polytetrafluoroethylene (PTFE) or perfluoroalkoxy (PFA). These materials can exhibit ice adhesion strengths as low as 0.1 kPa or even lower.

Provided ranges are approximate and can vary depending on multiple factors, including surface preparation, surface roughness, temperature, humidity, and the presence of impurities or contaminants. Additionally, specific test methods and conditions can also influence the measured adhesion values. Experimental testing using standardized methods is typically necessary to determine precise ice adhesion values for specific materials under specific conditions (fig. 1).
Fig. 1. Example of ice adhesion and friction testing

Coatings or paints can have a significant impact on the adhesion strength of ice to a surface. The influence of coatings on ice adhesion can vary depending on several factors, including the type of coating, its surface properties, and the specific conditions. Here are a few key points to consider:

Coatings can modify the surface energy of a material. Materials with lower surface energy tend to have reduced ice adhesion. Coatings designed with low surface energy properties, such as certain fluoropolymer coatings like polytetrafluoroethylene (PTFE) or polyvinylidene fluoride (PVDF), can decrease the ice adhesion strength.

Coatings can alter the surface roughness or smoothness of a material. Smoother surfaces generally tend to have lower ice adhesion due to reduced contact points for ice to adhere. However, excessively smooth surfaces can lead to poor mechanical interlocking and potentially lower ice adhesion. Optimal roughness or texture can be designed to minimize ice adhesion.

Certain coatings are specifically engineered to have ice-repellent properties. These coatings create a low-friction surface that inhibits ice adhesion and promotes easy ice removal. They often combine low surface energy with specific surface textures or structures to encourage ice shedding.

Some coatings may include adhesion-promoting additives or primers that improve the bond between the coating and the substrate. These additives can enhance the overall adhesion between the coating and the underlying material, potentially influencing ice adhesion indirectly.

Proper surface preparation and conditioning before applying the coating can play a crucial role in achieving optimal adhesion. Cleaning, degreasing, and appropriate surface treatment can enhance the bond between the coating and the substrate, potentially influencing ice adhesion as well.

Coatings and paints can be engineered to reduce ice adhesion and facilitate ice removal, providing potential benefits in various applications, including offshore structures, aircraft, and infrastructure in cold climates. However, specific coating systems and their performance should be evaluated based on the desired application and relevant environmental conditions.

Table 1 contains adhesion values for ice to different materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature, °C</th>
<th>Adhesion force, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>−2</td>
<td>440</td>
</tr>
<tr>
<td></td>
<td>−6</td>
<td>840</td>
</tr>
<tr>
<td>Wood</td>
<td>−3</td>
<td>470</td>
</tr>
</tbody>
</table>
When comparing the forces from ice adhesion to forces exerted by moving flat ice, it's important to note that the magnitudes of these forces can vary significantly based on multiple factors, including ice conditions, surface properties, and the specific circumstances of the interaction.

Adhesion Force of Ice: As mentioned earlier, the adhesion force of ice to a surface typically ranges from a few pascals (Pa) to several hundreds kilopascals (kPa). This force represents the strength of the bond between the ice and the surface, determining the ice's resistance to removal and its potential to accumulate on the structure.

Forces from Moving Flat Ice: The forces exerted by moving flat ice on a structure can be more complex and dependent on several factors, including ice velocity, ice thickness, ice density, and the contact area with the structure. Precise values for these forces are difficult to provide without specific details and circumstances. However, it is recognized that moving ice can generate substantial forces.

Ice loads due to ice movement can be significant during ice sheet collisions, ice drift, or ice ridge interaction. These forces are influenced by various factors, such as ice velocity and momentum, and can result in dynamic loads on the structure. The magnitude of forces from moving flat ice can range from several kilonewtons (kN) to several meganewtons (MN), depending on the ice conditions and the structure's design.

It's important to emphasize that ice loads, including those from moving flat ice, are typically evaluated and designed for specific structures using established engineering methodologies and guidelines. The precise determination of these forces requires detailed analysis based on ice models, field data, and ice load calculations specific to the project and location.

Reducing ice adhesion on offshore and port structures can be crucial to maintain their integrity and operational efficiency in cold climates.

Applying ice-repellent coatings or paints can help reduce ice adhesion. These coatings are designed to have low surface energy, making it difficult for ice to adhere. Hydrophobic or superhydrophobic coatings can be effective in repelling water and ice, facilitating ice shedding.

Modifying the surface roughness of structures can reduce ice adhesion. Smoother surfaces generally have lower ice adhesion, while surfaces with controlled micro or nanoscale roughness can help promote ice shedding. Surface treatments like shot blasting, laser texturing, or hydrophobic patterned surfaces can be employed to achieve the desired roughness.

Installing heating systems on critical surfaces can prevent ice formation or facilitate ice removal. Techniques such as electrical resistance heating, hot water circulation, or embedded heating elements can be used to raise the surface temperature and melt or prevent ice accumulation.

Implementing de-icing or anti-icing systems can help manage ice buildup. De-icing systems use mechanical or thermal methods to remove ice after it forms, while anti-icing systems work to prevent ice formation in the first place. Examples include the use of heating elements, heated cables, or pneumatic systems to remove or prevent ice.
Using materials that inherently repel ice can be advantageous. Certain materials, like certain polymers or coatings with low surface energy, can naturally resist ice adhesion. Incorporating these materials into the structure's design or applying them as protective coatings can help reduce ice adhesion.

Optimizing the design of offshore and port structures can minimize ice accumulation and adhesion. This can involve factors such as slope angles, streamlined shapes, or minimizing ledges or protrusions where ice can accumulate.

Regular monitoring and maintenance of structures during winter conditions are vital to identify and address ice accumulation promptly. Timely removal of ice can prevent excessive buildup and mitigate potential structural damage.

The effectiveness of these methods can vary depending on various factors, including environmental conditions, ice characteristics, and specific structure requirements.

3 Conclusion and discussion

Mitigating ice adhesion on offshore and port structures is essential for maintaining their safety, integrity, and operational efficiency in cold climates. The understanding of ice adhesion, its impact, and the methods to reduce it are crucial considerations in designing and maintaining such structures.

Ice adhesion is the molecular attraction between ice and a surface, and it can lead to increased structural loads, reduced stability, vibration, and restricted functionality. The adhesion force of ice can vary depending on temperature, surface properties, and other factors, typically ranging from a few pascals to several hundreds kilopascals. Direct numerical comparisons between ice adhesion and other ice loads, such as weight, wind forces, or impacts, are challenging due to the differing nature and measurements of these forces.

Various strategies can be employed to minimize ice adhesion. Surface coatings with low surface energy, such as ice-repellent coatings or paints, can reduce ice adhesion by inhibiting the bond formation between ice and the surface. Controlling surface roughness to promote ice shedding and employing heating systems or de-icing/anti-icing systems can also be effective in preventing or removing ice accumulation. Structural design considerations, including streamlined shapes and minimizing ice-trap areas, further contribute to reducing ice adhesion.

It is important to recognize that ice adhesion reduction methods should be tailored to specific applications and consider factors like environmental conditions, ice characteristics, and structural requirements. Professional expertise, adherence to regional guidelines, and compliance with industry standards are crucial in implementing appropriate strategies.

Overall, managing ice adhesion on offshore and port structures requires a multidisciplinary approach involving engineering, materials science, and ice physics. Advancements in understanding ice behavior, surface technologies, and structural design continue to drive improvements in minimizing ice adhesion and enhancing the resilience of these structures in icy environments.

The study and implementation of effective ice adhesion reduction techniques contribute to safer operations, extended service life, and improved functionality of offshore and port structures in cold regions. By mitigating ice-related challenges, these structures can operate more efficiently, ensuring the safe transportation of goods, facilitating energy production, and supporting vital infrastructure in icy conditions.
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References