Proceedings of the 3rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/140/2025.21883

Analysis of Reducing Cavitation in Aircraft Cryogenic System

Yibo Zhu

Aerospace Engineering Nottingham University of Ningbo, Zhejiang, China
Zyb2234959087@126.com

Abstract: Cavitation erosion is a distinct type of material damage that arises from the generation of stress fields due to the collapse of cavitation bubbles. This phenomenon leads to unique microstructural effects on materials, which differ significantly from those observed in other types of erosion. The evaluation of erosion damage through experimental methods reveals important insights into how materials respond to cavitation. Furthermore, various prevention techniques have been developed to mitigate these effects, highlighting the necessity for specialized approaches in addressing cavitation erosion. While the research surrounding cavitation phenomena in various industries is relatively comprehensive, its application in the field of aeronautical engineering remains underdeveloped. This paper, by means of a literature review, explores the applications of cavitation within the aerospace sector, specifically focusing on methods to resist cavitation effects.

Keywords: Cavitation, erosion, aircraft, simulation

1. Introduction

Cavitation is a phenomenon that has been the subject of extensive research due to its significant impact on various engineering applications, such as hydraulic systems, marine propellers, and biomedical devices [1] It occurs when the local pressure in a liquid drops below its vapor pressure, leading to the formation of vapor-filled cavities or bubbles. These bubbles can then collapse, creating high-pressure zones and potentially causing damage to nearby surfaces. Understanding the cavitation process is crucial for the design and operation of systems where it may occur [2]. Recent research has focused on understanding the cavitation process at a more fundamental level, using advanced experimental techniques and computational models. This has led to a better understanding of the dynamics of cavitation bubbles and the factors that influence their behavior. Many scientists are actively exploring various strategies to suppress cavitation in aircraft systems, recognizing its detrimental effects on performance and component longevity. One approach involves changing the turbine material to enhance its resistance to cavitation-induced erosion. Researchers are investigating advanced materials that can withstand the harsh conditions of high-speed fluid flows, focusing on properties such as hardness and surface roughness. Additionally, the application of protective coatings has emerged as a promising method to mitigate cavitation damage. These coatings can create smoother surfaces that reduce the likelihood of bubble formation and collapse. Furthermore, controlling operational parameters such as temperature and pressure is crucial in managing cavitation. By optimizing these conditions, it is possible to minimize the risk of cavitation onset. This paper briefly discusses the impact of cavitation on aircraft systems, highlighting the importance of understanding its mechanisms. It also outlines effective methods to address this challenge,

DOI: 10.54254/2755-2721/140/2025.21883

emphasizing the need for ongoing research and innovation in materials and design. Ultimately, these efforts aim to enhance the reliability and efficiency of aircraft, ensuring safer and more sustainable aviation practices in the future.

2. Mechanism and influencing factors of cavitation

2.1. The basic mechanism and principle of cavitation

2.1.1. Liquid Vaporization

When a liquid is in the dynamic state of flowing, it continuously courses through various sections of the pipeline or container. During this process, it may encounter a particular region where the local pressure experiences a sudden and significant drop. This pressure decline can be triggered by a variety of factors, such as a constriction in the flow path, a sharp change in the geometry of the conduit, or the operation of certain fluid machinery nearby. If, in this area, the pressure plummets to a level that is lower than the saturated vapor pressure corresponding to the current temperature of the liquid, a remarkable physical transformation begins to take place. The concept of saturated vapor pressure is crucial here. It represents the equilibrium pressure at which a liquid and its vapor coexist in a stable state at a given temperature. Once the local pressure dips below this critical value, the liquid molecules gain enough energy to break free from their liquid-phase constraints. As a result, the liquid starts to vaporize spontaneously, and minuscule bubbles start to emerge. These nascent bubbles are not just filled with pure vapor. In fact, they also incorporate the gases that were previously dissolved in the liquid. These dissolved gases, which had been in a homogeneous mixture with the liquid under normal pressure conditions, now come out of the solution and accumulate within the growing bubbles, further contributing to the complex composition of these tiny entities [1].

2.1.2. Bubble Collapse

When bubbles flow with the liquid to high-pressure areas, the external high pressure will cause the bubbles to collapse rapidly. The process of bubble collapse is very fast and will produce local high pressure and high temperature. The collapse of cavitation bubbles generates high pressures and temperatures, leading to shock waves that damage solid surfaces. When bubbles are near a solid boundary, their asymmetric collapse creates high-velocity microjets, resulting in intense water hammer effects. The interaction of these jets and shock waves can cause permanent deformation or fatigue in materials, depending on the stress levels. Damage is characterized by complex patterns rather than simple circular pits, and the collapse behavior of bubbles varies with their proximity to boundaries, allowing for multiple collapses before significant damage occurs [2].

2.1.3. Physical and Chemical Effects

The high pressure and high temperature generated during bubble collapse will cause damage to the surrounding material surfaces. This damage is mainly due to the high-speed impact of liquid particles towards the position where the bubbles collapse. In addition, the high temperature generated during bubble collapse may also trigger chemical reactions, further exacerbating the corrosion of materials [1].

2.1.4. Measures to Prevent Cavitation

In order to prevent the occurrence of cavitation, a series of measures can be taken, such as optimizing the hydrodynamic design to reduce the regions where the local pressure drops; selecting appropriate

DOI: 10.54254/2755-2721/140/2025.21883

materials to improve the cavitation-resistance performance of materials; controlling the temperature and pressure of the fluid to avoid liquid vaporization, etc. [2-4].

2.2. Factors affecting cavitation

2.2.1. Material Effects on Cavitation

The choice of material can significantly influence the cavitation process. Different materials have varying levels of resistance to cavitation-induced damage. For example, harder materials may be more resistant to the erosive effects of collapsing bubbles, while softer materials may be more prone to damage [3]. The surface roughness of a material can also play a role, as rough surfaces can act as nucleation sites for cavitation bubbles. Recent studies have shown that certain coatings and surface treatments can enhance a material's resistance to cavitation, making them promising candidates for applications where cavitation is a concern [4].

2.2.2. Liquid Properties and Cavitation

The properties of the liquid itself are also key factors in the cavitation process. Liquids with higher vapor pressures are more likely to undergo cavitation, as they can more easily transition from liquid to vapor under reduced pressure conditions. Similarly, liquids with lower viscosities tend to facilitate cavitation more readily, as their lower resistance to flow allows for quicker movement and bubble formation. The presence of dissolved gases can significantly affect cavitation as well. These gases can come out of solution during pressure fluctuations, contributing to bubble formation and enhancing the likelihood of cavitation events. Furthermore, the temperature of the liquid plays a crucial role in this process. Higher temperatures generally lead to increased vapor pressure, which in turn raises the probability of cavitation occurring. As the temperature rises, the liquid's ability to form vapor bubbles increases, exacerbating the cavitation phenomenon. Understanding these liquid properties is essential for designing and optimizing aviation systems. By selecting appropriate liquids and adjusting operational conditions, it is possible to effectively reduce the risk of cavitation, thereby enhancing overall system performance and reliability. These factors collectively determine the cavitation behavior of liquids under specific conditions, which is of significant importance in aerospace engineering.

2.2.3. Fluid Dynamics and Cavitation

The velocity and pressure of the fluid are crucial factors in the cavitation process. As fluid velocity increases, the local pressure can drop below the vapor pressure, which triggers cavitation. This phenomenon is commonly observed in high-speed flows, such as those encountered in pumps and turbines, where rapid fluid movement creates conditions conducive to bubble formation [5]. Moreover, the geometry of the flow path plays a significant role in influencing cavitation. Areas with high curvature or sudden changes in cross-sectional area can lead to localized pressure drops, increasing the likelihood of cavitation inception. For example, in a turbine, the blades' shape can create regions of low pressure, promoting cavitation. Understanding these dynamics is essential for designing systems that minimize cavitation-related damage, ensuring improved performance and longevity of hydraulic components. By carefully analyzing fluid velocity and flow path geometry, engineers can mitigate the adverse effects of cavitation in various applications [5].

DOI: 10.54254/2755-2721/140/2025.21883

3. Cavitation in aircraft cryogenic systems

3.1. Overview of aircraft cryogenic systems

The use of cryogenic fuels, such as condensed natural gas, liquid hydrogen, and propane, shows great promise for aircraft engines. The urgency of transitioning to cryogenic fuels stems from their high heat of combustion, cooling capacity, environmental safety, substantial natural reserves, and low cost. This study aims to model and optimize the thermal-hydraulic characteristics of cryogenic fuel systems, taking into account their specific applications in high-speed aircraft, particularly regarding long endurance, high heat transfer intensity, varying operating conditions, and fluctuating G-loads. Additionally, the influence of cavitation on the performance of the fuel system is examined, as it can significantly affect fuel delivery and combustion efficiency. To address this scientific challenge, a mathematical model and a parameter calculation procedure for the cryogenic fuel system have been developed, enabling parametric and optimization analyses across a broad range of operational conditions. The findings include the selection of cryogenic fuel system parameters for an advanced high-speed aircraft utilizing cryogenic methane. Furthermore, the study identifies the primary mechanisms by which various factors, including cavitation, impact the mass characteristics of the fuel system and the losses associated with fuel [6].

3.2. Cavitation in the aircraft cryogenic system

Cavitation in vortical structures presents a complex challenge in engineering, particularly in applications such as aircraft turbine engines. Cavitating vortices can occur on blade surfaces, within clearance passages, and at the hubs of various turbomachinery. For instance, micro vortices forming at the trailing edge of attached sheet cavitation can lead to significant erosion. Additionally, cavitating hub vortices in the draft tubes of hydro turbines can induce major surges and fluctuations in power output [7].

Recent studies indicate that vortex cavitation plays a crucial role in the inception process across a wide range of turbulent flows, yet most research has concentrated on the initial stages, with less focus on developed vortex cavitation. Notably, wave-like disturbances on vapor core surfaces are critical features, and instabilities within micro vortices significantly contribute to erosion mechanisms associated with sheet and cloud cavitation [7].

In specific conditions, intense sound at discrete frequencies may arise from interactions between tip vortex disturbances and oscillating sheet cavitation. Moreover, while there are similarities in vortex breakdown phenomena, differences also exist when compared to fully wetted flow scenarios. Simple vortex models can sometimes effectively describe the cavitation process in complex turbulent flows, such as those found in bluff body wakes and plug valves [7].

Although a dedicated vortex model for cavitation in jets is lacking, the inception mechanism appears linked to vortex pairing, which can generate negative pressure peaks exceeding the root mean square (rms) value by a factor of ten, and sometimes surpassing dynamic pressure by a factor of two. Importantly, cavitation is not merely a byproduct of vortical structures; it also serves as a mechanism for generating vorticity, further complicating its effects on turbine engine performance [7].

4. Methodology

4.1. Bubble Collapse Model

The bubble collapse model focuses on the dynamic behavior of bubbles as they collapse in a liquid and their effects on the surrounding medium. Typically spherical, bubbles experience collapse influenced by external pressure and internal gas pressure [2].

DOI: 10.54254/2755-2721/140/2025.21883

The Rayleigh Equation, formulated by Lord Rayleigh, is key to understanding bubble collapse. It accounts for the motion of the bubble wall during the collapse and derives the relationship between bubble wall velocity and radius based on energy conservation principles. The equation is expressed as: $\rho\frac{d^2R}{dt^2}+\sigma\frac{1}{R}=-P+P_{\infty}$ where ρ is the liquid density, R is the bubble radius, σ is the surface tension, P is the internal bubble pressure, and P_{∞} is the pressure of the surrounding liquid [2].

During the collapse, the internal pressure P is influenced by the compression of the gas inside the bubble, which can be described using the gas state equation. When bubbles are near solid boundaries, their collapse becomes asymmetric, leading to high-pressure regions and high-velocity microjets. This asymmetry results in shock waves that exert significant pressure on nearby solid surfaces.

The localized high pressure can also induce a water hammer effect, characterized by sudden pressure fluctuations during abrupt changes in fluid conditions. Through numerical simulations and experimental studies, researchers estimate that the maximum pressure during bubble collapse can reach thousands of atmospheres, highlighting the potential for considerable material damage.

4.2. Hydrodynamic simulation

Use CFD modules like COMSOL for in - depth cavitation analysis. These tools simulate fluid flow and bubble dynamics. CFD visualizes cavitation bubble formation, growth, and collapse, helping understand their impact on structures and fluid dynamics. Manipulating pressure, temperature, and fluid properties improves prediction accuracy. Cavitation magnitude can be measured via pressure measurement and fluid dynamics simulation.

4.3. Science method

Simulated flight environment experiments can be conducted alongside real-world testing methods to investigate the phenomenon of cavitation. By creating controlled conditions that mimic the operational environment of an aircraft, researchers can observe the onset and behavior of cavitation under various pressures and velocities. This approach allows for the collection of empirical data on how cavitation influences fluid dynamics and material integrity. Combining simulation with practical experiments provides a comprehensive understanding of cavitation's impact, enabling more accurate predictions and effective solutions for mitigating its adverse effects in aerospace applications [8].

5. Measures to mitigate cavitation in aircraft cryogenic systems

Currently, the predominant thermal spray materials are metals and ceramics, which inevitably contain defects such as porosity and exhibit a typical layered structure. This results in relatively low cohesive strength between flat particles, leading to the detachment of large particle clusters during the cavitation process[4]. Such detachment significantly limits the material's ability to resist cavitation erosion. Therefore, enhancing the density and cohesive strength of thermal spray coatings through effective treatment techniques is crucial for improving their uniformity and, consequently, their cavitation resistance. Research has confirmed that several modification techniques can be effective, including substrate preheating, coating heat treatment, thermomechanical processing, microwave post-treatment, and vacuum impregnation for pore sealing. By implementing these methods, it is possible to significantly enhance the cavitation erosion resistance of thermal spray coatings [4].

The use of auxiliary devices, such as fairings and diffusers, can also significantly reduce cavitation. These devices ensure a more uniform velocity distribution by controlling flow characteristics, thereby reducing sudden pressure drops that lead to cavitation. In addition, a streamlined fairing or wing cover can improve airflow around key components, further reducing the potential risk of turbulence and cavitation [7].

DOI: 10.54254/2755-2721/140/2025.21883

6. Conclusion

In conclusion, this study reveals the substantial impact of cavitation on aircraft cryogenic fuel systems. Through in - depth examination of the intricate interplay among material properties, fluid dynamics, and operating conditions, several key factors contributing to cavitation erosion have been precisely identified.

Optimizing material selection, such as choosing high - strength and corrosion - resistant alloys, and applying advanced coatings like ceramic - based coatings, can significantly enhance the resistance to cavitation damage. Additionally, the development of a robust mathematical model, which considers various physical parameters and boundary conditions, enables more accurate predictions and optimizations in real - world applications. This, in turn, allows engineers to design more resilient and efficient fuel systems.

As the aerospace industry increasingly adopts cryogenic fuels for their high efficiency and environmental advantages, effectively addressing the challenges posed by cavitation becomes crucial for improving fuel delivery and combustion performance. Targeted research on innovative anti - cavitation designs, including novel structural configurations and flow - control techniques, is expected to lead to a remarkable boost in aviation performance and sustainability, ensuring a more prosperous future for the aerospace sector.

References

[1] *Karimi A, Martin J L. Cavitation erosion of materials[J]. International Metals Reviews, 1986, 31(1): 1-26.*

[2] *Sreedhar B K, Albert S K, Pandit A B. Cavitation damage: Theory and measurements–A review[J]. Wear, 2017, 372: 177-196.*

[3] *Starke Jr E A, Staley J T. Application of modern aluminum alloys to aircraft[J]. Progress in aerospace sciences, 1996, 32(2-3): 131-172.*

[4] *Junkai Ma, Guoliang Hou, Yuning An et al. Research Progress of Thermal Spraying Anti-cavitation Erosion Coatings and Modification Technologies[J]. China Surface Engineering, 35(4): 113-127.*

[5] *Arndt R E A. Cavitation in vortical flows[J]. Annual review of fluid mechanics, 2002, 34(1): 143-175.*

[6] *Hampton W. The Problem of Cavitation Erosion in Aircraft Hydraulic Systems: A description of an unexpected problem encountered with the Trident hydraulic systems and the steps taken to find a solution[J]. Aircraft Engineering and Aerospace Technology, 1966, 38(12): 8-11.*

[7] *Yang H, Xu Y, Chen Z, et al. Cavitation suppression in the nozzle-flapper valves of the aircraft hydraulic system using triangular nozzle exits[J]. Aerospace Science and Technology, 2021, 112: 106598.*

[8] *Ding H, Visser F C, Jiang Y, et al. Demonstration and validation of a 3D CFD simulation tool predicting pump performance and cavitation for industrial applications[C]//Fluids engineering division summer meeting. 2009, 43727: 277-293.*