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CAVITATION IN HYDRAULIC MACHINERY AND WATER TREATMENT SYSTEMS: RECENT ADVANCES IN DETECTION, MODELLING AND MITIGATION STRATEGIES

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Abstract: Cavitation remains one of the most critical challenges affecting the performance, reliability, and service life of hydraulic machinery, particularly in pumps and turbines operating under variable load conditions. This review presents a comprehensive overview of the physical mechanisms governing cavitation inception, bubble dynamics, and collapse phenomena in hydraulic systems, including water supply, wastewater treatment, desalination, and hydropower applications. Emphasis is placed on the impact of cavitation on hydraulic efficiency, vibration behavior, material erosion, and structural integrity. Recent advances in experimental visualization techniques, numerical modeling approaches, and monitoring methods for cavitation detection are discussed. In addition, practical mitigation strategies—including optimized hydraulic design, material selection, surface treatments, and operational control—are critically evaluated from an industrial perspective. The paper aims to bridge theoretical understanding and engineering applications by highlighting current technological developments and identifying future research directions for improving durability and performance in hydraulic machinery.

Keywords: Cavitation; Hydraulic machinery; Pumps; Turbines; Erosion; Numerical modeling

INTRODUCTION

Cavitation remains one of the most critical operational challenges in hydraulic machinery, particularly in pumps and hydraulic turbines operating under variable flow and load conditions. Despite significant advances in hydraulic design and material engineering, cavitation continues to limit efficiency, reliability, and service life in industrial water systems, hydropower plants, irrigation networks, and process industries. Recent studies emphasize that increasing operational flexibility requirements, higher rotational speeds, and fluctuating demand profiles further intensify cavitation risks in modern installations [1-3]. In water and wastewater treatment facilities, cavitation not only affects pumping reliability but may also influence process stability, energy consumption, and maintenance frequency. In centrifugal pumps, cavitation typically occurs when the local static pressure falls below the vapor pressure of the liquid, leading to vapor bubble formation and subsequent collapse in higher-pressure regions. This phenomenon results in hydraulic performance degradation, including head drop, reduced discharge capacity, and efficiency losses. Experimental and numerical investigations published after 2020 report measurable efficiency reductions and significant vibration amplification even under partial cavitation regimes [4]. Similarly, in hydraulic turbines-particularly Francis and Kaplan types-cavitation in runner blades and draft tubes can lead to severe erosion, noise generation, and structural fatigue, ultimately compromising long-term operational stability [3,5].

Beyond technical performance, the economic consequences of cavitation are substantial. Maintenance costs, unplanned downtime, replacement of eroded components, and efficiency penalties contribute to increased life-cycle costs of hydraulic installations. Recent industrial assessments indicate that cavitation-related damage remains among the leading causes of premature failure in pumping systems and hydropower equipment [6]. In the context of energy efficiency targets and sustainability requirements, minimizing cavitation-induced losses has become a strategic engineering priority.

Although the fundamental physics of cavitation have been studied for decades, recent research focuses on improved detection techniques, advanced numerical modeling approaches, surface treatment technologies, and optimized operational strategies. However, there remains a need to integrate these developments from an engineering and application-oriented perspective.

The objective of this review is to provide a comprehensive and practice-oriented overview of cavitation in hydraulic machinery, with emphasis on pumps and turbines. The paper synthesizes recent advances in understanding cavitation mechanisms, evaluates its impact on performance and structural integrity, and discusses contemporary monitoring and mitigation strategies relevant to industrial applications. By bridging theoretical insights and engineering practice, this review aims to support more reliable and efficient hydraulic system design and operation.

FUNDAMENTALS OF CAVİTATİON MECHANİSM

Pressure Drop & Vapor Bubble Formation

Cavitation initiates when the local static pressure in a fluid falls below its vapour pressure, causing liquid to partially vaporize and form vapour bubbles [7,8]. In regions of high flow velocity, such as near pump impeller blades or turbine runner passages, the fluid accelerates and the static pressure decreases according to Bernoulli's principle [9]. When this pressure drop reaches the liquid's vapour pressure, microscopic nuclei in the fluid expand into vapour bubbles and detach from the wall or flow boundary layer.

According to Bernoulli's equation for incompressible steady flow:

$$P + \frac{1}{2}\rho V^2 + \rho g z = \text{constant} \qquad (1)$$

where P is static pressure, ρ is fluid density, V is velocity, and z is elevation.

An increase in velocity results in a decrease in static pressure. When:

$$P_{\text{local}} \leq P_{\text{v}} \qquad (2)$$

vapor bubbles are formed. This situation typically occurs at the impeller inlet of centrifugal pumps or along turbine runner blades under high load conditions [12,13].

Once formed, these vapour bubbles are carried by the flow into regions of higher pressure. When the local static pressure exceeds the vapour pressure again, the bubbles collapse abruptly-a process that marks the transition from vapour back to liquid. This collapse releases localized high energy, producing shock waves that can impact surrounding solid surfaces and cause material damage [7,15].

NPSH Concept

The Net Positive Suction Head (NPSH) is a fundamental parameter for predicting cavitation onset in hydraulic machinery. *NPSH Available (NPSHa)* represents the absolute pressure head at the pump suction inlet above the fluid's vapour pressure, while *NPSH Required (NPSHr)* is the minimum suction head needed by the pump to avoid significant cavitation [12,13]. Cavitation occurs when NPSHa falls below NPSHr, resulting in vapour bubble formation at the impeller eye or suction passages. Designers and operators use these values to ensure sufficient suction conditions and to minimize cavitation risk in centrifugal pumps and turbines. In engineering practice, the tendency of a pump to cavitate is evaluated using the Net Positive Suction Head (NPSH). The available suction head is defined as

$$\text{NPSH}_{\text{a}} = \frac{P_{\text{abs}}}{\rho g} + \frac{V^2}{2g} - \frac{P_{\text{v}}}{\rho g} \qquad (3)$$

where P_{abs} is the absolute pressure at the suction inlet, ρ is the liquid density, g is gravitational acceleration, V is the fluid velocity at the suction section, and P_v is the vapor pressure of the liquid. Cavitation occurs when the available value becomes lower than the required value specified by the manufacturer, expressed as $\text{NPSH}_a < \text{NPSH}_r$. Insufficient NPSH results in vapor formation at the impeller eye, leading to head drop, efficiency reduction, and increased vibration levels. Therefore, maintaining an adequate safety margin between NPSH_a and NPSH_r is a primary design and operational consideration in hydraulic systems [12].

Bubble Growth and Collapse

After cavitation inception, bubble dynamics are governed by pressure gradients, liquid properties, and flow field characteristics. Initially, small vapor nuclei grow as long as the local pressure remains below the vapour pressure. As the fluid moves downstream into higher-pressure regions, the bubbles may shrink and ultimately collapse. The collapse process is often asymmetrical near walls or in shear flows, leading to localized high-speed liquid jets and strong pressure pulses.

While detailed mathematical models like Rayleigh-Plesset, Keller-Miksis, or other bubble dynamics equations exist in literature, the key practical insight is that growth and collapse depend strongly on transient pressure fields and fluid properties rather than on steady-state conditions alone.

For example, after inception, the dynamic behavior of a cavitation bubble can be described by the Rayleigh-Plesset equation [10,11,14]:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left(P_{\text{b}} - P_{\infty} - \frac{2\sigma}{R} - \frac{4\mu\dot{R}}{R}\right) \qquad (4)$$

where R is the instantaneous bubble radius, $\dot{R}$ and $\ddot{R}$ represent the first- and second-time derivatives of the radius, P_b is the pressure inside the bubble, P_∞ is the surrounding liquid pressure, σ is the surface tension, μ is the dynamic viscosity of the liquid, and ρ is the liquid density. This equation demonstrates that rapid pressure recovery in the surrounding liquid can cause violent bubble collapse. Although detailed analytical solutions are complex, the practical implication is that higher pressure gradients and transient flow conditions intensify collapse severity, thereby increasing the likelihood of structural damage. In water treatment applications, dissolved gases, temperature variations, and fluid impurities may significantly influence bubble nucleation and collapse intensity.

Micro-Jet Formation

During asymmetrical bubble collapse-especially near solid boundaries-the collapse process does not occur uniformly. Instead, the side of the bubble facing lower pressure collapses faster, generating a high-speed micro-jet directed toward the boundary [7,15]. These micro-jets can reach velocities on the order of hundreds of meters per second and exert significant localized impact forces that contribute to erosion and material fatigue on pump impellers, turbine blades, and other wetted components.

This micro-jet phenomenon is one of the primary mechanisms by which cavitation causes surface damage in hydraulic machinery, and it is a focus of both experimental and numerical studies aimed at mitigation.

CAVİTATİON İN PUMPS AND TURBİNES

Cavitation in hydraulic machinery is particularly critical in water supply systems, wastewater treatment plants, irrigation networks, desalination facilities, and hydropower stations where pumps and turbines operate under variable hydraulic conditions. In such installations, cavitation not only reduces hydraulic efficiency but also affects operational continuity, maintenance costs, and process stability [16].

Cavitation in Pumps

Centrifugal pumps are extensively employed in water supply systems, wastewater treatment facilities, desalination plants, irrigation networks, and industrial fluid transport applications. Beyond water infrastructure, they are also used in aerospace, medical devices, wind power cooling circuits, and fuel transport systems [17]. Despite their wide applicability, centrifugal pumps remain highly susceptible to cavitation, which significantly affects hydraulic performance, structural integrity, and operational lifespan [18].

Cavitation initiates when the local static pressure drops below the vapor pressure of the liquid, resulting in the formation of vapor cavities of different sizes [19]. In centrifugal pumps, this condition typically occurs near the impeller eye due to flow acceleration and pressure reduction (Figure 1). As vapor bubbles are transported toward higher-pressure regions within the impeller passage, they undergo rapid collapse. This collapse produces localized shock waves and high-speed liquid microjets [20].

Experimental studies indicate that these microjets may reach velocities on the order of 100-200 m/s and generate extremely high localized impact pressures [22]. When repeated collapse events occur near solid boundaries, the resulting microjet impacts create microscopic pits on metallic surfaces. Over time, pit coalescence and crack propagation lead to severe surface degradation and cavitation erosion [23]. In the rotating flow environment of centrifugal pumps, the frequency of bubble formation and collapse is particularly high, causing repetitive impact loading that accelerates material fatigue and erosion processes.

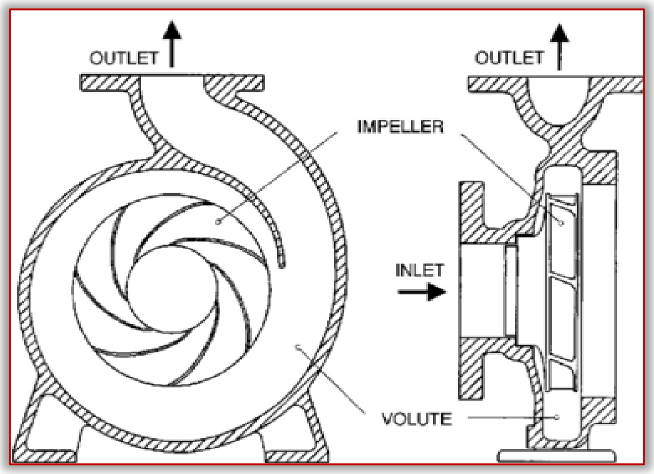

Figure 1. Schematic of a centrifugal pump showing backward–curved impeller blades. Fluid enters through the impeller eye, accelerates along the curved passages between hub and shroud, and exits radially into the volute or diffuser. Reproduced from [21] under the Creative Commons CC BY 4.0 license.

Rotating Flow Field Effects

Unlike static cavitation environments, centrifugal pumps operate in a complex rotating flow field characterized by:

- Strong velocity gradients
- Non-uniform pressure distribution
- Turbulent shear layers
- Coriolis and centrifugal effects

These factors significantly modify cavitation bubble dynamics. The generation, transport, and collapse of bubbles become strongly influenced by three-dimensional vortex structures and periodic pressure fluctuations (Figure 2). Consequently, predicting cavitation damage in rotating machinery is considerably more challenging than in stationary systems.

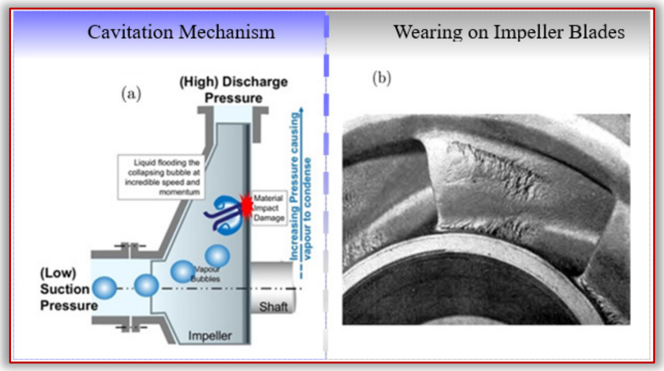

Figure 2. Formation and collapsing of vapor bubbles. Reproduced from [21] under the Creative Commons CC BY 4.0 license.

Recent research emphasizes that the relationship between cavitation structure and material damage in rotating flow fields remains insufficiently quantified. In particular, the correlation between rotational speed and erosion severity requires further systematic investigation.

— Experimental Approaches in Cavitation Research

Historically, much of cavitation erosion research has been conducted in non-rotating or simplified environments. Laser-induced cavitation experiments have been widely used to study single-bubble dynamics and surface damage mechanisms. For example, investigations of laser-generated cavitation bubbles demonstrated the formation of asymmetric collapse and localized wall impact loading [24]. Similarly, Yu et al. showed that boundary proximity strongly influences bubble collapse asymmetry and resulting erosion intensity [25].

Advanced visualization techniques combining high-speed imaging and acoustic measurements have enabled detailed analysis of bubble pulsation and micro-pit formation mechanisms [26]. Numerical investigations using Volume of Fluid (VOF) methods further clarified bubble-bubble and bubble-wall interaction processes [27].

However, translating these findings to rotating hydraulic machinery remains challenging due to additional dynamic effects introduced by rotation.

— Cavitation Erosion in Rotating Machinery

Research on cavitation in rotating flow fields generally focuses on four main directions:

1. Mechanistic understanding of rotating cavitation and its erosion patterns [28].
2. Experimental investigations using controlled hydraulic machinery test rigs under variable rotational speed and pressure conditions [29].
3. Numerical prediction models based on multiphase cavitation modeling and bubble dynamics theory for estimating erosion risk [19].
4. Development of cavitation-resistant materials and coatings [30].

In water and wastewater systems, material durability is especially important because suspended solids and dissolved gases may intensify surface damage mechanisms. Although stainless steels and titanium alloys provide moderate resistance, advanced coatings, nanostructured materials, and composite layers are increasingly investigated to enhance cavitation resistance.

Additionally, blade geometry optimization plays a crucial role. Improvements in blade inlet angle, tip clearance, and root configuration can delay cavitation inception and reduce vapor volume fraction within the impeller passage [31].

— Visualization Challenges in Rotating Flow Fields

Visualization-based analysis remains indispensable for understanding transient cavitation phenomena. High-speed imaging allows direct observation of bubble evolution, while post-test microscopic examination of thin metallic samples enables correlation between bubble collapse events and material damage patterns.

However, rotating flow visualization presents substantial technical challenges:

- ≡ Transparent casings must ensure both optical clarity and mechanical strength.
- ≡ High-speed imaging requires balancing short exposure time and spatial resolution.
- ≡ Synchronization between rotating components and imaging systems is complex.

Overcoming these experimental limitations is essential for establishing quantitative relationships between cavitation structures and erosion damage in centrifugal pumps.

▦ Cavitation in Turbines

Hydraulic turbines operating in hydropower plants and water regulation dams are subjected to high hydraulic heads, pressure gradients, and transient load conditions. These conditions make them particularly susceptible to cavitation phenomena. The selection of turbine type depends primarily on hydraulic head, discharge rate, and operational flexibility (Figure 3).

— Francis Turbines

Francis turbines are reaction-type machines widely used in medium- to high-head applications. Water enters radially at the runner periphery and exits axially through the draft tube. The curved runner blades are designed to convert both pressure and kinetic energy efficiently. Due to their adaptability to varying flow conditions, Francis turbines are extensively employed in large dams, river based plants, and pumped-storage systems.

— Pelton Turbines

Pelton turbines are impulse-type turbines suitable for high-head, low-flow conditions. Water is directed through nozzles as high-velocity jets that impinge on bucket-shaped runner blades, generating torque through momentum transfer. These turbines are particularly appropriate for mountainous regions and small hydropower installations with significant elevation differences.

— Axial-Flow (Kaplan) Turbines

Kaplan turbines are propeller-type reaction turbines optimized for low- to medium-head and high-flow conditions. They incorporate adjustable runner blades and wicket gates, allowing high efficiency across a broad operational range. Kaplan turbines are commonly used in river-type power plants and irrigation systems where discharge varies significantly.

— Banki-Michell (Crossflow) Turbines

Banki-Michell turbines, also known as crossflow turbines, are impulse turbines designed for low- to medium-head applications with variable-flow rates. Water passes transversely through the cylindrical runner and interacts with the blades twice-first at the outer periphery, then at the inner region-thereby improving energy extraction. Their simple construction, mechanical robustness, and tolerance to flow operate efficiently under fluctuations make them suitable for small-scale hydropower and rural electrification systems.

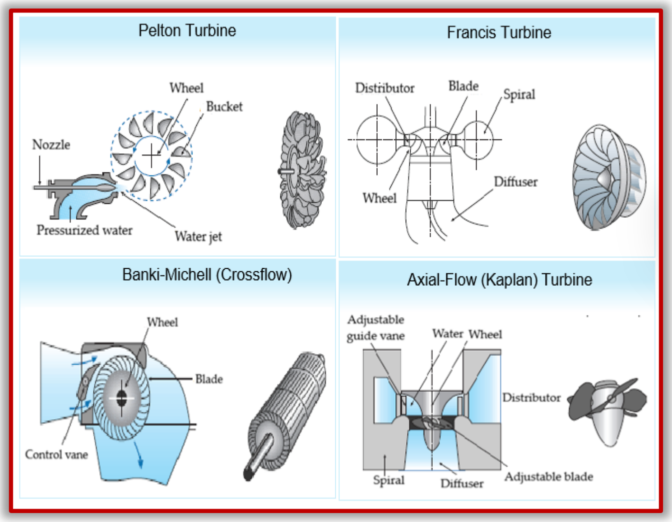

Figure 3. Illustration of Pelton, Banki–Michell, Francis and Kaplan turbines [32].

Recent high-speed visualization and computational studies indicate that vortex rope cavitation developing in the draft tube under part-load operation induces significant pressure fluctuations and low-frequency oscillations, potentially leading to structural fatigue [33-36].

In Kaplan turbines, blade tip cavitation and hub cavitation are frequently observed due to adjustable blade geometry and variable discharge conditions. Transient operations such as load rejection or rapid wicket gate closure can significantly intensify cavitation severity.

In pumped-storage hydropower plants, frequent start-stop cycles and rapid load transitions further increase cavitation-induced fatigue damage.

Cavitation Types in Francis Turbines

Cavitation in Francis turbines can occur in several distinct forms depending on operating conditions, blade geometry, and flow characteristics. Accurate identification of these cavitation types is essential to predict erosion, vibration, efficiency losses, and long-term structural degradation [37].

— Trailing Edge Cavitation

Trailing edge cavitation develops near the blade trailing edges, typically under off- design or partial-load conditions. Cavitation bubbles collapse downstream, often within the draft tube region. When confined to the trailing edge, damage is generally limited [38]. However, if the cavitating zone extends upstream toward the mid-chord region, erosion intensity and vibration levels increase significantly.

— Draft Tube Swirl Cavitation

This type forms within the low-pressure core of a helical vortex structure in the draft tube. It is primarily associated with residual swirl leaving runner under partial-load operation [38]. The precessing vortex rope generates periodic pressure pulsations, and structural vibrations reducing hydraulic efficiency. Mitigation strategies include draft tube geometry optimization, installation of anti-swirl fins, or controlled air injection to stabilize the vortex core.

— Leading-Edge Cavitation

Leading-edge cavitation occurs on the suction side near the blade inlet, especially under high-head conditions or large incidence-angles. Vapor bubbles formed in this region collapse violently, producing high-pressure shock waves that can cause severe surface erosion, vibration, and acoustic emissions. This form is considered one of the most erosive cavitation forms in Francis turbines.

— Inter-Blade Vortex Cavitation

Secondary vortices formed between adjacent runner blades can induce cavitation when flow separation occurs. These vortical structures can intermittently contact blade surfaces, causing localized erosion and unsteady loading. Although generally less destructive than leading-edge cavitation, inter-blade cavitation can become significant under unstable or high-head operating regimes.

— Traveling Bubble Cavitation

Traveling bubble cavitation appears as discrete vapor bubbles along the suction side, typically near the mid-chord or trailing edge. Bubble size and population increase with load and may peak under overload flow conditions. The collapse of these bubbles produce noise, pressure pulsations, and progressive surface damage, negatively affecting turbine reliability and performance.

Wang X et al. demonstrated that in the vaneless space of reversible pump-turbines, pressure pulsations can reach amplitudes significantly above baseline levels, indicating strong interaction between unsteady vortical structures and local pressure fields [39]. Wang T et al. extended this understanding to variable-speed Francis turbines, showing that pronounced draft tube vortex ropes form under partial load and generate large low-frequency pressure pulsations, consistent with trends observed in other studies where the vortex rope is most intense at 0.7–0.9 BEP of discharge [40]. Cheng H et al. quantified vortex rope strength, finding that an obvious vortex rope at 88 % of QBEP generates the highest periodic pressure fluctuation at the vortex rotation frequency f_v, while conditions farther from this operating point reduce both vortex coherence and pressure amplitude. Such vortex ropes produce a central low-pressure core susceptible to cavitation, as described by broader hydroturbine studies where negative pressures in the draft tube vortex core lead to cavity formation and erosion [41].

Cavitation in Pelton Turbines

In Pelton-type turbines, the buckets are exposed not only to cavitation but also to mechanical erosion mechanisms. Because water jets impinge on the bucket surface at very high velocities, abrasive wear due to suspended particles (silt erosion) is frequently observed. In addition to sediment-induced erosion, unstable interaction between the jet and the bucket surface may generate localized pressure drops, triggering cavitation. Inadequate bucket geometry or improper discharge angles can further intensify vapor formation.

For this reason, numerous experimental and computational studies have focused on optimizing Pelton bucket profiles to minimize cavitation susceptibility and erosion damage. Previous investigations have identified several characteristic erosion and cavitation regions on the bucket surface. These regions are generally associated with jet impact zones, flow separation areas caused by surface imperfections, secondary vortex formation, and improper outlet flow angles. In certain regions, damage may result from the combined effects of rain erosion and cavitation. Such spatial classification of cavitation zones provides valuable guidance for improving bucket geometry and operational stability.

▦ Cavitation in Propeller (Kaplan-Type) Turbines

Cavitation behavior in propeller-type turbines, including Kaplan turbines, strongly depends on operating conditions such as discharge factor and rotational speed. Similar to Francis turbines, different operating regimes correspond to distinct cavitation modes.

Under high-discharge conditions, cavitation may develop on the suction side of the blade due to local pressure reduction. In other operating ranges, vortex formation in the draft tube can occur, resembling the swirl cavitation observed in Francis turbines [38]. At certain blade incidence angles, leading-edge cavitation may form, while under different conditions cavitation may appear on the pressure side of the blade. Proper blade design and optimized incidence angles can significantly reduce the likelihood of these latter two cavitation types.

During partial-load operation, blade angle adjustments reduce the circumferential velocity component of the flow. As a result, draft tube swirl cavitation can be mitigated or completely suppressed. However, full-load operation remains critical for Kaplan turbines, as cavitation intensity may increase under these conditions.

One of the most critical cavitation issues in Kaplan turbines is clearance cavitation. Because Kaplan runners are equipped with adjustable blades, they lack a continuous shroud structure. Consequently, a clearance gap exists between the blade tips and the runner chamber. This gap can generate localized high-velocity leakage flows, resulting in pressure drops below vapor pressure and subsequent cavitation.

Clearance-related cavitation is typically categorized into two main forms:

- Tip clearance cavitation, which develops directly within the blade tip gap due to accelerated leakage flow and pressure reduction.
- Tip vortex cavitation, which forms when the leakage jet emerging from the gap rolls up into a vortex as it interacts with the suction side of the blade.

Although tip clearance and tip vortex cavitation generally do not significantly alter the critical cavitation coefficient (σ) or cause major efficiency losses, they may still contribute to localized erosion over time. In contrast, hub cavitation and leading-edge cavitation are considerably more detrimental, as they can induce severe erosion, vibration, and measurable efficiency degradation in Kaplan turbines.

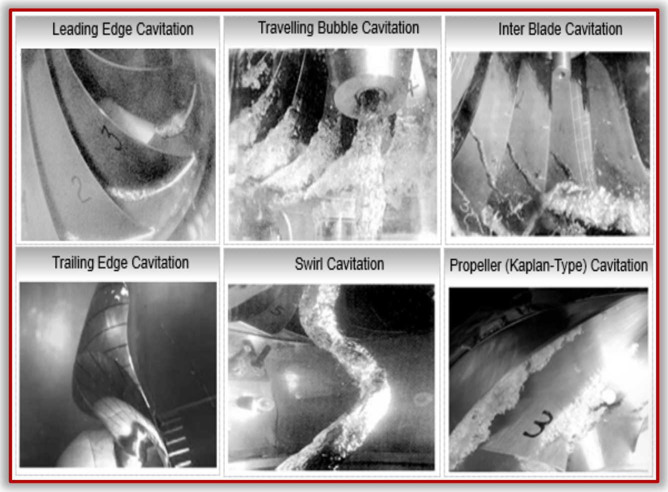

Figure 4. Examples of cavitation types in Francis and Kaplan turbines. Reproduced from [38].

EFFECTS OF CAVİTATİON ON HYDRAULİC TURBİNES

Cavitation significantly affects hydraulic turbine performance, structural integrity, and long-term operational reliability. Its impact is not limited to efficiency losses but extends to vibration, acoustic emission, material degradation, and reduced service life.

— Efficiency Loss

Cavitation disturbs the designed flow pattern within the runner and draft tube. The formation of vapor cavities reduces the effective flow area and alters pressure distribution, leading to hydraulic losses.

In Francis turbines operating under part-load conditions, vortex rope cavitation in the draft tube can cause measurable efficiency reductions. Industrial reports from large hydropower stations indicate efficiency drops of 1-3% during unstable partial-load operation. Although this value may seem small, in a 300 MW unit even a 1% efficiency loss corresponds to several megawatts of power reduction.

In pump-turbines operating in turbine mode, severe cavitation can also shift the best efficiency point (BEP), requiring operational adjustments.

- **Increase in Vibration**

One of the most critical industrial consequences of cavitation is increased vibration levels. The collapse of vapor bubbles produces localized pressure shocks, while vortex rope oscillations generate low-frequency pressure pulsations. The presence of vortex ropes markedly affects turbine dynamics. Zhou et al. reported that these vortices induce low-frequency pressure pulsations often at 0.2-0.4 × runner rotational frequency, which are strongest near partial load regimes, and contribute to significant unit vibration and acoustic noise [42]. Field measurements in high-head Francis units have shown that draft tube swirl cavitation can induce pressure fluctuations with dominant frequencies below 5 Hz. These low-frequency oscillations may resonate with structural components, increasing shaft vibration amplitudes.

In several pumped-storage plants, prolonged part-load operation has been linked to elevated radial bearing vibration levels due to cavitation-induced unsteady loading. Yu observed that vortex-associated pressure fluctuations vary spatially and temporally with operating conditions, reinforcing the importance of flow regime on vibration [43].

- **Noise Emission**

Bubble collapse generates broadband acoustic emissions, particularly in the high-frequency range. In industrial pump stations, cavitation is often first detected through abnormal noise before measurable efficiency degradation occurs.

In Kaplan turbines, tip clearance cavitation produces characteristic high-frequency noise patterns. Acoustic monitoring systems installed in some modern hydropower facilities use this signature to detect early-stage cavitation.

- **Material Erosion**

Cavitation erosion is caused by repeated micro-jet impacts and shock waves generated during bubble collapse near solid surfaces. Over time, this leads to pitting, surface roughening, and material removal.

Industrial inspections of Francis turbine runners frequently reveal severe pitting damage near blade leading edges and trailing edges. In extreme cases, erosion depth can reach several millimeters within a single operational season.

Pelton turbines are additionally exposed to combined silt erosion and cavitation damage, particularly in sediment-laden rivers. Hydropower plants in Himalayan and Alpine regions have reported accelerated bucket wear due to this combined mechanism.

Repair operations typically involve welding, grinding, and protective coating application during scheduled maintenance outages.

DETECTİON AND MONİTORİNG TECHNİQUES

Cavitation detection in hydraulic machinery relies on indirect measurement techniques, as vapor bubble formation is typically not directly observable under industrial operating conditions. Practical monitoring approaches focus on pressure fluctuations, acoustic emissions, vibration signatures, and numerical prediction tools [45-48].

- Pressure sensors installed in the draft tube or casing are commonly used to detect low-frequency oscillations associated with vortex rope cavitation. Industrial hydropower plants often monitor pressure pulsation amplitudes as an early-warning indicator of unstable operation.
- Acoustic emission methods are effective in identifying high-frequency noise generated by bubble collapse. These systems are particularly useful in pump stations where direct visual access is not possible.
- Vibration analysis is widely implemented in rotating machinery condition monitoring systems. Cavitation-induced unsteady loading increases broadband vibration energy, especially in part-load regimes.
- High-speed visualization techniques are mainly used in laboratory environments to investigate cavitation morphology. Although not practical for industrial units, they provide validation data for predictive models.

Finally, CFD-based cavitation modeling has become an essential design-stage tool. Modern multiphase models allow estimation of vapor volume fraction, pressure distribution, and erosion-prone zones before prototype manufacturing.

MİTİGATİON AND PREVENTİON STRATEGİES

Effective cavitation mitigation requires an integrated approach combining hydraulic design optimization and operational control.

- Proper pump/turbine selection is the first preventive step. Operating a machine outside its best efficiency point significantly increases cavitation risk. Therefore, matching design head and discharge conditions with actual site requirements is critical.
- Maintaining an adequate NPSH safety margin in pump systems prevents pressure from dropping below vapor pressure. Industrial practice typically includes conservative design margins to account for temperature variations and transient effects.
- Geometric optimization, including blade profile refinement, leading-edge curvature control, and draft tube shape modification, reduces flow separation and local pressure minima. Advanced CFD simulations are increasingly used to identify cavitation-prone zones during the design phase.
- Surface engineering solutions, such as hard

coatings (e.g., HVOF coatings, stainless overlays), improve erosion resistance. These are widely applied in hydropower rehabilitation projects.

Finally, operational parameter control plays a decisive role. Avoiding prolonged part-load operation, minimizing rapid load rejection events, and implementing controlled air injection in draft tubes are practical mitigation strategies used in modern hydropower plants.

CAVİTATİON İN WATER SUPPLY AND TREATMENT SYSTEMS

Cavitation phenomena are not only critical in traditional hydraulic machinery such as pumps and turbines but also play an increasingly important role in water supply and treatment systems. Unintended cavitation in pumping applications can significantly reduce system performance by disrupting flow continuity, lowering discharge pressure, and inducing vibration and noise, potentially leading to premature component wear and failure. These detrimental effects occur when local pressures drop below the fluid's vapor pressure, creating vapor cavities that implode downstream and erode pump surfaces if not properly managed, which is a key concern in municipal and industrial water distribution systems.

- Unintended Cavitation in Pumping Systems. In water pumping networks, cavitation is commonly triggered by insufficient suction head, rapid pressure drops, or design issues such as long suction lines and sharp bends. When cavitation occurs, vapor bubbles disrupt smooth flow, leading to reduced efficiency, increased energy consumption, and elevated maintenance requirements. These effects underscore the importance of design considerations that ensure adequate Net Positive Suction Head (NPSH) and stable operating conditions for pumps in water supply infrastructure.
- Controlled Hydrodynamic Cavitation for Water Treatment. In contrast to its destructive role in pumping systems, controlled hydrodynamic cavitation (HC) has emerged as an effective technique for water and wastewater treatment. Hydrodynamic cavitation generates intense local pressures and temperatures upon bubble collapse, producing oxidative radicals and mechanical shear that can degrade contaminants and inactivate microorganisms without requiring chemical additives. Reviews in the literature highlight that HC, alone or coupled with advanced oxidation processes, can significantly enhance removal of organic pollutants and chlorophyll a from water, with operating parameters such as cavitation pressure and retention time critically affecting treatment efficiency. For example, Patil et al. investigated the effectiveness of hydrodynamic cavitation for seawater treatment, comparing various water quality parameters before and after the process. The study reported that hydrodynamic cavitation achieved the highest reduction in turbidity (100%), substantial reduction in total suspended solids (TSS: 83.86%), and minor reduction in sodium ions (Na^+: 8.47%). After treatment, the seawater met the CPCB Water Quality Criteria for classes SW-I to SW-V, making it suitable for diverse uses including bathing, contact water sports, commercial fishing, mariculture, ecologically sensitive zones, aesthetics, harbour navigation, and controlled disposal. The treated water had a SAR value of 1.72, indicating suitability for all soil types and crops, and a WQI of 65, corresponding to fair quality appropriate for industrial and irrigation purposes. Furthermore, recycling the treated seawater for an additional 24 hours improved water quality even further, demonstrating the potential of hydrodynamic cavitation for sustainable water reuse.

Taken together, these perspectives illustrate how cavitation can be both a harmful phenomenon in water pumping systems and a useful tool in water treatment applications. Bridging traditional hydrodynamic knowledge with innovative cavitation engineering enables the design of more resilient water infrastructure and environmentally sustainable treatment technologies.

CONCLUSİONS

Cavitation in hydraulic machines remains a critical phenomenon influencing efficiency, structural integrity, and operational reliability. In this review, fundamental mechanisms of cavitation, including pressure drop, vapor bubble formation, NPSH limitations, bubble growth and collapse, and micro-jet formation, were systematically discussed. The analysis demonstrates that cavitation is not only dependent on local pressure conditions but also significantly influenced by flow instabilities such as vortex rope formation and draft tube turbulence in Francis turbines.

Experimental and numerical studies have shown that partial-load operations and guide vane deviations exacerbate vortex-induced pressure pulsations, leading to increased vibration, noise, and potential material erosion. Moreover, the interaction between cavitation and hydrodynamic instabilities can amplify structural stresses and reduce turbine performance. Detection and monitoring techniques, including pressure sensors and flow visualization, provide valuable tools for identifying early cavitation and associated instabilities.

Mitigation strategies such as draft tube modifications, damping devices, and optimized runner design have been demonstrated to reduce cavitation severity and its adverse effects. However, the effectiveness of these strategies is highly dependent on turbine type, operating conditions, and local flow structures.

In conclusion, a comprehensive understanding of cavitation mechanisms, coupled with detailed monitoring and targeted mitigation, is essential for enhancing the performance, reliability, and longevity of hydraulic turbines. Future research should focus on integrating advanced numerical simulations with experimental validations to optimize turbine designs and control strategies under a wide range of operational conditions.

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