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Hydrodynamic Cavitation: Principles, Applications, and Challenges in Wastewater Treatment

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***Abstract*— Refractory and recalcitrant contaminants are typically found in industrial wastewater and are challenging to eliminate using standard physical, chemical, and biological methods. Because HC may produce a locally intense system with high levels of temperature, pressure, and reactive radicals, it has been one of the most promising AOPs in recent decades. Complex contaminants in sewage may oxidize as a result of vapor bubbles collapsing in a liquid. This paper has covered the fundamentals of HC in great detail, including reactor components, cavitation mechanisms, and the chemical reaction pathways involved in HC. A comprehensive review has also been carried out relating to practical applications of HC in the treatment of wastewater of some industrial processes in terms of advancements achieved in reducing toxicity removal of color and reduction of chemical oxygen demands. Additionally, the synergistic effects of HC in the presence of oxidizing agents such as ozone and hydrogen peroxide, that shown a significant increase in treatment efficiencies, are discussed. Hydrodynamic cavitation is offered as a sustainable, energy-efficient, and very promising technique for advanced industrial wastewater treatment, despite current issues with reactor erosion, scale-up restrictions, and regulation of cavitation intensity.**

***Index Terms*— Hydrodynamic Cavitation, Wastewater Treatment, COD Reduction.**

I. INTRODUCTION

Large volumes of wastewater contaminated with complex, persistent pollutants, including dyes, medications, pesticides, and phenolic compounds, are constantly produced as a result of the fast industrialization and urbanization processes. However, due to their stability and poor biodegradability, all traditional wastewater treatment techniques, including biological, chemical, and physical ones, frequently fail to fully eliminate these pollutants, which exacerbates secondary pollution and raises operational costs. Because Advanced Oxidation Processes (AOPs) are based on the generation of highly reactive hydroxyl radicals (•OH), which can mineralize organic contaminants into innocuous end products like CO2 and H2O, they have become viable solutions in this regard [1]. Hydrodynamic Cavitation (HC) is one of the AOPs that has drawn the most interest as an economical, energy-efficient, and sustainable method of treating wastewater. When a liquid flows through a constriction device such as an orifice plate, venturi tube, or rotor-stator assembly, local pressure drops below the liquid's vapor pressure, resulting in hydrodynamic cavitation. This causes the creation of microbubbles and their subsequent collapse.

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During the collapse of the bubbles, extreme conditions are established locally, such as temperatures of 5000 K and pressures of 1000 atmospheres, and hydroxyl radicals and other reactive oxygen species that break down organic pollutants [2]. The mechanism of pollutant degradation by HC is a combination of physical, chemical, and thermal processes. Further, even though the thermal and chemical effects of bubble collapse produce reactive radicals responsible for oxidation processes, mechanical shear and micro-jet impacts also contribute to the disintegration of suspended materials and microbial cell walls[3]. The process can be used separately and also combined with other AOPs, such as the addition of hydrogen peroxide, ozonation, the Fenton oxidation process, and photocatalysis, which significantly improves efficiency due to synergistic effects[4]. Many studies have shown that HC has been effectively used to degrade wastewater from textile colors, petrochemical effluents, and distillery waste wash. This makes hydrodynamic cavitation an environmentally friendly approach for industrial wastewater treatment because of its key advantages: low chemical consumption, easy scale-up, and minimal amount of sludge produced. Nevertheless, there are many pending issues to be resolved for practical applications involving cavitation erosion, optimization of reactor design, and energy efficiency. Continuous research is being performed, mainly to optimize the shape of the cavitating device, operating flow conditions, and hybridizing HC with renewable energy-driven AOPs to further improve the overall performance and sustainability of the technique. Hydrodynamic cavitation, hence, happens to be one of the most innovative, eco-friendly oxidation techniques with huge potential for the efficient and sustainable treatment of industrial wastewater [5].

II. Cavitation

Cavitation normally occurs when the pressure in a liquid is reduced to a level below its vapor pressure, allowing the formation, growth, and subsequent collapse of vapor-filled bubbles or cavities. In most cases, it is induced by high-velocity flow of fluid through narrow passages such as orifices, venturi tubes, or on pump impeller blades. It can also be stimulated by the action of strong acoustic excitation, such as ultrasonic irradiation. The three primary phases of this process are the nucleation of microbubbles on active sites, such as contaminants or trapped gases; the growth of these bubbles in low-pressure areas; and the dramatic collapse that occurs when these bubbles re-enter higher-pressure areas. Extreme microenvironmental conditions, including temperatures exceeding 5000 K, pressures above 1000 atm, high shear forces, and shock waves, are produced by the implosive collapse of these bubbles and can encourage a wide range of physical and chemical processes. Uncontrolled cavitation is a critical technological challenge because it results in material erosion and early failure of hydrodynamic devices such as pumps, turbines, and marine propeller systems[2]. On the other hand, hydrodynamic and acoustic cavitation can be harnessed to develop efficacious applications for different sectors such as food processing, purification and disinfection applications, disinfection and sludge disintegration, emulsification and bioactive compound extraction, and medical applications such as lithotripsy procedures. Water molecules are broken down into extremely active hydroxyl radicals, or •OH, when the bubbles burst. This leads to sophisticated oxidation processes that reduce organic contaminants to simpler and less dangerous species. Stronger cavitation and more violent bubble activity are indicated by low values of the dimensionless cavitation number, σ. According to recent studies, controlled cavitation offers a novel, energy-efficient, and ecologically friendly chemical processing and environmental remediation platform. As a result, it may be a highly sought-after substitute for sustainable treatment methods [3].

III. Types of Cavitation

Cavitation is a very beneficial phenomenon in wastewater treatment and process intensification since these quick pressure oscillations induce it, and understanding the wide varieties of cavitation is required due to these consequences. Figure 1 shows different types of cavitation.

There are two broad types of cavitation: tension-driven and energy deposition cavitation. Of the models based on tension-driven cavitation, acoustic cavitation and hydrodynamic cavitation are relatively novel and useful methods for wastewater treatment. As a result of the collapse of the cavitation bubbles, the temperatures and pressures of the environment increase tremendously, and the resulting shear stress enhances the degradation of pollutants, enhances mass transfer, and also helps in the formation of oxidative radicals that oxidize recalcitrant organic substances in the wastewater. Acoustic cavitation has the advantages of better control and faster degradation, whereas the hydrodynamic process is more energy-efficient [4].

Optical cavitation and particle cavitation are important subfields of advanced material processing and cleaning, and both are energy-based. Optical cavitation takes place when an intense laser beam is directed at a substance.

As such, optical cavitation can be viewed as the process that makes it possible to target material locations where energy is needed. In addition, when there is an interaction between solid particles and fluid flow, particle cavitation can occur. The process of particle cavitation can be seen as an enhancement of cavitation to accelerate oxidation and decompose organic materials faster. Combining these several cavitation techniques can improve overall process efficiency and offer very attractive prospects for novel environmental cleanup technologies and large-scale commercial applications [5]. In this paper, we are mainly focusing on hydrodynamic and Acoustic cavitation as they are used for the treatment of wastewater.

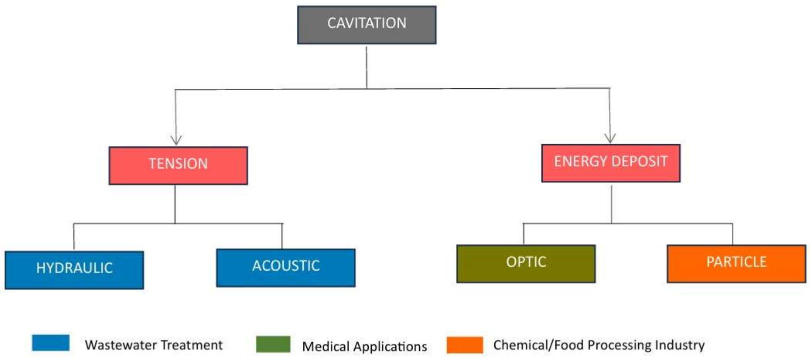

Figure 1. Types of Cavitation

A. Hydrodynamic Cavitation

The process known as hydrodynamic cavitation happens when a liquid passes through an area of abrupt pressure drop, vaporizing and producing tiny vapor bubbles. Figure 2 demonstrates Hydrodynamic cavitation. These bubbles burst violently when they reach an area of higher pressure, unleashing powerful energy in the form of micro-jets, shock waves, and concentrated high pressures and temperatures [6]. Or in other words, cavitation is a phenomenon where vapor bubbles form, grow, and then abruptly collapse as a result of rapid pressure changes in a liquid, typically brought on by high-velocity flow, obstacles, valves, or pumps. Controlled cavitation has been used more and more in industrial and environmental processes, but uncontrolled cavitation is undesirable in hydrodynamic gear because it results in erosion, noise, vibration, and loss of efficiency. For example, it has been shown that hydrodynamic cavitation pretreatment greatly boosts the amount of methane produced from lignocellulosic feedstocks, such as wheat straw, increasing the efficiency of producing renewable energy [7] [8].

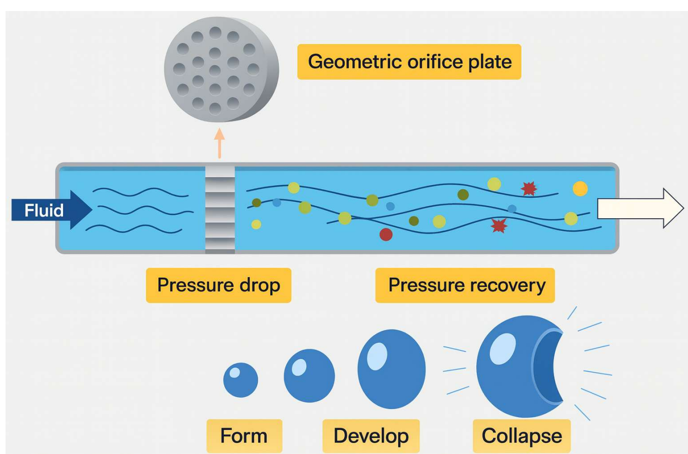

Figure 2. Hydrodynamic Cavitation [9]

Research has demonstrated its efficacy in pretreatment of biomass to increase the yields of biogas production, emulsification and microbial cell disruption for biotechnological applications, and wastewater treatment for lowering organic load and heavy metals [10]. Table 1 presents the changes in wastewater properties following hydrodynamic cavitation treatment.

TABLE I. HYDRODYNAMIC CAVITATION TREATMENT OF VARIOUS WASTEWATERS

Sr. No.	Type of wastewater	Treatment type	Conditions	Findings	References
1	Distillery wastewater (biomethanated)	HC	Inlet pressure: 5 bar 5 passes	Reduced in COD by 28%, TOC by 15%, and color by 40%, while increasing soluble COD by 30%	[11]
2	Distillery vinasse (spent wash)	Vortex-based HC	Mode of operation- Continuous recirculation system Inlet pressure range- 2–6 bar	Increased soluble COD by 30%, reduced color by 40%, and decreased total COD by 20%, while improving methane yield by 25%	[12]
3	Industrial effluents (mixed organics)	HC / HC + AOPs	Inlet pressure: 3–6 bar Flow velocity at throat: High enough to ensure cavitation number < 1 Number of passes: 3–5 passes	HC 35% COD removal, while hybrid HC + oxidant systems 70% COD reduction and 80% removal of recalcitrant organics	[13]
4	Waste-activated sludge	HC	Optimal pressure: 3–5 bar Passes studied: 1–5 passes	Increased sludge solubilization by 35%, reduced particle size by 50%, and improved dewaterability by 30%	[14]
5	Cooking wastewater	HC + Fenton oxidation	Operating mode: Continuous flow with recirculation Inlet pressure: 0.3–0.6 MPa (3–6 bar) Number of passes:4	Reduced COD by 30%, while the hybrid HC + Fenton process achieved 70% COD reduction, along with 85% phenolic removal and 45% TOC reduction	[15]
6	Refinery wastewater	HC	Inlet pressure: 1–3 bar Number of passes: 2–4 passes Equivalent treatment time: 10–30 minutes	55% COD reduction, 70% pollutant removal, 40% TOC reduction, and 70% pathogen removal	[16]

B. Acoustic Cavitation

When high-intensity ultrasonic waves travel through a liquid, they produce alternating cycles of compression and rarefaction, which cause small bubbles to develop, grow, and violently collapse. This phenomenon is known as acoustic cavitation. Figure 3 demonstrates Acoustic cavitation. Usually starting around dissolved gases or other contaminants in the liquid, these bubbles grow throughout rarefaction cycles before popping under compression. Extreme localized circumstances are created when these bubbles implode, including shock waves, micro-jets, chemically active free radicals like hydroxyl radicals, and temperatures as high as 5000 K and pressures as high as 1000 atm. [17]. Acoustic cavitation's strong physical and chemical properties make it extremely beneficial in a variety of industries, including the food and beverage industry for microbial inactivation and homogenization, the energy and environmental sectors for biomass pretreatment and improving biogas production, the medical field for therapeutic ultrasound, drug delivery, and lithotripsy, and the water and wastewater treatment industry for breaking down persistent pollutants. Acoustic cavitation can be advantageous when managed, because of its extremely damaging localized stresses, it can also harm equipment [18].

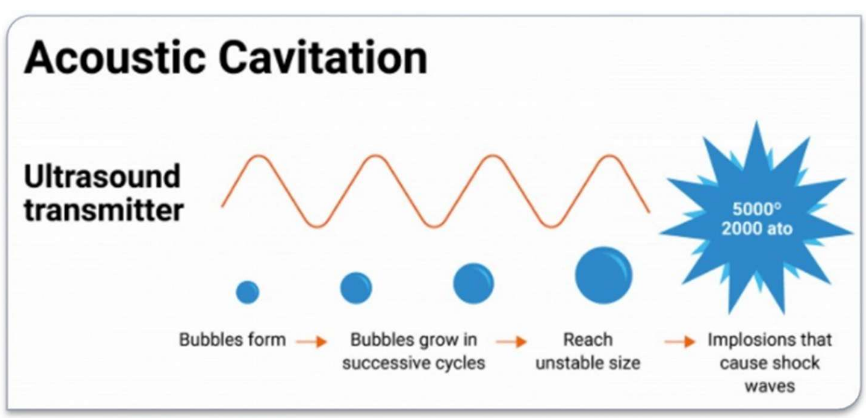

Figure 3. Acoustic Cavitation [19]

IV. APPLICATION OF HYDRODYNAMIC CAVITATION

A. Hydrodynamic Cavitation Induced Decomposition/Degradation Reactions

In addition to producing extremely reactive species, hydrodynamic cavitation can enhance chemical reactions by creating harsh circumstances. The massive implosion and shear forces created when vapour bubbles collapse give enough energy to thermally break down organic contaminants or break molecular bonds, which can satisfy the need to break down macromolecules and eliminate microbes [20][21]. Rajoriya et al [21][22] identified the rhodamine 6G degradation process, which was brought on by OH· radical assault. By adding tert-butanol and using hydrodynamic cavitation, the researchers discovered that tert-butanol could neutralize OH· radicals to create the less reactive tert-butanol radical, which slowed down the rate of deterioration. The findings showed that OH· radicals were the primary cause of the degrading efficiency and the rate-limiting factor. Hydrodynamic cavitation (HC) mainly uses a mix of mechanical, thermal, and chemical processes to cause disintegration and degradation reactions in wastewater. Localized hot spots with extremely high temperatures and pressure are created when vapour bubbles develop and violently collapse when liquid is driven through a constriction, like a venturi or orifice. Reactive species like hydrogen and hydroxyl radicals (•OH) are created when water molecules collapse, and these radicals are very good in oxidizing and decomposing complex organic pollutants. Shockwaves, shear forces, and microjets mechanically break up suspended particles, sludge flocs, and microbial cells, improving solubilization and biodegradability, while the extreme heat inside the bubbles causes volatile chemicals to thermally decompose in addition to radical oxidation [23]. Alongside radical oxidation, the extreme heat causes the volatile compounds inside the bubbles to thermally decompose, while shockwaves, shear forces, and microjets mechanically break up microbial cells, sludge flocs, and suspended particles, improving solubilization and biodegradability. HC and its combinations have demonstrated notable COD, color, toxicity, and microbial load reduction efficiency. Pollutant mineralization is further enhanced by hybrid arrangements, such as coupling HC with ozone, hydrogen peroxide, or photocatalysts. Recent research shows that HC has the ability to break down dyes, phenols, medications, and micropollutants found in wastewater, despite concerns about energy efficiency and scale-up. As a result, hydrodynamic cavitation has become a practical, eco-friendly pretreatment or polishing stage in integrated wastewater treatment systems. Figure 4 shows a schematic representation of organic degradation by hydrodynamic cavitation [24].

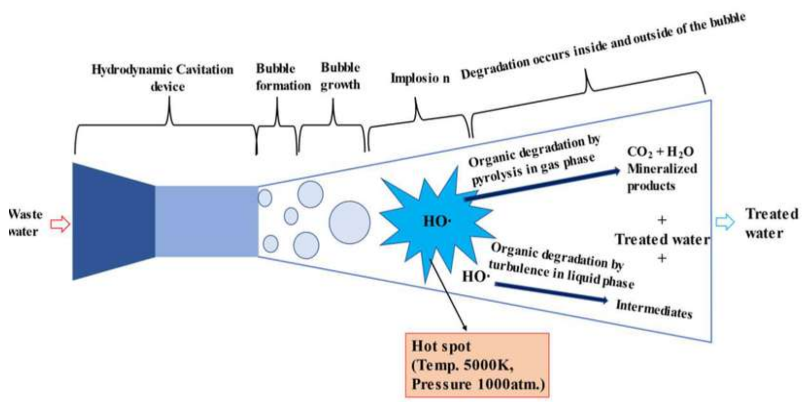

Figure 4. Schematic representation of organic degradation by hydrodynamic cavitation [25].

B. Application of Hydrodynamic Cavitation in Extraction/Emulsification

The mechanical action of cavitation can considerably improve interfacial interactions between the liquid and gas phases. In fact, the sudden collapse of cavitation bubbles can produce turbulent microjets and extremely high temperatures and pressures in their immediate vicinity, which can cause some noticeable structural and mechanical changes in the host fluid. HCRs significantly reduce the interphase mass transfer constraints by sustaining large interfacial areas and microscale turbulence through the continuous production and implosive collapse of many oscillating bubbles. These special physicochemical conditions have made it possible to successfully use HCRs in a variety of process intensification scenarios, as well as the extraction of bioactive substances [21]. Due to the strong physical and chemical consequences that define the bubble collapse, hydrodynamic cavitation is finding more and more uses in extraction and emulsification. In extraction, bubble implosion increases mass transfer and solvent penetration by creating shock waves, microjets, and strong shear forces that break the plant cell walls. It has been demonstrated that hydrodynamic cavitation improves the release of rich bioactive components from natural matrices, including polyphenols, flavonoids, essential oils, and pigments, while reducing extraction time and solvent consumption when compared to other traditional approaches. Hydrodynamic cavitation reduces droplet sizes and increases interfacial surface areas by imposing severe turbulence and shear in the zone of cavitation, resulting in the production of extremely stable, fine oil-water emulsions [26]. The production of free radicals can modify surface-active materials somewhat, improving an emulsion's stability. As a result, HC is particularly helpful in culinary applications where the creation of nano or microemulsions and the efficient extraction of bioactives are greatly desired. When compared to acoustic cavitation, HC is thought to be more energy-efficient, scalable, and ecologically benign, making it one of the potential green technologies for industrial processing. However, careful optimization of reactor design and operational parameters is necessary to achieve optimal efficiency [27]. Figure 5 shows emulsification using Hydrodynamic Cavitation.

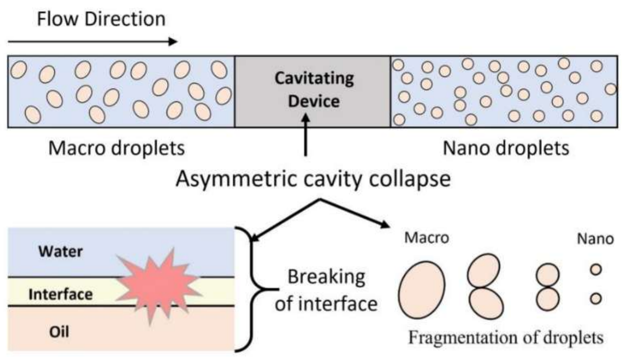

Figure 5. Emulsification using Hydrodynamic Cavitation [28].

C. Application of hydrodynamic cavitation in biodiesel production

Biodiesel is considered a promising substitute for petroleum fuels because it can be easily produced through the transesterification of vegetable oils, non-edible oils, or animal fats with alcohol [29]. Although it plays an important role in the bio-based economy, its production is often constrained by slow reaction rates and poor mass transfer between oil and alcohol. Recently, hydrodynamic cavitation reactors (HCRs) have gained attention for wastewater synthesis, as they enable faster and more efficient continuous production of treated water [30]. Samani et al.[31] evaluated a rotor–stator HCR for energy fuel synthesis using safflower oil and achieved an optimal yield of 88.62% at 60 s, 1% catalyst, and an 8:1 alcohol–oil ratio. In their report, Mohod et al, Innocenzi and Prisciandaro [32] demonstrated that the use of an HCR reduced energy consumption by 40%, while the usage of waste oil resulted in a relative drop in production costs. Similarly, Chuah et al. [33] demonstrated that, in comparison to mechanical stirring, hydrodynamic cavitation enhanced reaction kinetics with a rate constant 7.7 times greater. As a result, hydrodynamic cavitation appears to be a practical and affordable method for producing biodiesel.

V. Challenges and Limitations of Hydrodynamic Cavitation

The process of formation and subsequent drastic breaking-down of micro-bubbles in a flowing liquid due to sudden changes in pressure is called hydrodynamic cavitation. The resultant collapsed micro-bubbles create extreme temperatures and shear-force sites, which are used for mass transfer and formation of reactive compounds. There are many processes based on this phenomenon, such as emulsification, biomass pretreatment, and sewage treatment. Although HC has immense potential for efficiency and energy saving, its adoption is not widespread industrially. This is largely due to concerns about its stability and reliability in terms of its lifespan.

A. Difficulty in achieving stable cavitation intensity

Cavitation and its collapse in HC are affected by the considerations of many interrelated variables, namely temperature, fluid type, flow rate, pressure, and reactor design. Taken collectively, these variables are difficult to master to provide an uninterrupted cavitation process. This is the reason why there is little variation in the result of different systems or the same system under different tests, despite the same operating conditions [34].

B. Challenges in reactor scale-up and design optimization

The designs that are best in the lab environment may not work effectively when transferred to a production setup. As you move from a test setup to a production setup, the effect of fluid flow and cavitation, where the fluid moves faster, will be evident to you. This is a very important aspect. Scaling becomes difficult and complicated [21].

C. Risk of erosion and material degradation

The collapsing bubbles in hydrodynamic cavitation create strong microjets that pit and abrade reactor walls. Because of their effects, these microjets increase operating costs by necessitating material selection and maintenance [35].

D. Reduced performance in viscous or particulate-rich fluids

High viscosity fluids, heavily filled suspensions, and feeds with diverse compositions complicate the nucleation process and lessen the collapse intensity in hydrodynamic cavitation (HC). As a result, HC will use more energy and be less effective [6].

E. Incomplete understanding of cavitation mechanisms

The fundamental features of hydrodynamic cavitation are still unknown, including the bubble phenomena, the production of radicals, and the way turbulence interacts with the process. In order to help design reactors and modify the settings to control the process, not much is done [36].

F. Dependence on combined or hybrid treatment methods

In numerous applications, standalone hydrodynamic cavitation (HC) fails to attain sufficient degradation, pretreatment efficacy, or pollutant elimination. Integration with oxidants, chemical agents, or complementary advanced processes becomes necessary, thereby elevating system complexity and operational expenditures [37].

G. Formation of unwanted by-products

Hydrodynamic cavitation can occasionally create unwanted intermediates or interfere with later treatment procedures. For example, improper cavitation conditions might make some wastewaters less biodegradable or lead to the production of potentially hazardous chemicals [38].

H. Economic and operational barriers in full-scale systems

The hydrodynamic cavitation principle in HC reactors is simple, and there are no complex designs. However, there are extra costs related to the utilization of pumps and recirculation systems when HC is used on a wide scale. Furthermore, achieving stability is an issue that prevents HC from being widely used in commerce [39].

VI. Conclusion

Hydrodynamic cavitation (HC) is one of the most novel oxidation processes being developed to remove persistent contaminants from wastewater. HC enhances biodegradability and increases lightning and pollutant decomposition by generating radicals through the induction of high localized concentrations. When used alone or in conjunction with other oxidation agents, HC is very beneficial. Research and development studies are gradually increasing their application as an efficient and sustainable technology in controlling wastewater in industries, despite the fact that energy efficiency, cavitation mechanism, and reactor materials are considered as factors. Hydrodynamic Cavitation is one of the most modern oxidation processes being developed for the removal of persistent contaminants from wastewater. Cavitation can improve wastewater biodegradability by employing highly reactive species, resulting in faster pollutant degradation. Cavitation, when used alone or in combination with other oxidation procedures, has a significant impact on treatment capacity. Cavitation has been shown to improve mass transfer and break down difficult to degrade organics. Although existing limitations include a lack of energy efficiency, adequate process mechanisms, and material durability, research is focused on improving the design. As a result, an increasing number of studies see cavitation as a potential and efficient technology for managing industrial wastewater.

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