Comparing Several Orifice Flange Shapes for Hydrodynamic Cavitation Treatment and COD Reduction in Textile Wastewater

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ABSTRACT

Textile industry wastewater contains potentially harmful metals, such as nickel and copper, and has a high Chemical Oxygen Demand (COD). This study investigated the use of hydrodynamic cavitation to reduce COD and color levels in textile wastewater using various orifice plate designs, including 1-star, 1-circular hole, 5-star, and 5-circular hole patterns, combined with two orifice plates in succession. The results showed that the 1- and 5-circular hole arrangements led to significant reductions in COD (78% for 5-circular hole and 65% for 1-circular hole) and color (27% for 5-circular hole and 25% for 1-circular hole). The 1-star pattern design reduced COD by up to 79% and color by 33%, whereas the 5-star pattern design reduced COD by up to 60% and color by 20%. The study concluded that the most effective orifice plate for eliminating COD from textile wastewater is a combination of an 1-star pattern and a 5-circular pattern design. These findings demonstrate the potential of hydrodynamic cavitation as an effective method for reducing harmful pollutants in textile industry effluents.

Keywords-wastewater; cavitation bubble; orifice pattern; turbulence; piping design; chemical oxygen demand; biochemical oxygen demand

I. INTRODUCTION

Cavitation is the process of forming, expanding, and periodically bursting tiny bubbles within a short amount of time. This process creates incredibly advantageous conditions for the reduction or elimination of contaminants. In environmental protection technologies, cavitation effects are beneficial in enabling chemical reactions, particularly when these reactions include the breakdown of chemicals that pose a serious risk to the environment and human health. This particularly applies to technologies involving the application of cavitation in environmental protection.

Hydrodynamic cavitation [1, 2] is the process of cavitation bubble formation, growth, and collapse in a liquid when the local pressure of the fluid is lower than the saturated vapor pressure. Hydrodynamic cavitation is similar to acoustic cavitation in that it can occur in a variety of ways, each with its own unique features and methods. Hydrodynamic cavitation has been shown to be a highly successful technique for reducing Chemical Oxygen Demand (COD) and purifying wastewater by introducing an orifice plate in the line of flow [3]. An orifice plate is a critical tool in the field of fluid dynamics for quantifying and regulating the flow of different fluids, such as air, water, and other liquids, inside conduits, and tubing systems [4]. Cavitation nuclei in water begin to grow when the pressure falls below the local saturated vapor pressure and their internal pressure is greater than the surface tension. Thus, the growing nuclei become unstable and burst when the flow pressure recovers [5]. A simple but effective method for producing cavitating conditions involves the use of an aperture plate in a cavitation device [6].

Basic pollutant degradation mechanisms, bubble dynamics models including chemical reactions, and cavitation reactor pressure distribution modeling are all subjects of ongoing theoretical investigations [7]. In [8], a method was developed to boost reaction rates using a setup that incorporates hydrodynamic cavitation. Hydrodynamically created cavities are expected to operate in stable cavitation mode to provide the necessary sonochemical effects. However, it is difficult to provide reliable operational and design solutions. This is particularly true for sonochemical reactors that use ultrasonic irradiation, as the cavitation activity of these reactors has a particularly clear dynamic nature. In a novel form of hydrodynamic cavitation reactor, the converging-diverging nozzle is proposed as the pressure variation. HC's impacts on several model compounds for dissolved organic matter required to drive the radial motion of the cavitation bubbles were examined [9]. To achieve the maximum feasible amount of mineralization, a variety of operational parameters related to the latter, as assessed by the total organic carbon content, were investigated [10].

Many chemical reductions that may occur when various types of industrial water experience hydrodynamic cavitation are discussed in this section. Moreover, the COD of the industrial wastewater was decreased in several studies by using orifice plates. The present study focuses on rotor generators of hydrodynamic cavitation, which have garnered significant interest owing to their promising outcomes and wide applicability [11]. Hydrodynamic cavitation is a fluid-dynamic technique used in the textile industry to clean wastewater because it produces vapor-filled holes that quickly close [12]. Although the process of eliminating impurities and altering dissolved organic matter has seldom been observed, the use of ozone in conjunction with hydrodynamic cavitation has generated significant interest in improving wastewater treatment [13]. This study employed hydrodynamic cavitation to reduce COD concentrations by utilizing an aperture plate with a single 1.5-mm-diameter hole. The sample was compressed at two, three, four, five, and six bars for 30, 60, 90, 120, and 180 min, respectively [14]. An orifice device, which consists of different-sized orifice plates mounted on a flange and a centrifugal pump to enable water flow, is the main component associated with hydrodynamic cavitation. authors in [15] concluded that hydrodynamic cavitation is a type of oscillation device used for wastewater treatment. Hydrodynamic cavitation, in combination with other cutting-edge oxidation techniques (such as H_2, O_2, and plasma), is used to break down Rhodamine B dye. This procedure has the potential to significantly increase the overall degradation efficiency [16]. A study of the cavitation-generating process revealed the existence of significant chemical and physical effects [17]. Hydrodynamic cavitation causes concentrated hot patches, the release of highly reactive free radicals, and increased mass transfer rates because of the turbulence produced by liquid circulation currents [18].

The optimal orifice plate, which is to be used as a cavitating device is determined by several criteria, including pH, reactor temperature, and operating pressure. This study utilized a new pipe design and introduced orifices with varied patterns, such as stars and circulars, to reduce the COD and color of textile wastewater. The 1 and 5-circular hole configurations were employed, which significantly reduced COD by 78% and color by 27% for the 5-circular hole and 65% COD and 25% color for the 1-circular hole. While a 5-star pattern design can decrease COD by up to 60% and color by 20%, an aperture plate with an 1-star pattern design can reduce COD by up to 79% and color by 33%. These findings indicate that the most effective orifice plate for removing COD from textile wastewater was a star design with an 1-star pattern and a 5-circular pattern.

II. MATERIALS

This project involved connecting two Orifice Polyvinyl Chloride (PVC) plates in series using PVC pipes. In the proposed configuration an 8 mm plate with an 1- or 5-star orifice was connected in series to a similar plate with one or five circular holes. All materials were purchased from Aroma Treaders, GIDC, and Ankleshwar, including the elbow, reducer, 2.5-radius pipe, nipple, fitting plate, and nut bolt for fitting the orifice with the flange.

The orifice plate with one hole and five holes is depicted in Figure 1. The diameter of the circular hole was 8 mm. Figure 2 shows definite star patterns with one and five stars. The all-star edges had a 360 °angle. Furthermore, the distribution of the five evenly spaced holes in the orifice plate is shown in the last image.

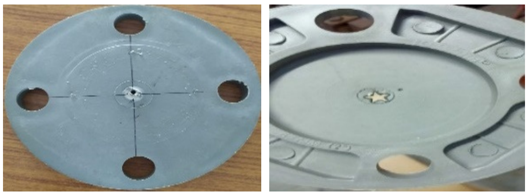

Fig. 1. Orifice plate with one circular or star-shaped orifice.

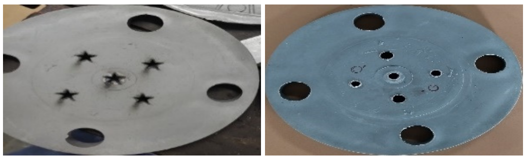

Fig. 2. Orifice plate with five circular star-shaped orifices.

III. METHOD

A. Experimental Set up

Figure 3 depicts the orifice flanges connected to the pipe section. The orifice flanges were connected in series, and a valve was connected at the end of the pipe section to manipulate the flow. The orifice plates were replaced successively by assembling various combinations. The pipe with orifice plates was attached to a square tank, as evidenced in Figure 4.

Fig. 3. Two Orifice flanges were connected in series with different orifice-plate patterns.

Fig. 4. The complete experimental setup.

Industrial water was introduced into the tank to a predetermined level. Subsequently, the pump was activated from the suction side by drawing water through the orifice flange setup. As the water passed through the orifices of the plate, a cavitation was formed downstream. Consequently, the collapse of the bubbles reduced COD. The reduction efficiency may range from 30% to over 90% depending on various factors, including the degree of cavitation, exposure duration, water properties, and initial COD concentration.

B. Piping Design

Several critical factors influence piping design and ensure safety, efficiency, and adherence to industry standards. The following section outlines the key considerations that typically shape the design of pipe systems:

1) Fluid Attributes

Type of Fluid: The selection of materials, pipe diameter, and pressure rating is contingent upon the characteristics of the fluid—whether it is a gas, liquid, or slurry. The operating temperature and pressure of the fluid affect the choice of the material and pipe thickness necessary to withstand these conditions without structural failure [19].

2) Required Flow

The required flow rate determines both the pipe diameter and the type of fitting required. Maintaining the velocity within appropriate parameters is crucial, as excessive fluid velocity may result in erosion, noise, and vibration [20].

3) Content Selection

The selection of materials is influenced by environmental factors and corrosiveness of the fluid. In addition, the cost and availability of the materials must be considered. A balance between the material performance and economic feasibility is essential.

4) Mechanical Strain

It is imperative to design piping systems that can withstand internal stresses without rupturing. Such systems must also be capable of accommodating external stresses, including the weight of the pipe itself, fluid, insulation, and potential seismic activity or wind forces. The physical configuration of a facility influences pipe routing, which must be optimized with respect to space utilization, accessibility, and maintenance requirements. The design of piping systems must consider thermal expansion and contraction, which may necessitate the incorporation of expansion loops, couplings, or bellows [20].

5) Maintenance and Inspection

The pipes should be strategically positioned to facilitate ease of maintenance, inspection, and repair. When undertaking the design process, it is imperative to consider the longevity and durability of the materials and components utilized [19].

6) Environmental Considerations

The design should minimize the environmental impact, encompassing fluid leakage, emissions, and waste management. The design of outdoor pipes must consider meteorological variables, such as elevated temperatures, low temperatures, and humidity.

7) *Economic Factors*

Cost efficiency necessitates that the design achieve an equilibrium between initial expenditures and long-term operational and maintenance costs. Optimizing the design is substantial for reducing energy consumption, particularly in the pumping and heating/cooling systems [21]. Figure 5 presents a schematic of the proposed cavitation system.

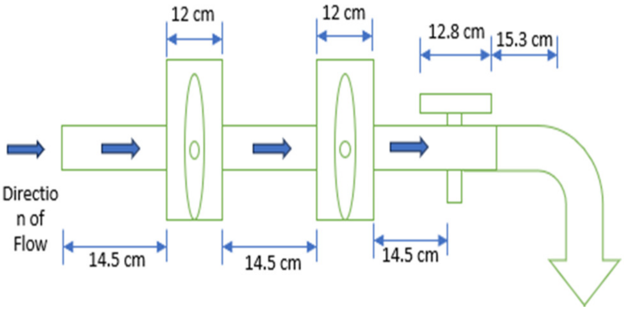

Fig. 5. Design of pipe and orifice.

C. Mechanism

Cavitation refers to the formation of vapor bubbles in a liquid when the local pressure drops below the vapor pressure of the liquid. This phenomenon occurs in areas of rapid pressure change, typically in high-speed fluid flow or around objects that move quickly through a liquid. Propellers frequently suffer from this phenomenon. The rotation of propeller blades generates low-pressure regions on their posterior surfaces. Cavitation bubbles form if this pressure is below the water vapor pressure. These bubbles subsequently collapse upon entering higher-pressure areas, resulting in noise and vibrations, erosion of the propeller surface, and lower propeller efficiency.

Several phenomena result from the collapse of cavitation bubbles, including surface damage from shock waves, which may occur because of the high-amplitude shock waves generated by the sudden collapse. Microjets: The asymmetric collapse of proximate bubbles induces high-velocity microjets to impinge on the surface, causing damage. Shock waves generate intense acoustic emissions. Pitting: Repeated collapse of bubbles and impact from microjet erosion surfaces. Performance degradation: The presence of bubbles diminishes the lift and efficiency. In conclusion, cavitation bubbles originate in low-pressure regions and propagate into high-pressure zones, where they collapse, producing detrimental forces and effects. Cavitation management is a critical component in the design of hydraulic equipment including pumps and propellers.

Various physical and chemical processes, many of which are induced by cavitation, contribute to the reduction in COD in water. The following section enumerates the primary mechanisms involved. Localized high-pressure and intense shockwaves are generated when cavitation bubbles collapse near the solid surfaces. These shockwaves can accelerate the decomposition of organic compounds by destabilizing them, dispersing contaminants more extensively, and fragmenting complex chemical structures. Owing to the exceptionally high pressures and temperatures generated during bubble collapse, a process termed sonolysis occurs upon bubble collapse. During sonolysis, highly reactive hydroxyl radicals (OH•) are produced as a result of water molecule dissociation [22]. These radicals possess the capability to oxidize organic molecules, decompose the molecules, and consequently reduce COD.

D. Factor Influencing Hydrodynamic Cavitation

The factors that affect hydrodynamic cavitation are discussed in detail below.

- Fluid velocity: The formation of cavitation bubbles is facilitated by the reduced pressures associated with increased velocities. The incidence of cavitation increased in constricted areas as the velocity increased.
- Fluid pressure: Bubble formation increases at lower pressures, thereby promoting cavitation. As ambient pressure rises, bubble formation becomes more challenging. The geometry of the flow systems, including sharp edges, rough surfaces, and abrupt changes in the flow path geometry, can result in localized low pressures and subsequent bubble formation. Smooth transitions and rounded edges mitigate the cavitation potential [23].
- Dissolved gas: A larger decrease in pressure is required to produce cavitation in fluids with high dissolved gas concentrations. Degassing the fluid increases the cavitation probability.
- Fluid temperature: The probability of cavitation decreases as the temperature increases, owing to the reduction in both vapor pressure and gas solubility. Conversely, lower temperatures produce the opposite effect.
- Fluid viscosity: Fluids characterized by higher viscosity demonstrate increased resistance to cavitation and flow. Conversely, fluids with a lower viscosity exhibit a greater propensity for cavitation.
- Turbulence: Turbulent flows facilitate the formation of cavitation bubbles owing to the generation of localized pressure fluctuations. Cavitation occurs less frequently in laminar flow.
- Period of exposure: Cavitation bubbles are more likely to form when a fluid is subjected to low pressure for an extended duration. Shorter exposure times decreased the probability of cavitation.

E. Cost Estimation

The following steps were undertaken to calculate the cost estimate for the reduction in COD in wastewater using the hydrodynamic cavitation method:

1. Identification of the Experimental Setup: The research focuses on the utilization of circular and star-patterned orifice plates as a means of reducing COD in textile wastewater.
2. The type of orifice plate and flow rate have a significant influence on the reduction efficiency.

3. Calculate the operating expenses: The cost of the orifice plates, the pump's energy consumption, maintenance, and any extra chemicals or materials used are all considered as operating expenses. These costs are typically obtained from suppliers or industry standards, in the absence of explicit cost figures for these components. The cost per unit of COD reduction was calculated by dividing the total operating cost by the quantity of COD reduced, expressed in mg/L or kg/day.

In the present study, based on COD reduction and a few assumptions, the operating cost was calculated. It is assumed that 4.15 rupees per kWh is the energy cost for pump operation, the cost of orifice plates is 4150 rupees, the operating hours are 10 hours per day, the energy consumption is 2 kWh/h, and the daily maintenance cost is 830 rupees. Thus, the power cost was 2 kWh × 4.15/kWh × 10 h = 83 rupees/day. Summing all the costs gives a total cost of 5063 rupees (83 rupees per day for energy, 830 rupees per day for maintenance, and 4150 rupees for the orifice plate). The COD at the start was 2100 mg/L, and after treatment (1-star plate), it was reduced to 434.24 mg/L. Thus, the COD decrease was 1665.76 mg/L. The flow rate was 1L/min (60 L/hour). The daily number of COD reduced was 1665.76 mg/L×60 L/h ×10 hours = 99945.6 mg = 99.94 g/day. Therefore, the cost per COD g reduced was 5063 rupees / 99.94 g = 50.66 rupees / g COD. The real costs may differ from this simplified example, depending on the operating conditions and cost considerations discussed in the article.

IV. RESULTS AND DISCUSSION

The results of the COD and color reduction of the setup, which consisted of orifice plates with one and five orifices connected in series, are shown in Table I. When the orifice plates had one circular hole, the COD was reduced by 65% and the color by 25%. However, the COD decreased by 78% and the color decreased by 27% when one plate was replaced by a plate with five orifices.

TABLE I. COD AND COLOR REDUCTION OF THE SET UP WITH CIRCULAR HOLE ORIFICE PATTERNS (1 L/min FLOW RATE, 8 s AND INITIAL COD IS 2100)

Sr. No	Hole type	Hole Number	Final COD	% COD Reduction	% Color Reduction
1	Circular	1	725	65	25
2	Circular	5	456	78	27

Table II displays the results of the experiments using star-shaped orifice plates. The stars had a diameter of 8 mm with edges that are 360° angled. The COD decreased by 79% and the color decreased by 33% when a plate with one star orifice was used. The COD and color were reduced by 60% and 20%, respectively, when a 5 star-shaped orifice was utilized.

TABLE II. COD AND COLOR REDUCTION OF THE SET UP WITH STAR-HOLE ORIFICE PATTERNS (1 L/min FLOW RATE, 8 s AND INITIAL COD IS 2100)

Sr. No	Hole type	Hole Number	Final COD	% COD Reduction	% Color Reduction
1	Star	1	434	79	33
2	Star	5	820	60	20

For an enhanced visualization of the results, Figure 6 illustrates the differences between the one-hole and five-hole designs in COD and color reduction. The COD was reduced by 65% when utilizing a plate with one circular hole and 78% when utilizing a plate with five circular holes. A color decrease of 25% was observed for the single-orifice plate, and 27% for the five-orifice plate. It can be inferred that as the number of holes increases, greater COD reduction will be achieved, due to more intense cavitation. The results show that multiple-hole designs are more effective. The five-hole plate design demonstrated superior performance in terms of both COD and color reduction compared to the single-hole design. This finding suggests that increasing the number of orifices in the plate can lead to more efficient treatment outcomes. However, marginal gains in color reduction were achieved. Although the difference in color reduction between the two designs was less pronounced (27% vs. 25%), it still favored the five-hole design. This implies that multiple orifices may offer a slight advantage in addressing the color removal of treated wastewater.

The results from the 1- and 5-star patterns are compared in Figure 7. A single-star orifice plate reduced the COD by 79%. The 5-star type reduced COD by only 60%. The color reduction was 33% and 20% for the plates with a single star orifice and 5-star orifices, respectively. The circular orifice plate was effective in producing the intended color and COD decrease. However, when star orifice plates were utilized, the COD was reduced, but the COD reduction diminished as the number of stars increased. This phenomenon can be attributed to the fact that in the case of a single hole, a larger COD drop occurs because a single star pattern creates a substantial void and a significant amount of pressure. Star-shaped orifice patterns demonstrated a reverse trend, with single-star designs outperforming multiple-star designs in both COD and color reduction. This suggests that the shape and configuration of the orifices play a crucial role in treatment effectiveness.

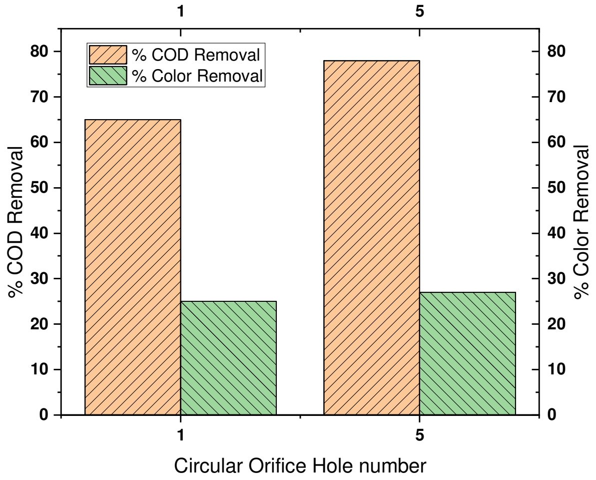

Fig. 6. Experimental work with circular section hole in orifice plate to COD and Color removal.

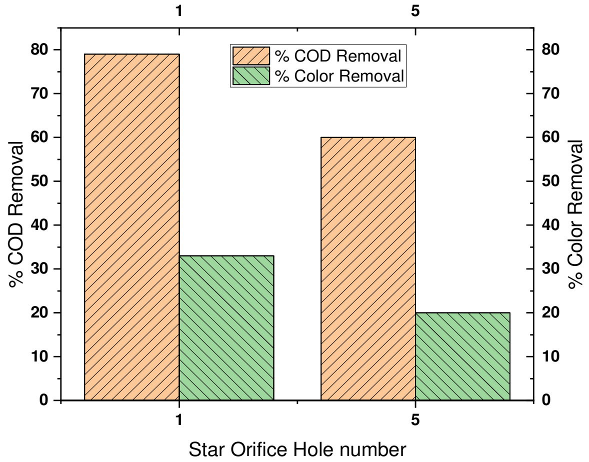

Fig. 7. Experimental work with a star section hole in an orifice plate for COD and color removal.

V. CONCLUSIONS

This study investigates the use of hydrodynamic cavitation with various orifice plate designs to reduce Chemical Oxygen Demand (COD) and color levels in textile wastewater. The orifice plate designs tested include 1-star, 1-circular hole, 5-star, and 5-circular hole patterns. This research demonstrates that using star-shaped orifice plates and various orifice flange configurations, such as employing one- and two-orifice flanges in sequence, represents a novel approach. The results show that the 1-star pattern design can reduce COD by up to 79% and color by 33%, whereas the 5-circular hole pattern can reduce COD by 78% and color by 27%.

The use of circular and star-patterned orifice plates effectively reduced the COD and color content of textile wastewater. However, the optimal configuration for COD reduction was found to be a combination of an 1-star hole pattern and 5-circular hole pattern.

The COD reduction mechanism involves sonolysis, which occurs during bubble collapse. This process generates extremely high pressures and temperatures inside the bubble, leading to the dissociation of water molecules and production of highly reactive hydroxyl radicals (OH•) that decompose organic molecules.

The experimental results demonstrated the significant impact of orifice plate design on wastewater treatment efficiency. While the 5-hole circular pattern outperformed the single-hole design in terms of both COD and color reduction, the star-shaped orifices exhibited an inverse relationship. The single-star orifice plate proved to be more effective than the 5-star configuration, achieving higher COD and color reduction rates. These findings underscore the complex interplay between the orifice number, shape, and treatment effectiveness.

The hydrodynamic cavitation method using strategically designed orifice plates shows promise as an effective technique for treating textile wastewater, particularly for reducing COD and color. Further research in this area can lead to more efficient and sustainable wastewater treatment solutions for the textile industry.

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