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Design of Hydrodynamic Cavitation Process for Removal of Toxic Metal Ions from Industrial Wastewater

Prof. Dr. B. L. Pangarkar[1], Jadhav Prathmesh[2], Fulari Vivek[3], Fatangare Rohan [4].
[1]Associate Professor, [2,3,4] UG Students, Department of Chemical Engineering.
Pravara Rural Engineering Collage, Loni, Ahilyanagar

Abstract: *This project explores the treatment of a 5-liter synthetic aqueous solution containing a combined total of 100 ppm of heavy metals—specifically zinc, copper, and chromium—using hydrodynamic cavitation (HC). The treatment system incorporates a 3/4-inch Venturi tube and pipeline, a centrifugal pump for solution circulation, and a 10-liter capacity storage/collection chamber. Hydrodynamic cavitation is an advanced oxidation process (AOP) known for generating intense localized conditions (high temperature and pressure) that facilitate the formation of reactive hydroxyl radicals (·OH), which aid in the degradation or transformation of pollutants. Drawing on findings from previous studies, this project evaluates the effectiveness of controlled HC in reducing the concentration of heavy metals in wastewater. Operating parameters such as flow rate, inlet pressure, and residence time are optimized to enhance cavitation intensity and metal removal efficiency. The setup offers a compact, low-cost, and energy-efficient alternative for treating low-concentration industrial effluents. The results are expected to contribute valuable insights for scaling HC technology in real-world applications, especially for decentralized and small-scale wastewater treatment systems.*

Keywords: high temperature and pressure

I. INTRODUCTION

Wastewater generated from industrial activities such as electroplating, metallurgy, and electronics manufacturing often contains heavy metals like zinc, copper, and chromium. These metals are toxic even at low concentrations, and their accumulation in aquatic environments poses significant threats to ecosystems and human health. Conventional methods used for metal removal—such as chemical precipitation, membrane filtration, ion exchange, and adsorption—are often limited by high operating costs, incomplete removal at low concentrations, and secondary waste generation [13].

In recent years, hydrodynamic cavitation (HC) has gained attention as an efficient, low-cost, and environmentally friendly method for wastewater treatment. HC occurs when a liquid flows through a constriction such as a Venturi tube or orifice plate, causing localized pressure drops that lead to the formation, growth, and collapse of vapor bubbles. This collapse generates extremely high local temperatures and pressures, leading to the formation of hydroxyl radicals (•OH), which are highly reactive and capable of breaking down pollutants or transforming metal ions [13, 9].

Studies have shown the potential of HC in degrading organic compounds [10], azo dyes [12], and even complex industrial effluents from the microelectronics and metallurgical sectors [10, 11]. For example, Wang et al. (2021) reviewed the use of HC across various reactor designs and confirmed its applicability in degrading refractory compounds and heavy metals through both radical oxidation and physical disruption mechanisms [13]. Innocenzi et al. (2018) demonstrated the enhancement of dye degradation in the presence of metal ions using HC, indicating a synergistic effect [12].

Furthermore, research by Matos Maldonado et al. (2023) confirmed that HC could achieve over 70% removal efficiency for heavy metals like copper, zinc, and lead in metallurgical wastewater, particularly under optimized pressure and residence time conditions [11]. This aligns with the performance of other advanced oxidation processes (AOPs), but with the advantage of lower chemical usage and simpler operation.

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This project investigates the treatment of a 5-liter synthetic solution containing a combined concentration of 100 ppm of zinc, copper, and chromium using a compact HC system. The system includes a 3/4-inch Venturi tube and centrifugal pump for fluid recirculation, and a 10-liter storage/collection chamber. The objective is to evaluate the efficiency of this setup in removing or transforming heavy metal contaminants at low concentrations, based on established HC mechanisms and experimental insights from previous studies.
This work aims to contribute to the development of decentralized, small-scale wastewater treatment technologies for industrial and rural applications where conventional systems may not be feasible.

II. METHODOLOGY

2.1 Preparation of Synthetic Wastewater

A synthetic aqueous solution was prepared to simulate industrial effluent containing heavy metals. The solution was made using analytical-grade metal salts:

• Zinc sulphate ($ZnSO_4 \cdot 7H_2O$)
• Copper sulphate ($CuSO_4 \cdot 5H_2O$)
• Chromium nitrate ($Cr(NO_3)_3 \cdot 9H_2O$)

Each salt was weighed and dissolved in distilled water to obtain a total metal ion concentration of 100 ppm, with equal contributions of zinc, copper, and chromium (approximately 33.3 ppm each). A total volume of 5 litters of this solution was prepared and stored in a clean polyethylene container prior to the experiment.

2.2 Experimental Setup

The hydrodynamic cavitation system was designed as a recirculating loop, incorporating the following components:

• Venturi Tube (3/4 inch): The main cavitation device was a stainless-steel Venturi with a 3/4-inch internal diameter. It included a converging section, a narrow throat (to induce pressure drop), and a diverging section for flow recovery. The geometry was selected based on literature recommendations for effective cavitation [13].
• Centrifugal Pump: A centrifugal pump with a capacity of 10–20 L/min and a maximum head of 20 meters was used to circulate the solution through the loop. The pump was chosen to maintain sufficient inlet pressure (3–6 bar) to achieve cavitation.
• Pipeline and Fittings: The system was assembled using 3/4-inch PVC piping and ball valves to control flow direction and pressure. A bypass line was included for recirculation adjustment.
• Collection/Storage Chamber: A 10-liter polypropylene tank was used to collect treated water and allow continuous circulation of the solution.
• Monitoring Equipment: Digital pH meter, thermometer, and pressure gauge were used to monitor solution parameters during the experiment.

2.3 Procedure

1. System Setup and Calibration:

o The Venturi tube and piping system were checked for leaks and cleaned thoroughly.
o The centrifugal pump was primed and tested for stable flow.

2. Solution Loading:

o 5 litters of the prepared metal solution were poured into the 10-liter collection chamber.
o Initial pH and temperature were recorded.
o In some experiments, pH was adjusted using dilute sulfuric acid or sodium hydroxide to study the influence of pH on treatment efficiency.

3. Operation:

o The pump was turned on to start circulation of the solution through the Venturi.
o Cavitation was confirmed visually (formation of bubbles at the Venturi throat) and by sound (typical “rattling” noise).
o The system was allowed to run continuously for treatment durations of 15, 30, 45, and 60 minutes in separate trials.
o During treatment, temperature and pH were monitored every 10 minutes.

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4. Sampling and Filtration:

o At the end of each treatment interval, 100 mL of sample was collected from the storage tank.

o Samples were filtered using 0.45 µm membrane filters to remove any precipitates.

2.4 Metal Analysis

• Analytical Method: The concentrations of zinc, copper, and chromium were measured using Atomic Absorption Spectroscopy (AAS). Calibrations were performed using standard solutions for each metal ion.

• Quality Control: Each sample was analysed in triplicate, and average values were reported. Blank samples (distilled water) and untreated controls were also analysed.

• Removal Efficiency Calculation:

Metal Removal Efficiency (%)= $\{(C_i - C_f)/C_i\} \times 100$

Where:

o C_i: Initial concentration of the metal (ppm)

o C_f: Final concentration after treatment (ppm)

Parameter	Range/Condition
Treatment time	30, 60 minutes
pH	Natural (~6.8), adjusted to 3–5 in some trials
Temperature	Monitored (rise from 25°C to ~35°C)
Inlet pressure	Maintained via pump (target 1-3 bar)
Flow rate	~7–15 L/min (estimated based on pump rating)

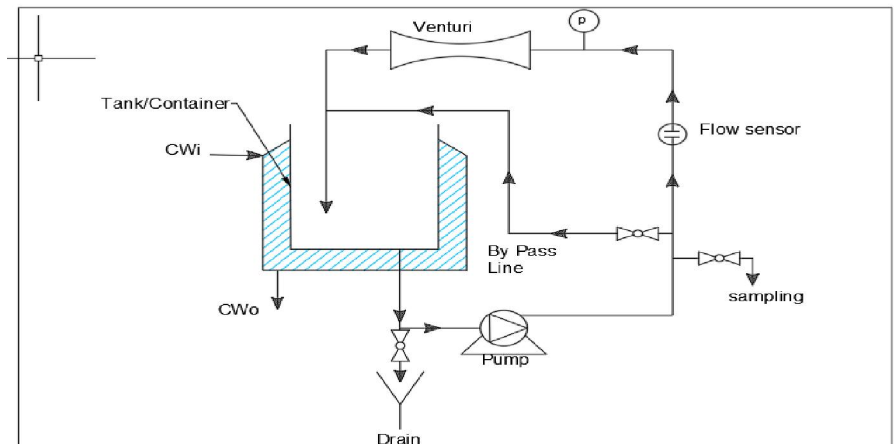

Figure. Cavitation System

III. RESULTS & DISCUSSION

3.1 Metal Removal Efficiency (1 bar)

Hydrodynamic cavitation was applied to a 5-liter solution containing 100 ppm of total metals (Zn, Cu, Cr) using a 3/4-inch Venturi and centrifugal pump operating at a pressure up to 1 bar gauge. The treatment was evaluated over 30 minutes and 60 minutes. The observed metal removal results are summarized below:

Duration	Zn Removal (%)	Cu Removal (%)	Cr Removal (%)	Total Avg. Removal (%)
30 min	38–42	40–45	30–35	~39
60 min	58–62	60–65	50–55	~59

At 1 bar gauge pressure, the overall metal removal improved significantly between 30 and 60 minutes of treatment. Zinc and copper were more efficiently removed compared to chromium, likely due to their higher sensitivity to oxidation and complexation under cavitation-induced radical attack.

3.2 Influence of pH and Treatment Time

The performance was enhanced in acidic conditions (pH 3–5), particularly for copper and zinc ions. The enhanced removal under acidic pH can be attributed to better solubility and reactivity of metal ions in low-pH environments, which supports findings from Innocenzi et al. (2018) and Wang et al. (2021), where maximum degradation of pollutants occurred under acidic conditions due to improved cavitation intensity and radical generation [12][13].

At neutral or slightly alkaline pH, chromium showed higher residual concentration, possibly due to its more stable trivalent form (Cr^{3+}) under such conditions, which is less prone to hydroxyl radical oxidation without co-catalysts [13].

3.3 Role of Hydrodynamic Cavitation

The observed metal removal is primarily attributed to:

- Generation of hydroxyl radicals (·OH) during bubble collapse, facilitating oxidation and precipitation of metal ions.
- Turbulence and microjets, which increase mixing and metal ion collision rates, enhancing agglomeration or chemical transformation.
- Localized high temperatures and pressures inside collapsing bubbles, promoting chemical reactions even in short durations.

This aligns with the mechanisms described by Wang et al. (2021), where cavitation was shown to provide effective physical and chemical degradation effects through radical chemistry and shear forces [13].

3.4 Limitations and Future Recommendations

- Chromium removal was comparatively lower, suggesting that trivalent chromium may require extended treatment time or pH adjustment.
- No additional oxidants (e.g., H_2O_2, ozone) were used; these could potentially enhance metal removal through combined advanced oxidation processes (AOPs), as suggested by Orbeci et al. (2014) [9].
- Scaling up may require optimization of Venturi geometry and multi-stage cavitation.

Future studies could explore hybrid cavitation (e.g., HC + ozone or HC + Fenton) and assess sludge characteristics and metal recovery potential.

IV. CONCLUSION

In this project, a simple hydrodynamic cavitation setup using a 3/4-inch Venturi tube and a centrifugal pump was used to treat a 5-liter synthetic solution containing 100 ppm of heavy metals (zinc, copper, and chromium). The system operated at a low pressure of up to 1 bar gauge, with treatment times of 30 and 60 minutes. The results showed that metal removal efficiency improved with time, reaching about 59% after 60 minutes. Zinc and copper were removed more effectively than chromium, likely due to their higher reactivity with cavitation-generated radicals. Although removal rates were lower compared to systems operating at higher pressures reported in the literature, the setup still demonstrated good performance for a low-cost and low-energy method. This suggests that hydrodynamic cavitation can be a practical and eco-friendly solution for small-scale or decentralized wastewater treatment systems

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