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Hydrodynamic cavitation as an imperative technology for the treatment of petroleum refinery effluent

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ABSTRACT

Hydrodynamic cavitation (HC) is an advanced oxidation process (AOP) which is used in this study for the treatment of wastewater from a petroleum refinery. Bacterial load as well as chemical oxygen demand (COD) has been successfully reduced to approved discharge standards for water reuse purpose. A cavitating reactor with three different geometric configurations was used for the treatment. These reactor configurations include the orifice (CN0) and venturi with different throat diameters (CN1 and CN5). Individual reactor configurations are optimized for processing parameters such as operating pressure and number of passes of the wastewater through the cavitating zone. The maximum bacterial disinfection and COD reduction were obtained using CN5 reactor operated at 5 bar pump discharge pressure and the extent of reduction was found to be 59.17% and 52% respectively. The energy and cost estimation has also been carried out for this treatment process and approximate values are 1.11 kW h/m^{3}of energy usage and 5.54 Rs/m^3 (0.078 \$/m^3) respectively after 10 pass treatment. The disinfection percentage can be further improved by increasing the number of passes and integrating it with other advanced oxidation processes.

1. Introduction

Although numerous efforts have been made to substitute the fossil fuels, crude oil remains an essential first choice. The current global demand of crude oil is 99.3 million barrels per day (mbpd), which clearly indicates its dominance and it is expected to rise upto 107 mbpd by 2030. However, it generates an enormous amount of wastewater of about 0.4–1.6 times higher than the quantum of crude oil processed [1]. The primary wastewater generating sources in petroleum industries are crude oil refining, production of fuels and the waste generated from the intermediates of the lubricants and petrochemicals [2]. The major components composed of this wastewater are polycyclic aromatics contents [3], oil and grease [4], nitrogen and sulphur compounds [5] and bacteria [6]. The rough estimates of the threatening pollutants present in Petroleum Refinery Effluent (PRE) are illustrated in Table 1. These pollutants are serious toxic hazards to the surrounding atmosphere as well as aquatic life [3–7]. The rise in demand of fuel is clearly indicating the generation of higher amount of wastewater and likely to be polluting fresh water bodies which will adversely impact the existing water quality. Therefore the Environmental Protection Agency (EPA) of USA and the Central Pollution Control Board (CPCB) of Government of India has set minimum discharge standards for the PRE as shown in Table 2.

Typical refinery wastewater treatment plant (WWTP) uses a defined sequence of processes i.e. physical [8,9], physio-chemical [10,11], chemical [12], and biological treatment [13–15]. New technologies have also been reported which include membranes [14,16] and microwave assisted catalytic wet air oxidation [17]. These methods have several limitations including the low elimination of organic compounds, low reaction rates, generation of solid sludge and they works in limited pH range [18,19]. Chemical oxidation method also realizes very low reaction rates [20] and requires a large number of oxidants to treat a large volume of PRE, hence restricts its application.

The available treatment plant is not able to meet the guidelines for discharge of PRE mainly for COD and bacterial count (CFU). Currently activated sludge process (ASP) is being used in the industry to treat the effluent, hence the microbial concentration in the treated effluent is high and it becomes a trouble. Eventually, these bacteria form scale (or Biofouling) on the inner side of the pipeline surfaces. The aromatic compounds such as phenols cannot be completely treated using

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Table 1
Characteristics of wastewater from the Petroleum Refinery.

Sr. No.	Parameter	Combined wastewater (Range)	Unit
1	Flow	10000–15000	m^3/day
2	pH	6–10	–
3	Temperature	30–45	°C
4	Suspended solids	100–500	mg/L
5	BOD (5 days 20 °C)	300–500	mg/L
6	Oil and Grease (total)	500–3000	mg/L
7	Sulphides	50–320	mg/L
8	Phenolic compounds	20–40	mg/L
9	Ammonical nitrogen	50–70	mg/L

Table 2
Environmental Standards for minimum discharge of Petroleum Oil Refineries Effluent for threatening components.

Sr. No.	Parameter	As per EPA norms	As per CPCB norms	Unit
1	pH	6–8.5	6–8.5	
2	Oil and Grease	5	5	mg/L
3	BOD (3 days 27 °C)	15	15	mg/L
4	COD	125	125	mg/L
5	Suspended solids	20	20	mg/L
6	Phenols	0.35	0.35	mg/L
7	Sulphides	0.5	0.5	mg/L
8	Ammonical nitrogen	15	15	mg/L

common bacteria, and traces of these compounds are present in the treated effluent. Therefore, both CFU and COD reductions are necessary for the refinery effluent. Therefore, it was decided to treat this further, using viable technique and reuse of it in the same plant. Advanced oxidation processes (AOPs), which are chemically based on a hydroxyl radical (˙OH) and have great potential to degrade or mineralize a wide range of organic molecules [21–25]. The oxidation potential of ˙OH is higher (+2.8 V) as compared to other oxidants like ozone (2.07 V), H_2O_2 (1.78 V), HOCl (1.49 V) and chlorine (1.36 V) [26].

Among the numerous AOP's, hydrodynamic cavitation (HC) has attracted the attention of many researchers considering its unique features such as chemical free operation, great potential to degrade a wide range of organic molecules, easy to implement on a large scale, requires minimum space, simple in operation, cost-effective and less energy intensive [27]. Hydrodynamic cavitation can be generated by using a constriction in the flow, such as an orifice plate, venturi or throttling a valve [28–36]. According to Bernoulli's principle, when liquid flows across a constriction, the kinetic energy of the liquid increases at the expense of the pressure energy [28,29]. If the decrease in pressure is sufficient to cause the pressure around the point of vena contracta to fall below the threshold pressure for cavitation (usually vapour pressure of the liquid medium being pumped at the operating temperature), vapour cavities are generated [30,31]. These cavities expand in the downstream section and eventually collapse as the pressure recovers. During the passage of the liquid through the constriction, boundary layer separation and turbulence occurs and a substantial amount of energy is lost in the form of a permanent pressure drop due to local fluid turbulence. Very high-intensity fluid turbulence is also generated in the downstream of the constriction; its intensity depends on the magnitude of the pressure drop and the rate of pressure recovery; which in turn, depends on the geometry of the constriction and the downstream flow conditions of the liquid, i.e. the scale of turbulence. The intensity of turbulence has a profound effect on cavitation intensity. Thus, by controlling the geometric and operating conditions of the reactor, the required intensity of the cavitation for the desired physical or chemical change can be generated with maximum energy efficiency [29,32,33].

The collapse pressure generated by the cavity can be of the order of several hundreds of bars, which is sufficiently high to rupture the biological constituents of water including the microbial cells causing its death and viability. The asymmetric collapse of cavities also results in high-speed liquid jet causing cell disruption [34,35]. Local fluid shear rates around such jets are adequate to destroy several types of microorganisms [32,36]. The major causative effects of cavitation can be classified as physical and chemical.

The physical effects include the generation of shock waves, the water-hammer effect and radial bubble motion. The chemical effects of cavitation during the cell disruption are due to the generation of free radicals [37]. Their extent depends on the intensity of cavitation and cavity contents which can be varied by the manipulation of the operating parameters such as the cavitation number, geometry of the cavitation element, the initial concentration of the cell suspension, number of passes through the cavitation zone, temperature and viscosity [38,39] along with the dissolved gas content of the liquid. A cell is likely to get disrupted due to high-velocity jet or shock wave produced by a collapsing cavity and the pollutant can get mineralized by the hydroxyl (˙OH) radical produced which oxidizes the former [29,33,40]. Depending on the end use of water, the extent of disruption of cells should be controlled by controlling the intensity of cavitation, which in turn can be controlled by tuning the operating parameters. When one is interested in obtaining periplasmic enzymes, low-intensity cavitation which is just sufficient to break the outer cell wall should be used [35,41]. High-intensity cavitation is required when one needs to ensure that viable microbial count is substantially reduced like in water disinfection applications or to recover the cytoplasmic enzymes. Wastewater from petroleum industries contains mainly phenol, sulphides, hydrocarbons, oil and grease, dissolved solids and some organics which are broadly expressed in terms of COD and BOD [42–46]. The idea is to treat the secondary effluent (i.e. wastewater coming from biological treatment of wastewater) using hydrodynamic cavitation up to an approved discharge standard so that the treated water can be reused for the cooling tower as a makeup water. In this work, the issue of microbial load and COD reduction is targeted using simple, economical and maintenance free process called hydrodynamic cavitation.

This study explores the possibility of the use of hydrodynamic cavitation as a post process to treat the secondary effluent (wastewater coming from biological treatment unit) to meet the discharge limits of PRE without the addition of chemicals and then treated water can be reused for the cooling tower as a makeup water.

2. Materials and methods

2.1. Materials

Wastewater used for the study was the effluent from the petroleum refinery near Mumbai, India coming out of the secondary treatment. The effluents generated from all the units in the refinery are mixed and sent to the WWTP, hence the effluent coming to the biological treatment stage has a composition that is average of all the individual effluent streams. The effluent stream goes through process of oil-water separation, equalisation, flocculation and air floatation, followed by biological treatment. The samples used for present study were collected from an Activated Carbon Filter (ACF) connected at the outlet of the biological treatment plant. Visually, the initial collected water sample appeared clear to a certain degree with a light odour. Plate Count Agar (Standard Methods Agar) was procured from Hi-media (REF Product Code M091). Sodium Chloride and Ethanol were procured from SFCL (Extra pure, SFCL Product Code 40,123). Autoclave (Osworld Autoclave steam sterilizer, JRIC-39) and laminar cabinet (IMSET, operating frequency: 50 Hz) were used.

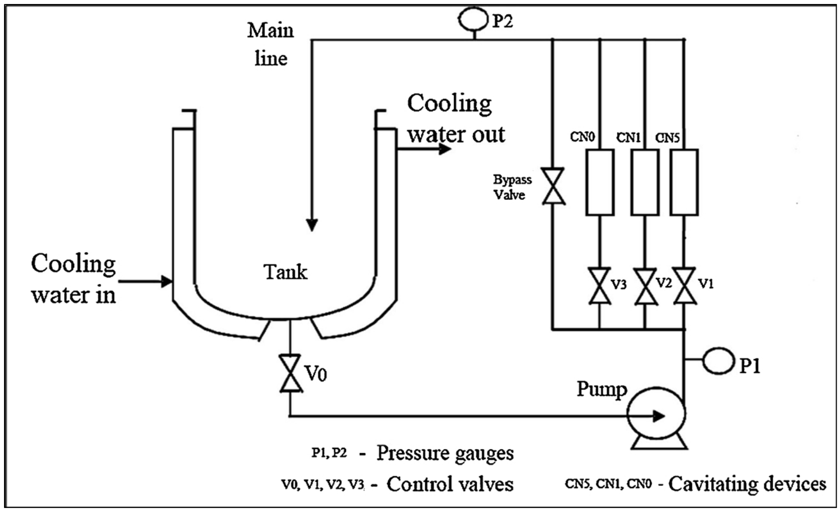

Fig. 1. Schematic representation of Hydrodynamic Cavitation reactor setup.

2.2. Analytical methods

Analysis of COD was carried out using the standard method. The enumeration of the microorganisms present in each sample was done using heterotrophic plate count (HPC) method [47].

2.3. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. The hydrodynamic cavitating reactor was procured from Hyca Technologies Pvt. Ltd., Mumbai, India. It includes a holding tank of 20 L volume, a positive displacement pump, control valves (V_0, V_1, V_2 and V_3), three main lines accommodating different cavitating reactor configurations, and a bypass line. A 2 Hp reciprocating pump with a variable frequency drive (VFD) was used in the setup with a max pressure of 15 bar and maximum flow rate of about 1500 lph. The initial volume used for the treatment during various trials and respective flowrates are mentioned in Table 3.

The suction side of the pump is connected to the bottom of the tank and discharge from the pump branches into the main lines and a bypass line. The three main lines house the three reactor configurations, namely CN0, CN1 and CN5 reactor. Material of construction for all the cavitating devices was Stainless Steel 304. CN0 reactor consisted of an orifice plate with throat to pipe diameter ratio between 0.05–0.2, whereas CN1 and CN5 reactors were cavitating venturies with throat to pipe diameter between 0.1–0.2 and 0.2–0.3 respectively. CN1 was designed to produce intense cavitation as compared to the CN5 reactor. Designs of these devices are proprietary and cannot be disclosed here. The flow was allowed to pass through one of the devices at a time using the valves V_1, V_2, and V_3. Additional valve is also provided to pass the flow through the bypass line. The inlet pressure can either be controlled by using bypass flow controlling valve or by controlling the frequency of the pump. However, if the system is controlled using bypass valve then water gets partially treated using cavitating reactor and part of the water passes through bypass line and remains untreated as it is bypassed. This reduces the effectiveness of the system. Hence the flow was always controlled using the frequency of the pump to ensure the homogeneous treatment throughout the reactor volume. A variable frequency drive (VFD) was used to adjust the number of piston strokes per unit time of the pump, which controls the total flow generated and hence the inlet pressure to the cavitating device. It was ensured that both the mainline and bypass line terminate well inside the tank below the liquid level to avoid any induction of air into the liquid due to the plunging liquid jet. Pressure gauge P_1 and P_2 are used to monitor the inlet and outlet pressure of the cavitating device.

Table 3
Operating conditions.

Device	Pressure	Volumetric flow Rate (lpm)	Cavitation Number
CN0	3	5.71	0.21
	5	6.75	0.15
	7	7.55	0.12
CN1	3	10.24	0.34
	5	12.33	0.23
	7	13.46	0.19
CN5	3	10.70	0.31
	5	13.27	0.20
	7	17.89	0.11

2.4. Experimental procedure

The samples were collected from the outlet of a wastewater treatment plant in the refinery which is based on biological processes. The experiments were conducted in the premises of the petroleum industry near the WWTP using the hydrodynamic cavitation reactor setup described in Section 2.3. Samples were taken directly from the WWTP without any intermediate storage time. These samples were then treated using hydrodynamic cavitation at different conditions (inlet pressure and Cavitation number) using fixed solution volume and for a constant number of circulations (passes) through the cavitating device. The experiments were carried out at ambient temperature (approx 30 °C) without any temperature control. The initial solution volume was adjusted, so that to get 1 circulation per minute at all the operating pressures. Three different reactor configurations were used in this study (namely CN0, CN1 and CN5). The samples were collected after 0, 10, 30 and 50 passes and were analysed for COD and total bacterial count (CFU/ml) in the laboratory at Institute of Chemical Technology, Mumbai. Energy efficiency of hydrodynamic cavitation process is low when it is operated beyond 50 passes and it is no longer economically viable. Hence experiments were carried out only till 50 passes.

3. Results and discussion

3.1. Treatment using hydrodynamic cavitation reactor based on orifice (CN0) Reactor

The number of cavitating events is controlled using operating pressure; hence pressure is the dominating parameter in the phenomena of cavitation. The sample water was treated using CN0 reactor at

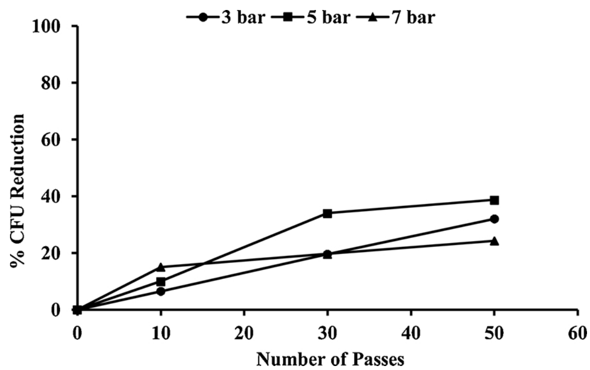

Fig. 2. Effect of operating pressure and number of passes on CFU/ml reduction for the CN0 reactor (Initial CFU = 6.18×10^5 CFU/ml for 3 bar, 3.0×10^5 CFU/ml for 5 bar, 2.92×10^5 CFU/ml for 7 bar).

operating pressures of 3, 5 and 7 bar respectively. The water was continuously circulated for upto 50 passes through the cavitating reactor. Samples for the analysis were collected after an interval of 10, 30 and 50 passes respectively.

The water samples used in the study were containing initial bacterial count 6.18×10^5, 3.0×10^5 and 2.92×10^5 CFU/ml and the COD 236.67, 141.67 and 150 mgO_2/L for 3, 5 and 7 bar operating pressure batches respectively. The maximum bacterial reduction after 50 passes was obtained as 32.04%, 38.66% and 24.32% at 3, 5 and 7 bar operating pressures respectively. It was observed that bacterial disinfection was initially enhanced with increasing operating pressure from 3 bar to 5 bar, and then reduces when the operating pressure is increased to 7 bar (Fig. 2). The main reason behind this observation is, the number of cavitating events increases with the increase in operating pressure initially, hence it influences the maximum zone in the water body resulting into higher disinfection of bacteria. In addition to this, the choked cavitation may be taking place at pressures higher than 5 bar due to a higher rate of generation of vapour cavities. These cavities then agglomerate and the overall collapsing intensity of the formed cavity cluster reduces significantly [33].

The results for COD reduction at 3, 5 and 7 bar operating pressure are shown in Fig. 3. Maximum COD reduction obtained after 50 passes were37.39%, 29.41% and 1.11% for operating pressure of 3, 5 and 7 bar respectively. It can be observed that COD reduction was highest at 3 bar, and decreased on increasing the operating pressure to 5 bar and 7 bar. In fact, at 7 bar, negligible COD reduction was observed, confirming that the flow might be entering in the super cavitation (Chocked cavitation) regime at this pressure.

At 5 bar operating pressure, there is less COD reduction as compared to 3 bar, but the Colony Forming Unit (CFU) removal has increased. This can indicate that at this operating condition, more cavities might be undergoing asymmetric collapse. Asymmetric collapse results in energy dissipation in the form of high shear stress, which is effective in microbial cell disruption [48], but the extent of COD reduction may be less in this case. However, when the cavity collapses symmetrically the energy dissipation is in the form of an increase in local temperature and pressure. This leads to splitting of water molecules inside the cavity and the formation of a high amount of $^{\cdot}OH$ radicals along with other radicals such as $H^{\cdot}$, $HO_2^{\cdot}$ and $O^{\cdot}$ [36,49]. These radicals can then react with the pollutant molecules and oxidize them. This kind of collapse is favoured to get a reduction in the COD of the wastewater.

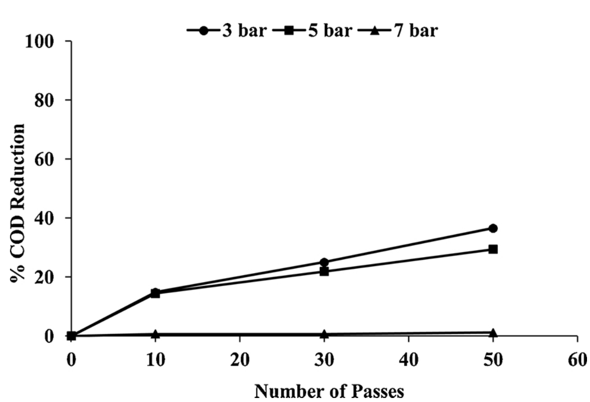

Fig. 3. Effect of operating pressure and number of passes on COD reduction for the CN0 reactor (Initial COD = 236.67 mgO_2/L for 3 bar, 141.67 mgO_2/L for 5 bar and 150 mgO_2/L for 7 bar).

3.2. Performance of CN1 reactor

The CN1 reactor was a cavitating venturi. Experiments using CN1 reactor were also carried out at operating pressures of 3, 5 and 7 bar. An additional experiment was also carried out using air injection. An inlet port was available at the throat of the venturi. The air was allowed to get sucked in the water flow due to low pressure zone formed at the throat region. Hence, no external mechanism was required for the addition of air in the venturi. Air is injected at the throat in such a manner that it helps in increasing physical as well as chemical effects associated with cavitation. The cavities produced can consist of air, water vapours or a mixture of air and water vapours. The air bubbles generated in the flow are capable of generating high shear forces and can act as nuclei for cavity generation. This results in the formation of shock waves that can carry out physical transformations. Additionally, the oxygen present in the air helps in the formation of extra $^{\cdot}OH$ radicals, and also creates a possibility of direct oxidation in the high temperature regions near cavity collapse ;thus resulting in the higher extent of oxidation of pollutant molecules [28,29,32,33,50].The initial CFU/ml is found in various effluent samples as 7.48×10^6, 1.24×10^6, 1.29×10^6 and 7.84×10^4 and the COD128, 72, 104 and 96 mgO_2/L for 3, 5,7 and 5 bar with air injection respectively. Figs. 4 and 5 shows COD and CFU reduction at different operating conditions (3, 5 and 7 bar and with air injection). It can be seen that after 50 passes without any air injection, reduction in the bacterial count is highest at lower pressure (47% reduction at 3 bar pressure), whereas at higher pressure the COD reduction is higher (54% reduction at 7 bar). With the air injection, bacterial disinfection is 70% and COD reduction was 28% after 30 passes. The microbial disinfection and COD reduction at 5 bar after 30 passes without air injection was 13% and 8.33% respectively.

The injection of gas gives several advantages in terms of physical and chemical effects associated with cavitation [51–53]. Since air is easily and freely available around us so the trial experiment is carried out with it. This is an alternative way to increase the number of cavitation bubbles by injecting gases at the throttling section where suction

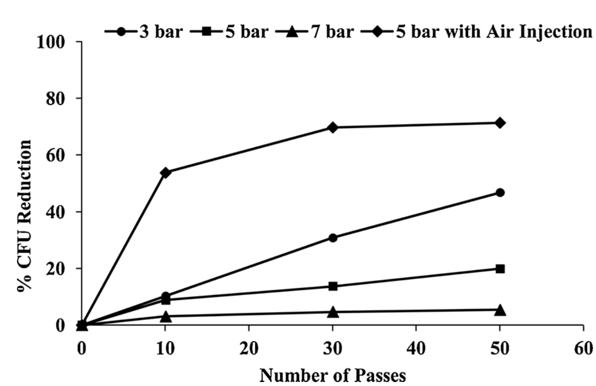

Fig. 4. Effect of operating pressure and number of passes on CFU/ml reduction for the CN1 reactor (Initial CFU = 7.48×10^6 CFU/ml for 3 bar, 1.24×10^6 CFU/ml for 5 bar, 1.29×10^6 CFU/ml for 7 bar and 7.84×10^4 CFU/ml for 5 bar with air injection).

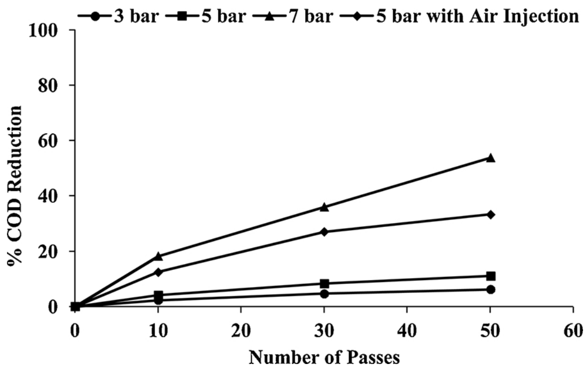

Fig. 5. Effect of operating pressure and number of passes on COD reduction for the CN1 reactor (Initial COD = 128 mgO_2/L for 3 bar, 72 mgO_2/L for 5 bar, 104 mgO_2/L for 7 bar and 96 mgO_2/L for 5 bar with air injection).

is generated. Additionally, this suction helps to suck the gases and helps to save the energy required to inject the gas. The suction of the gas is controlled using the flow controlled valve. The injected gas acts as nuclei for the generation of cavitation bubbles. In addition to this, the mixture of bubble contents changes according to the injected gases and these forms gaseous, vapour and gas-vapour mixed cavities. These cavities go under several reactions during cavitation and form numerous radicals $^{\cdot}OH$, $H^{\cdot}$, $HO_2^{\cdot}$, $O^{\cdot}$ and $N^{\cdot}$. The population of $^{\cdot}OH$ also increases due to excess availability of oxygen through the trapped air into bubbles resulting in the higher degradation of organic pollutants as well as an increase in the bacterial disinfection rate. The several mechanisms of radical formations due to various induced gases have been reported in the literature [36,49].

3.3. Performance of CN5 reactor

The CN5 reactor was also a cavitating venturi with the largercross-sectional area as compared to CN1. The experiments were conducted at the same operating conditions as the other two reactors, i.e. at 3, 5 and 7 bar operating pressure for 50 passes through the reactor. The initial CFU/ml in waste effluent are found 7.5×10^5, 1.09×10^7, 3.17×10^5 and 6.15×10^4 and initial COD values 72, 64, 186.67 and 136 mgO_2/L for 3, 5,7 and 5 bar with air injection respectively. Figs. 6 and 7 show the results of CFU/ml and COD for the experiments. It can be observed that this reactor gives optimum results in terms of microbial disinfection as well as COD reduction at operating pressure of 5 bar. The maximum microbial disinfection obtained at this pressure was 71.43% and COD reduction is 33.33% after 50 passes.

The cavitating reactor CN5 operating at a pressure of 5 bar was successful in treating petroleum effluent with higher efficacy, hence to

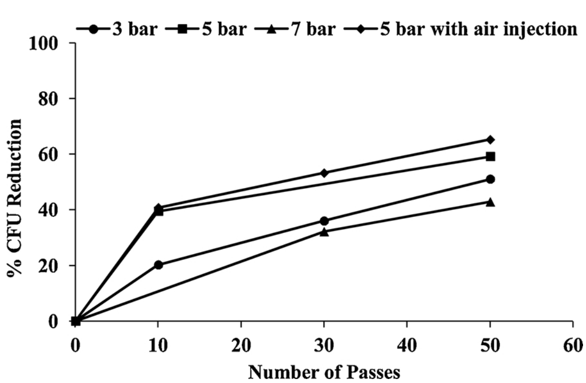

Fig. 6. Effect of operating pressure and number of passes on CFU/ml reduction for the CN5 reactor (Initial CFU = 7.5×10^5 CFU/ml for 3 bar, 1.09×10^7 CFU/ml for 5 bar, 3.17×10^5 CFU/ml for 7 bar and 6.15×10^4 CFU/ml for 5 bar with air injection).

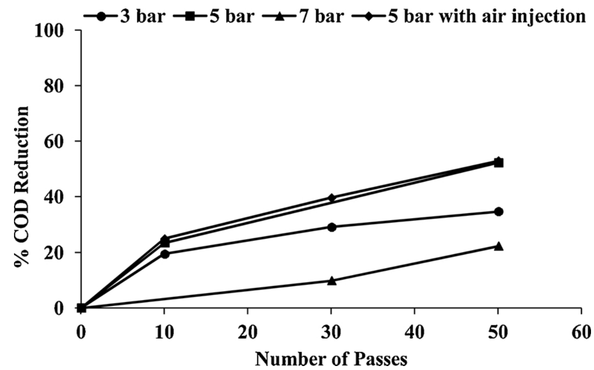

Fig. 7. Effect of operating pressure and number of passes on COD reduction for the CN5 reactor (Initial COD = 72 mgO_2/L for 3 bar, 64 mgO_2/L for 5 bar, 186.67 mgO_2/L for 7 bar and 136 mgO_2/L for 5 bar with air injection).

ensure its efficacy the trial was repeated at same conditions. It was also showing good agreement with the previous results (Figs. 6 and 7) operated under the same conditions (bacterial disinfection = 70% and COD reduction = 30%). As CN5 reactor operated at 5 bar pressure was seen to be more effective, hence additional experimental runs were carried out with air injection. In this study, the air was injected at throat using natural suction generated due to the low pressure region formed downstream of the throat. This reduces the external energy requirement for air injection. Since this is a closed loop system, the air eventually gets solubilised and the excess undissolved air is released to atmosphere in the holding tank. The reduction in COD as well as CFU is found to be higher with air injection operated at 5 bar pressure as compared to without air injection at the same operating conditions (Fig. 7). The addition of air increases the number of gaseous and gas-vapour cavities at downstream of cavitating reactor, hence cavitation events per unit volume increases resulted in higher efficacy [51–53]. Still further trials are needed to confirm and optimize the air flowrate to get maximum disinfection as well as COD reduction.

The feasibility of the process on a commercial scale depends on the cost required for the treatment. As operating pressure increases the power utilization and associated cost also increases to run the pump. If the number of passes increases then the processing time will also increase. Hence, the optimization of the processing parameters like operating pressure and number of passes is important. The ideal processing conditions in terms of feasibility are 5 bar operating pressure and 30 passes for wastewater treatment and the cost of treatment is 16.61 Rs/m^3 (0.23 \$/m^3) at same processing conditions. The expected cost of the treatment for different operating pressures and for different passes is reported in Table 4. The estimation of energy as well as costing is briefly elaborated in the Appendix-I.

4. Conclusion

The amount of energy required to kill the bacteria is lesser compared to the energy required for COD removal. Hence at lower operating pressure, the bacterial disinfection is observed to be higher whereas COD reduction was less. The optimum reactor geometry and

Table 4
Costing for different operating pressures with different passes.

No. of Passes	Cost Rs/m^3 (\$/m^3)		
	3 bar	5 bar	7 bar
1	0.28 (0.0039)	0.55 (0.0077)	0.83 (0.012)
10	2.76 (0.039)	5.54 (0.078)	8.31 (0.12)
30	8.28 (0.12)	16.61 (0.23)	24.94 (0.35)
50	13.80 (0.19)	27.69 (0.39)	41.57 (0.58)

optimum inlet pressure were chosen based on the maximum removal of COD and the maximum bacterial disinfection of water. Based on these criteria, CN5 reactor operating at 5 bar inlet pressure was found to be the optimum. The bacterial disinfection obtained was 70% in this case, while COD reduction was about 30% and the estimated cost of the treatment was about 16.61 Rs/m^3 (0.23 \$/m^3).It can be seen that maximum reduction in the bacterial count takes place in first 10 passes, and the CFU destruction rate decreases with subsequent passes. Hence for most energy efficient process, the cavitation reactor can be operated with 10 passes. The expected cost of the treatment for 5 bar operating pressures and for 10 passes is 5.54 Rs/m^3 (0.078 \$/m^3) giving 40% CFU reduction and 22% COD reduction. It is observed that the reduction in COD as well as CFU is higher with air injection operated at 5 bar pressure in CN5 reactor, still further optimization is needed to confirm and optimize the air flow rate, operating pressure and number of cycles to get maximum disinfection as well as COD reduction.

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Appendix A

Estimation of Energy and Cost

For CN5 reactor operated at 5 bar pressure for 10 passes

Inlet fluid pressure = 500000 Pa

Density of water = 1000 kg/m^3

Outlet pressure (P_2) = 101325 Pa

Volumetric flow rate at 5 bar pressure (V_O) = 13.27 lit/min

= 2.21×10^{-4} m^3/s

Initial volume = 13.27 lit

= 0.01327 m^3

Hence, the initial volume of wastewater in the tank was taken to be 13.27 lit. So that 1 pass gets completed in 1 min.

Therefore, Time for 10 passes = 10 min

Energy dissipated into the system (J) = Pressure drop across the cavitating device (Pa) × Volumetric flow rate through the cavitating device (V_O) × Circulation time through the device

$= (500000-101325) \times 2.21\times 10^{-4} \times (10\times 60)$

= 52864.3050 J

= 52.8643 KJ

Cost of treatment/m^3 of water = Power × Cost of Power (Considered as 5 Rs/kWh)

= ((Pressure drop across the cavitating device × Volumetric flowrate × time of treatment in hr)/m^3 of volume treated) × Cost of Power

$= (((500.000-101.325) \times 2.21\times 10^{-4} \times (10/60)) / 0.01327) \times 5$

$= 1.1066 \times 5$

= 5.537 Rs/m^3 (0.078 \$/m^3) (Assuming 1 \$ = 71.14 Rs)

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