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Hydrodynamic Cavitation as Pretreatment for Removal of Hardness from Reverse Osmosis Reject Water

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Abstracts: In the present investigation, the treatment of reverse osmosis reject water hardness by hydrodynamic cavitation with the addition of sodium bicarbonate was studied. Hydrodynamic cavitation (HC), which is formed as a result of fluid pressure and velocity variation, has attracted great attention in industrial wastewater treatment due to its simple design and ease of operation. The influence of wastewater recirculation flow rate and the number of holes in the metal plate on the percentage removal of calcium hardness was studied. The study used a two-factor factorial design with three levels, plates with(3, 5 and 9 holes)and a recirculation flow rate of (0.6, 1 and 1.5 L/min) with a treatment time of 60 minutes. Calcium hardness, total dissolved solids, pH and liquid temperature were evaluated as a function of time. The results show that as the flow rate and the number of orifices increase, the percentage of hardness removal increases. A linear correlation of hardness removal with respect to flow rate and number of orifices in the metal plate is also observed. For the recirculation flow rate of 1.5 L/min and a plate with 9 holes, a maximum removal rate of 66.76 % was achieved. It was also observed that the temperature increases as a function of time, reaching up to 75°C, while pH and total dissolved solids decrease during the treatment time. Hydrodynamic cavitation represents an environmentally friendly mechanical treatment technology and, considering that the removal efficiency is higher than 60%, it is an alternative as a pretreatment for the removal of water hardness

Keywords: Hydrodynamic Cavitation, Orifice Plate, Hardness Removal, Inverse Osmosis.

1. INTRODUCTION

Groundwater resources are considered an essential source of water in most countries of the world[1]. Leaching of various chemical species from natural rocks and soil fertilizers during agricultural and quarrying processes has led to dangerous contamination of water resources[2]. Unfortunately, groundwater is associated with water hardness, as water moving through soil and rock dissolves small amounts of natural minerals and transports them to the groundwater supply[3]. The world health Organization recommended preserving the concentrations of Ca2+ and Mg2+ ions lower than 75 mg/L and 50 mg/L in the drinking water respectively[4].In a study, samples of tap water were collected from 2017 to 2020 from different countries in Africa, Asia, Europe; and it was determined that the average hardness exceeded 100 mg/L[5]. The presence of water hardness in municipal water networks can economically affect households and industry in general[6]. In addition, the minerals also induce scaling problems and serious failures in boiler pipes, heat exchangers and household appliances such as washing machines, dishwashers and steam Irons[7]. To remove divalent ions, various methods such as effective water softening means, chemical precipitation, ion exchange process, nanofiltration, reverse osmosis, and electrochemical systems have been widely applied[8]. The ion exchange (EX) process is widely used due to its simplicity, ease of operation and high removal efficiency[9]. However, it consumes a significant amount of sodium chloride (NaCl) and generates additional wastewater during the cation resin regeneration process. Nanofiltration is a pressure-driven membrane filtration process with pore sizes from 0.7 to 5 nanometers [10]. Previous studies investigated the effect of nanofiltration membrane type (TW30, NE70 and NE90) and feed pressure on ion rejection and reported that the TW30 membrane at a pressure of 10 bar produced the highest removal of calcium, magnesium and chloride, with 96.1, 98.7 and 90.3%, respectively[11]. Cavitation is a physical phenomenon consisting of the formation, growth and subsequent collapse of cavities that occur in small time intervals, releasing large levels of energy[[12] [13]. The hydrodynamic cavitation performance is affected by various parameters such as inlet pressure, cavitation device, location of the cavitation device, flow rate, diameter and material of the pipe, etc.[14]. When the fluid flows through the constriction of the device, pressure and kinetic energy are exchanged and the fluid velocity increases at the expense of the decrease in local pressure[15]. Due to the violent internal collapse of the formed cavities and the intensification of the mass transfer rates, highly reactive free radicals (predominately HO* and H*) are released from the hot spots produced through the thermal destruction of the molecules, with an estimated temperature of up to 5000 K. and a pressure of around 1000 bar inside the cavities[16]. Cavitation is known to generate extremely active hydroxyl radicals (OH*) upon dissociation of water molecules (Equation 1) and reactive radical species due to cleavage of dissolved oxygen in solution (Equations (2) and (3)[17]

H_2 O→〖OH〗^*+H^* (1)

O_2→2O^* (2)

O^*+H_2 O→2〖OH〗^* (3)

Hydrodynamic cavitation (HC) is an emerging technology, widely recommended for water and wastewater treatment, as this mechanism involves less maintenance, simplicity in operation, simple construction and significant efficiency.[18]. When the temperature of the hydrodynamic cavitation reactor is not controlled by a cooling system, there is a substantial increase in the fluid temperature as a function of time[19]. Previous studies were reported by the temperature increase at 51°C of sugar cane juice in a 17-hole metal plate at a pressure of 3.5 bars in a treatment time of 40 minutes[20]. In previous studies on water softening with hydrodynamic cavitation, a reduction in hardness of 83% was observed at an inlet pressure of 3 bars when cavitation was performed with a Venturi tube. When an orifice plate was used for cavitation, hardness was removed by 91% at a pressure of 2 bars [12]. HC performance increases when integrated with other processes, e.g. aeration, oxygenation, Fenton[21], UV[22] , ozone[23], TiO2 nanoparticles [24]. Some advantages of HC equipment are simplicity of construction, low cost, high energy efficiency and easy scalability[25]. HC have demonstrated application in food processing, extraction of valuable products, biofuel synthesis, emulsification and waste remediation, including broad spectrum contaminants such as pharmaceuticals, bacteria, dyes and organic pollutants. [15]. Previous studies have revealed that the performance of hydrodynamic cavitation in hardness removal depends on multiple parameters such as inlet pressure, orifice diameter, number of orifices, velocity, pipe material, etc. Under such circumstances, it is difficult to decide which is the most significant parameter governing the effectiveness of hydrodynamic cavitation[12]. Reverse osmosis (RO) is a well-developed technology for the production of drinking water. One of the main drawbacks of reverse osmosis is the volume of concentrate (reject) produced during the process, which involves the management and treatment of RO concentrates. The calcification process, which converts calcium ion (into calcium carbonate) solid phase, is widely used for calcium removal in various industries.

The present work examined the removal of calcium ions from wastewater from a reverse osmosis plant by hydrodynamic cavitation and sodium bicarbonate addition. The effect of the wastewater recirculation flow rate and the number of holes in the metal plate on the percentage removal of calcium ions present in the wastewater, pH variation, total dissolved solids and liquid temperature was studied. Recently, we have discovered quite successfully, the installation of an orifice plate in a universal joint, a hydrodynamic cavitation device that is easy to install, clean and maintain, replacing conventional installations that use flanges to fix the orifice plate.

2. MATERIEL AND METHODS

2.1. Materials

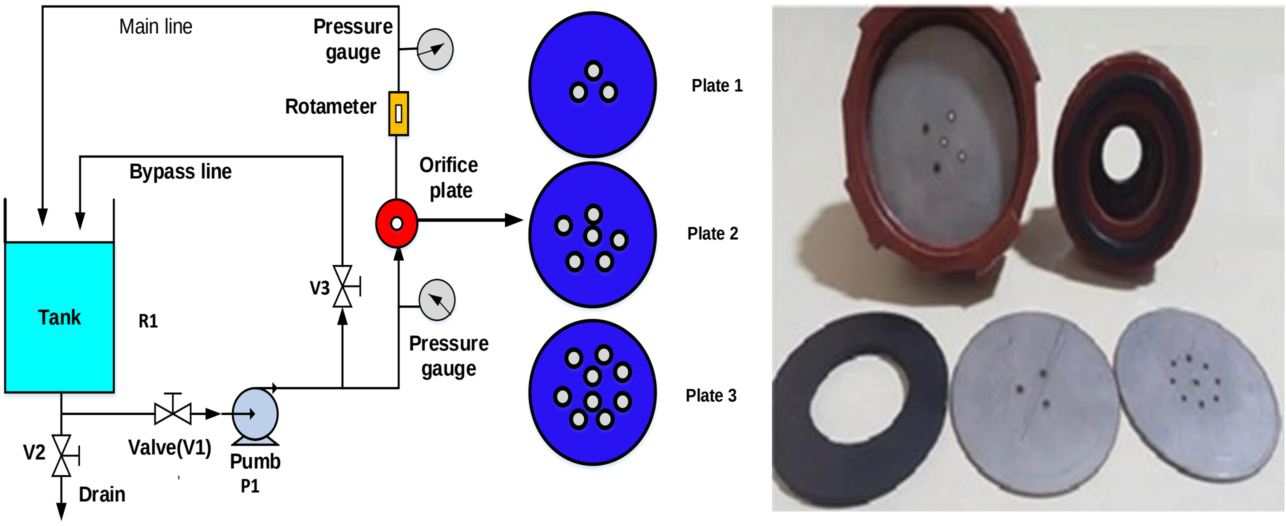
Wastewater (reject) from the reverse osmosis module, with a production capacity of 150 L/h of permeate and 200 L/h reject stream, was used. The total sample of 90 L was collected at the outlet point of the waste effluent. Calcium hardness was measured using 0.01M concentration ethylenediaminetetraacetic acid (EDTA), based on the method and procedure [26]. The conductivity was measured using an ADWA AD 330 conductivity meter and pH with ADWA, instruments made in, Hungary and Romania, total dissolved solids meter with HANNA HI 98311. The physicochemical character-istics of the wastewater whose mean values are shown in Table 1.

Table 1. Initial physicochemical characteristics of wastewater.

Parameters	**Unit**	**Average value**
Total Hardness	mg $CaCO_3$/L	510.0
Conductivity	µS/cm	1484.75
STD	mg/L	757.06
pH	--	8.0
Temperature	°C	18.53

2.2. Experimental Setup and Procedure

Hydrodynamic cavitation experiments were carried out using the newly constructed apparatus, as shown in Figure 1. The reactor (R1) has a volumetric capacity of 4 liters. The 1Hp centrifugal pump (P1) drew the liquid from R1 and sent it to the main pipe and through the cavitation device. The hydrodynamic cavitation device is equipped with a 0.5-inch diameter universal joint containing a gasketed orifice plate. In each test, the wastewater sample was recirculated for 60 minutes and samples were taken at 0, 20, 40 and 60 minutes, where total hardness, conductivity, total dissolved solids, pH and temperature were measured. Liquid flow through a bypass line was controlled by a regulating valve. The system was equipped with a flow meter (rotameter) and two pressure gauges (manometer). To vary the flow rate, the pump flow was diverted with the help of the bypass line.



a)

b)

Figure 1a. Schematic representation of hydrodynamic cavitation reactor set-up; Figure 1 b. Orifice plates.

2.3. Design Parameters of Orifice Plates

Cavitation generation mainly depends on geometrical parameters (shape, size, and single/multiple holes) of the orifice plate .[20].The hydrodynamic cavitation device consists of 0.5 inch diameter (12.7 mm) and 1.3 mm thick 316 stainless steel circular metal plate with 3, 5 and 9 circular holes of 1 mm diameter. The metal plate is inserted into a 1-inch diameter PVC universal joint. Table 2 shows the characteristics of the orifice plates.

Table 2. Orifice plate characteristics.

Plate number	N° of holes(n)	Diameter of each hole	Flow area	α	β
		(d_h)(mm)	mm^2	mm^{-1}	
1	3	1	2.355	4	0.019
2	5	1	3.925	4	0.031
3	9	1	7.065	4	0.056

Two parameters are used to characterize the orifice plate, i.e., α and β, which are defined as[27]. The alpha(α) parameter was calculated using equation (4).

$$\alpha=\frac{\text{Total perimeter of the holes}}{\text{Total area of opening}}=\frac{n2\pi(d_h/2)}{n\pi(d_h/2)^2}=\frac{4}{d_h} \tag{4}$$

A parameter α is defined as a ratio of throat perimeter to flow area[36], was calculated using equation(4). The parameter, β which can be defined as the ratio of total flow area or area of holes to the cross-sectional area of the pipe, was calculated using equation(5).

$$\beta=n\left(\frac{d_h}{d_p}\right)^2 \tag{5}$$

where, n = total number of the holes on the orifice, d_h= orifice hole diameter, mm; d_p= pipe diameter, mm(12.7 mm)

The number of passes can be determined using Equation 6.

$$\text{Number of passes of liquid}=\left(\frac{\text{Volumetric flow rate}}{\text{Total volume of water(L)}}\right)\text{x Treatment time(min)} \tag{6}$$

The velocity of the orifice plate, was calculated using equation (7). Volumetric flow rate(Q); area (A)=$\frac{\pi}{4}{d_h}^2$

$$v=\frac{Q}{A} \tag{7}$$

2.4. Experimental Design

A design of experiments (DOE) factorial design was used to investigate the effect of the number of orifices and flow rate (factors) on the removal of calcium hardness (response).The number of plate holes can affect the flow rate and then decide the strength of the HC effect[28]. Therefore, it is necessary to study the influence of the number of plate holes on hardness removal. A general full factorial design of two factors at three levels, number of orifices (3,5 and 9) and flow rate (0.6, 1 and 1.5 L/min) has been considered, resulting in nine experiments with their corresponding replication, having a total of 18 experiments.Sodium bicarbonate of 530 mg/L concentration was added to each experiment, according to studies carried out by[29]. Table 3 shows the low, medium and high levels at which the factors were tested. The high level was represented with a plus sign (+1), the medium level with the sign (0), and the low level with a minus sign (-1). The statistical software Minitab 17 was used to carry out the experimental design and analysis of variance (ANOVA)

Table 3. Independent variables.

Factors	Unit	Levels		
		Low (-1)	Medium (0)	High (+1)
Number of holes (X_1)	---	3	5	9
Flow (X_2)	L/min	0.6	1.0	1.5

2.5. Calculation of Removal Percentage (%)

The Efficiency of Removal Of Hardness (Calcium) Was Calculated Using Equation (8)

$$R=\left(\frac{C_0-C_T}{C_0}\right)\text{ X }100\% \tag{8}$$

Where, Removal Efficiency (R) C_0 (Mg/L) And C_T (Mg/L) Are The Initial And Final Hardness Concentration, Respectively.

3. RESULTS AND DISCUSSIONS

3.1. Results of the Studied Variables

Table 4 details the results of the total hardness of the treated water and the percentage of removal after the application of hydrodynamic cavitation for the different levels of the operating factors. As can be seen in Table 4, the experimental conditions had a substantial influence on the responses since the percentage of hardness removal varied from 56.37 % to 66.76%.

Table 4. The design matrix and responses for the experimental values.

Experiments	X1 Number of holes	X2 Flow L/min	Average hardness (mg/L)	Hardness removal percentage(%)
1	3	0.6	222.5	56.37
2	3	1.0	200.5	60.69
3	3	1.5	188	63.14
4	5	0.6	210	58.82
5	5	1.0	195	61.76
6	5	1.5	183	64.12
7	9	0.6	211.5	58.53
8	9	1.0	172.5	66.18
9	9	1.5	169.5	66.76

Table 5 shows the descriptive statistics for the percentage of hardness removal, it is observed that the standard deviation is 3.56 and the mean is 61.82%.

Table 5. Standard deviation of hardness removal percentage.

Response	N°	Mean	SE Mean	StDev	Minimun	Q1	Median	Q3	Maximun
Hardness removal	9	61.82	1.19	3.56	56.37	56.68	61.76	65.15	66.76

The process allowed a significant removal of water hardness (61.82 % mean table 5), however, these relatively low results are possible due to the levels taken for wastewater recirculation flow, cavitation device inlet pressure, treatment time and sodium bicarbonate concentration. Also the simultaneous precipitation of magnesium ions in the process.

3.2. Removal of Hardness

The effects of the two independent variables and their interactions on the percentage of hardness removal were analyzed using the Pareto diagram. The independent variables investigated were the number of holes in the metal plate (X1) and the wastewater recirculation flow rate (X2), while the percentage of hardness removal (Y) was the response variable. The maximum percentage has been identified as 66.76, which corresponds to experiment 9, where the input parameters are 9 for the number of holes in the metal plate and 1.5 L/min for the flow rate. Experimental run 1 produced the lowest per-centage of hardness removal. Similar effects of the number of holes in the plate and the flow rate on hardness reduction have been observed [30] they have reported the effect of the diameter and number of holes of the plate on the efficiency of softening and disinfecting the water. Figure 2 shows the effect of the number of holes in relation to the percentage of removal with the number of passes of the fluid operating at a flow rate of 1.5 L/min. It can be seen that for the same number of passes, when the number of holes is increased, there is greater removal of hardness. According [15] a greater number of passes through the orifice configuration, the liquid experiences cavitation conditions a greater number of times, resulting in higher degradation rates.

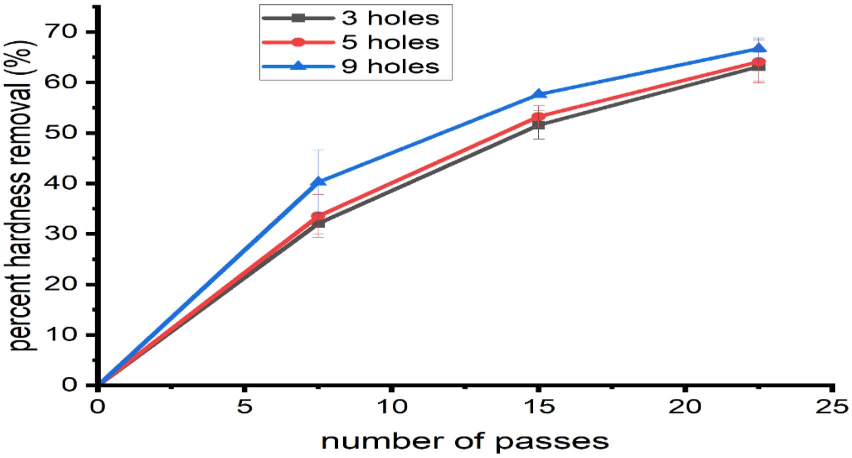


Figure 2. Effect of number of passes on the hardness removal (experiments were in duplicate and results were shown as average ± standard deviation).

The results of the effect of the main factors and interaction of the factors with respect to the response variable, can be observed through a Pareto diagram. Figure 3 shows the highest and lowest values of the effects on the percentage of hardness removal, the factor X1 (flow rate) and X1X2 (flow rate interaction and number of holes) are observed, respectively. This means that X2 has been evaluated as the factor that most influences the percentage of hardness removal, while the combination X1X2 as the least significant factor, which means that these three combinations of factors have a significant impact on the removal of hardness. the hardness. Furthermore, the critical standardized effect has been calculated as 2.26.

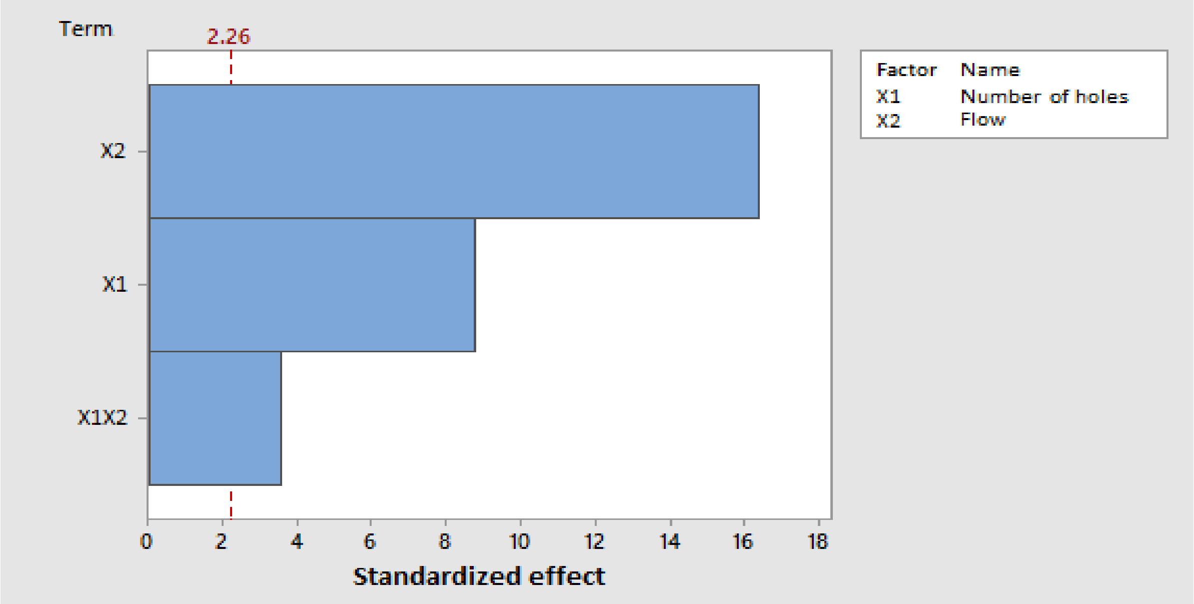


Figure 3. Pareto diagram of standardized effects (bars crossing the reference line are statistically significant).

According to Figure 4, it is observed that the variation of the flow rate has the strongest effect on hardness removal, it shows more slope with respect to the other factor, especially in the change from low to medium level. This also implies that increasing the number of holes in the metal plate favors the increase in the percentage of hardness removal.

The graphs showed that the factors work best (providing higher percent hardness removal) at their highest levels. Therefore, it can be concluded that, when performing removal by hydrodynamic cavitation, flows of 1.5 L/min are preferred over 1 L/min and 9 holes on 5 holes. Previous studies have revealed that single-hole plates have lower cavitation formation characteristics and multi-hole plates have high cavitation characteristics[31]. Similar results were reported by [31] have reported, with higher flow rate and multiple holes rapid dye degradation is achieved even at lower flow rates due to a higher tendency to cavitation.

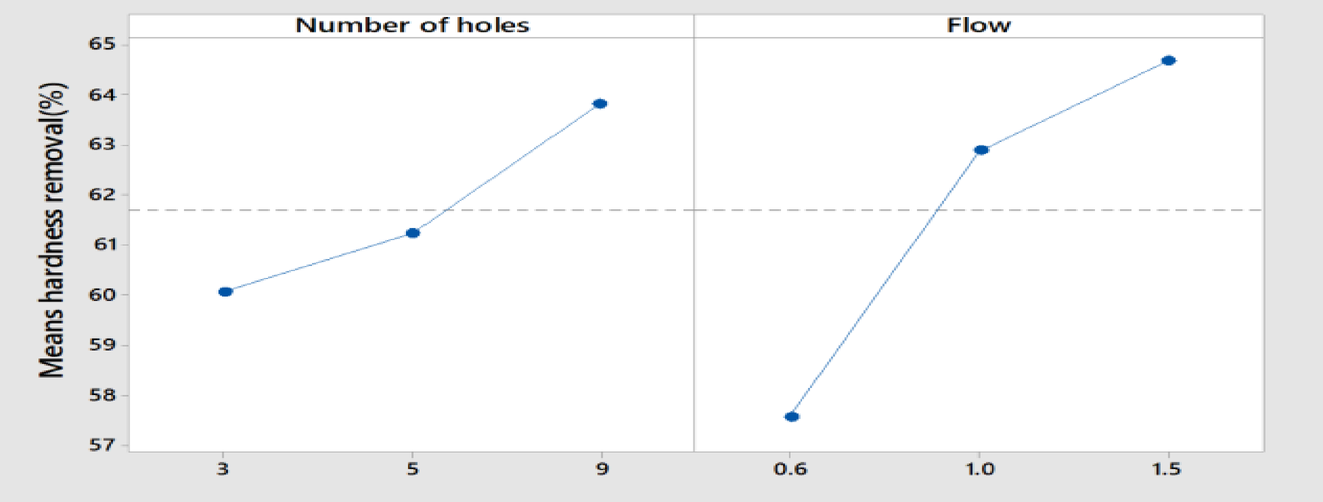


Figure 4. Main effects of 2 factors (X1. number of holes, X2. flow) at three levels.

3.3. Analysis of ANOVA

The summary analysis of variance (ANOVA) is presented in Table 6. Based on the P values at the <0.05 significance level, flow and number of orifice plates had statistically significant effects on response. P values less than 0.05 indicate that the model terms are significant, as observed for the number of plates and flow rate. For the quadratic hardness re-moval model (Table 6), the model F-value of 32.08 implies that the model is significant.

Table 6. Analyses of variance (ANOVA) for hardness removal.

Source	GL	SC Ajust.	MC Ajust.	Valor F	Valor p
Model	5	191.717	38.343	32.08	0.000
Linear	2	180.691	90.345	75.59	0.000
Number of holes	1	42.986	42.986	35.96	0.000
Flow	1	138.605	138.605	115.96	0.000
Square	2	15.558	7.779	6.51	0.012
Number of holes*Number of holes	1	0.242	0.242	0.20	0.661
Flow*Flow	1	15.316	15.316	12.81	0.004
Interaction of 2 factors	1	1.448	1.448	1.21	0.293
Number of holes*Flowl	1	1.448	1.448	1.21	0.293
Error	12	14.343	1.195		
Lack of fit	3	10.710	3.570	8.84	0.005
Pure error	9	3.633	0.404		
Total	17	206.060			

Note: df = degree of freedom, SS = sum of squares, MS = mean square, F = value F, p=Value p

Figure 5 shows the best combination of factor settings to achieve the optimal response, it turned out to be: number of holes in the metal plate of 9 and flow rate of 1.4818 L/min for a removal percentage of 67.1597%. The optimal values of the independent variables were calculated using the Minitab 17 software.

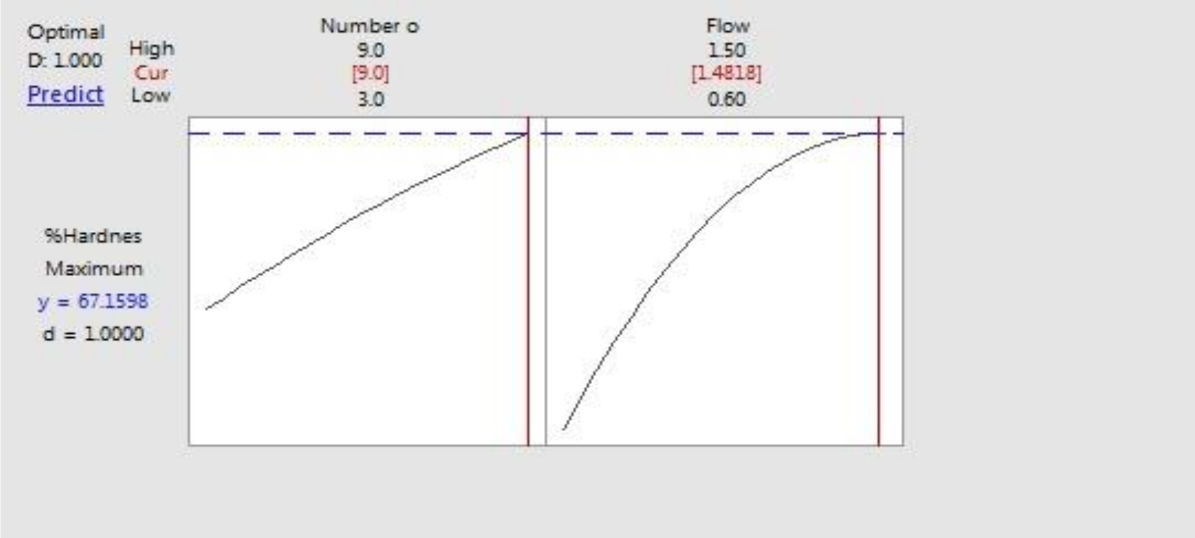


Figure 5. Optimization plot for factorial design.

The result of the percentage of removal of the hardness of our investigation carried out can be compared with other works carried out under different operating conditions. [32] used a flow of 50 L/min , nine number of hole , one mm hole diameter and in a time of 120 minutes was also used. In this work, a percentage of removal of the average hardness quite similar to our work, equal to 79.36% in different operating conditions, was obtained. This information is shown in Table 7, adapting and modifying from [32].

Table 7. Comparison of the percentage of hardness removal

Plate number	Nº of hole	Percentage removal of the hardness of river water (%)	Plate number	Nº of hole	Percentage removal of the hardness of reject water from reverse osmosis (%)
Plate 1	1	75.6	Plate 1	3	60
Plate 2	6	80.0	Plate 2	5	61.52
Plate 3	9	82.5	Plate 3	9	63.82

In accordate with Bharathi [33] the dissolved calcium in the water reacts with the added sodium bicarbonate and becomes insoluble calcium carbonate according to reaction (Equation 9)

$$Ca_{(aq)}^{2+} + 2\,HCO_{3(aq)}^{-} \leftrightarrow CaCO_{3(s)} + H_2O_{(l)} + CO_{2(g)} \quad (9)$$

Results of water hardness removal with hydrodynamic cavitation accompanied by chemical reagents were reported by [32][29][34]. The synergistic effect between hydrodynamic cavitation with sodium bicarbonate can be attributed to the fact that hydrodynamic cavitation (HC) increases the homogenization and agitation of the mixture, thus facilitating the calcium ions to come into contact with the carbonate ions for the formation of calcium carbonate.

From Table 8 it is observed that there is an improvement in the percentage of hardness removal with an increase in the value of β. Maximum 63.82% removal was achieved with for the 9-hole plate (β = 0.056). Sivakumar et. al[15] observed similar results for degradation of rhodamine B. Table 8 shows the plates (Plate 1, Plate 2 and Plate 3) have the same alpha value (4 min-1). However, the plate with the highest number of holes achieves a higher percentage of hardness removal (63.82%) in 60 minutes of treatment. Malade & Deshannavar[35] observed similar behavior in decolorization of Reactive Red 120. Rajoriya et. al[36] also shows an increase in the percentage of blue reagent discoloration.

Table 8. Percentage of hardness removal as a function of β.

Plate number	N° of holes(n)	α(mm^{-1})	β	Average hardness removal percentage(%)
1	3	4	0.019	60.06
2	5	4	0.031	61.56
3	9	4	0.056	63.82

During the orifice-based HC process, with an increase in inlet pressure, recirculation flow rate and number of holes in the plates, there was an increase in the percentage of calcium hardness removal, however, these relatively low results are possible due to the levels taken from the wastewater recirculation flow rate, cavitation device inlet pressure, treatment time and simultaneous precipitation of magnesium ions in the process. [37] observed that the intensity of cavitation increased with decreasing temperature in water, it is possible the low hardness removal is due to the considered increase of temperature (77°C). This conclusion was derived from the fact that the degradation performance worsened with temperature[38]

3.4. Liquid temperature analysis

Figure 6 shows the increase in water temperature in the hydrodynamic cavitation reactor with nine holes for the flow rates (0.6L/min, 1L/min and 1.5L/min) in 60 minutes of treatment. It is observed that during the first 30 minutes the temperature increases linearly, then the increase is more moderate until reaching an average temperature of 74 °C. The rapid rise in solution temperature can be attributed to heat generation due to the collapse of cavitation bubbles. In addition, the heat generated by the friction between the solution and the pipe wall will also slightly increase the temperature of the solution. It is observed that as time passes the temperature increases, there is no significant variation at different flows of recirculation of wastewater. [39] observed similar behavior in experiments with rotor reactors R1, R2 and R3 for flows of 40, 60 and 80 L/h with 14, 20 and 26 holes, respectively. [19] within 120 min, the temperature increased to almost 55 ºC and remained constant thereafter. [32] in its experimental module it provides an external heat exchanger unit to control the temperature in the feed vessel tank, which is necessary as cavitation results in the production of heat, which increases the temperature of the effluent stream. [40] reported the increase in solution temperature with the use of a hydrodynamic cavitation device increases by 62.37°C, without using HC device it increases by 35.64 after 40 minutes of continuous circulation. These results are consistent with the results obtained in our work developed with HC. During the orifice-based hydrodynamic cavitation process, with an increase in flow rate and number of holes in the plates, there was a significant increase in liquid temperature.

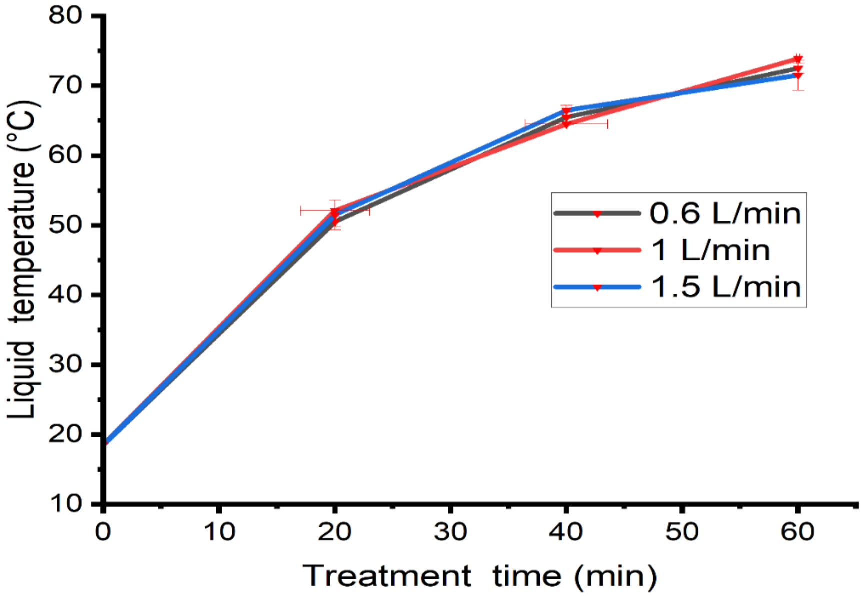


Figure 6. Increase in temperature of water with hydrodynamic cavitation with nine holes, for the different flow rates (experiments were in duplicate and results were shown as average ± standard deviation).

3.5. pH Analysis

Figure 7 shows the behavior of the pH of the residual water in the hydrodynamic cavitation reactor as a function of time and number of holes with a recirculation flow rate of 1.5 L/min. The same trend of pH decrease is observed as the treat-ment time elapses for the three orifice plates. A pH decrease of 7.5% is achieved in 60 minutes. [30] have observed pH reduction for composite samples with different numbers and diameters of holes, reaching a maximum reduction of 2.98%. The carbon dioxide from equation (9) combines with the water, forming carbonic acid and the dissociation of the acid into hydrogen ions and bicarbonate causes a drop in pH which is why the pH decreases over the treatment time[41]. During the orifice-based HC process, with a variation of orifices in the plates, there was an increase in liquid acidity, a decrease in pH.

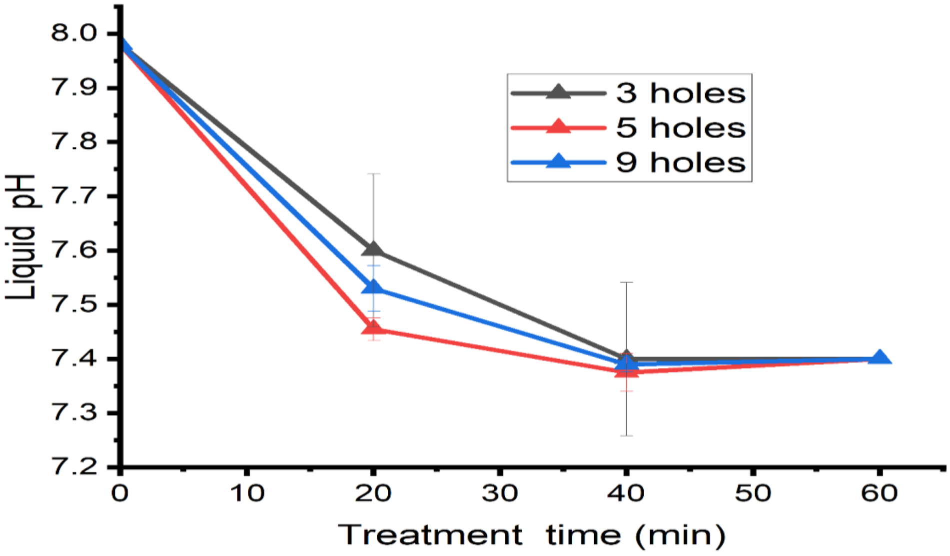


Figure 7. Mean values of water pH in the reactor for the different numbers of holes in the plate tested. (Experiments were in duplicate and results were shown as average ± standard deviation).

3.6. Analysis of total dissolved solids

Figure 8 shows the behavior of the TDS of the residual water in the hydrodynamic cavitation reactor as a function of time for the different numbers of holes operating at a flow rate of 1.5 L/min. Figure 8 shows the decrease in TDS as time goes by, where the 9-hole plate had the best result, reaching a 36.99% reduction. Redekar et al. (2020) have observed a decrease in TDS for composite samples with different numbers and diameters of holes, reaching a maximum reduction percentage of 16.76%.

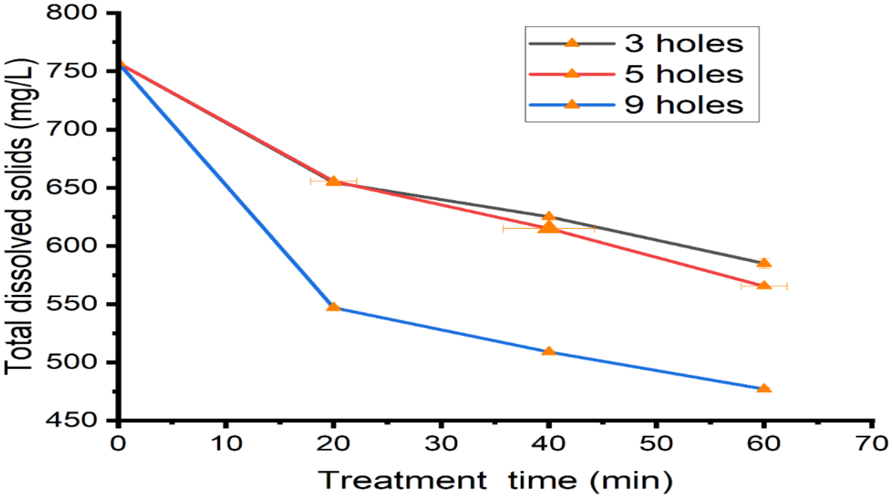


Figure 8. Mean values of total dissolved solids in the reactor for the different numbers of holes in the plate tested (ex-periments were in duplicate and results were shown as average ± standard deviation).

3.6. Feed Pressure Effect

Inlet pressure and flow rate are the most important operating parameters affecting the cavitation process[42]. The effect of inlet pressure (0.14 , 1 and 1.86 bar) on hardness removal was evaluated for 60 minutes of treatment. Figure 9 shows, the percentage of hardness removal increases with increasing pressure for pressure from 0.14 bar (56.3%) to 1.86 bar (66.7% removal) for the metal plate with 9 holes. Malade & Deshannavar[35] found similar trend and observed that 3-hole plate produce maximum decolorization of Reactive Red 120 at a pressure of 3.5 kg/cm2. Dhanke & Wagh[43] investigate the effect of inlet pressure for the degradation of AR-18 in a 3-hole plate HC reactor.

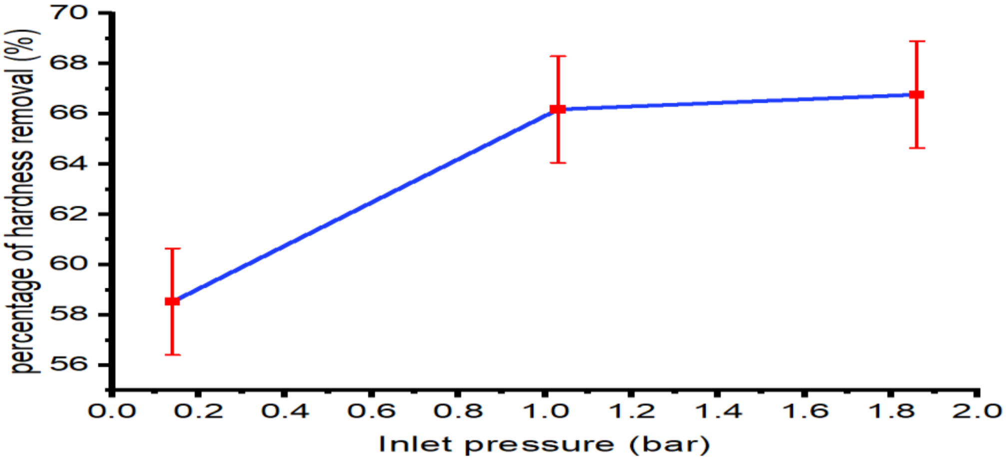


Figure 9. Effect of inlet pressure on percent hardness removal for 9-hole plate (experiments were in duplicate and results were shown as average ± standard deviation.

4. CONCLUSION

The full factorial design method is a very powerful tool to study the influence of the main factors in the processes, significantly reducing the number of experiments, saving experimental time, amount of reagents and sam-ples. In this study, a hydrodynamic cavitation system is constructed and the effects of the independent variables (number of holes in the metal plate and flow rate) on hardness removal are evaluated. Based on the results of this study, we draw the following important conclusions.

- The results show that, as the flow rate and the number of holes increase, the percentage of hardness removal in-creases, obtaining, for a recirculation flow rate of 1.5 L/min and a plate with 9 holes, a maximum removal per-centage of 66.76%.

- The hardness removal efficiency increased with increasing orifice plate inlet pressure (0.2 - 2 bar).

- The temperature fluctuated within the range 20~75°C over a treatment time of 60 minutes. Likewise, it is ob-served that- the temperature increase has a linear correspondence with the flow rate and number of orifices in the metal plate.

- Solution pH and total dissolved solids decrease during the treatment time.

- In the future, the evaluation of other factors of the orifice plate HC process and the addition of sodium bicarbonate to the system, can further improve the water hardness removal effect, which provides a synergistic effect.

- Based on this research, the hydrodynamic cavitation process represents a sustainable removal technique as it does not produce secondary contamination.

- In further studies, I recommend evaluating hardness removal at higher levels of pressure, flow rate, sodium bi-carbonate concentration and time to achieve a higher degree of water hardness removal.

- Hydrodynamic cavitation is a technology that is being used for water treatment and removal of calcium ions, is an option as well as various technologies that are used to treat water, however the use of hydro-dynamic cavitation is an option, economical and environmentally friendly, so it is open the study to im-prove efficiency.

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