

Decolourization of Rhodamine B: a swirling jet-induced cavitation combined with NaOCl

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Abstract

A hydrodynamic cavitation reactor (Ecowirl) based on swirling jet-induced cavitation has been used in order to allow the degradation of a waste dye aqueous solution (rhodamine B, RhB). Cavitation generated by Ecowirl reactor was directly compared with cavitation generated by using multiple hole orifice plates. The effects of operating conditions and parameters such as pressure, pH of dye solution, initial concentration of RhB and geometry of the cavitating devices on the degradation rate of RhB were discussed. In similar operative conditions, higher extents of degradation (ED) were obtained using Ecowirl reactor rather than orifice plate. An increase in the ED from 8.6% to 14.7% was observed moving from hole orifice plates to Ecowirl reactor. Intensification in ED of RhB by using hydrodynamic cavitation in presence of NaOCl as additive has been studied. It was found that the decolourization was most efficient for the combination of hydrodynamic cavitation and chemical oxidation as compared to chemical oxidation and hydrodynamic cavitation alone. The value of ED of 83.4% was reached in 37 min using Ecowirl combined with NaOCl (4.0 mg L⁻¹) as compared to the 100 min needed by only mixing NaOCl at the same concentration. At last, the energetic consumptions of the cavitation devices have been evaluated. Increasing the ED and reducing the treatment time, Ecowirl reactor resulted to be more energy efficient as compared to hole orifice plates, Venturi and other swirling jet-induced cavitation devices, as reported in literature.

Highlights

A HC reactor based on swirling jet-induced cavitation is proposed.

The swirling jet reactor is more energetically efficient as compared to the hole orifice plates.

A different geometry of the HC device affects the intensity of the cavitation.

Synergetic effect between HC and NaOCl are related to the additional •OH radicals production.

The hybrid scheme based on HC and NaOCl is most energy efficient.

Keywords

Energy efficient; Rhodamine B degradation; Swirling jet-induced cavitation; Sodium hypochlorite; Synergetic effect.

Abbreviations

AC	Acoustic cavitation
ED	Extent of degradation
HC	Hydrodynamic cavitation
RhB	Rhodamine B

1. Introduction

Dye pollutants are extensively employed to impart colour in various industrial processes, such as textile, plastic, leather, food, dyeing, paper, printing, pharmaceutical and cosmetic industries [1–3]. Even a very low concentration of dyes in the effluents is highly visible and undesirable. Many of these are toxic, carcinogenic or even mutagenic to life forms [4–6]. Moreover, the presence of these contaminants in water bodies reduces the light penetration and the oxygen transfer, hence affecting aquatic life [7]. In consequence, occurrence of dyes in wastewaters led to serious environmental and human health issues [8].

The dye under consideration in this study is Rhodamine B (RhB, tetraethylrhodamine, molecular formula: $C_{28}H_{31}N_2O_3Cl$; molecular weight: 479.01 mol^{-1} ; colour: basic violet 10). RhB, a basic dye of xanthene class, non-volatile and highly soluble in water, methanol and ethanol, is commonly used for dyeing textiles, paper, soap, leather, jute, food and drugs. Further, as RhB shows a high degree of persistence, it is commonly used as a systemic marker in a variety of animals [9] and as a water fluorescent tracer for wildlife studies [10,11]. The colour of the dye is bright reddish violet.

Both carcinogenicity [12] and toxicity [13] of RhB towards human and animals and genotoxicity in plant systems [6] have been experimentally proved. Further, more and more stringent environmental legislations have required many efforts to develop technologies that are able to remove dyes and minimize hazardous effects caused by industrial wastewaters. As reviewed by Robinson et al. [8], various techniques had been proposed for removing dyes from wastewaters, such as biological [14], physical [15–17] and chemical [15,18,19] processes.

Recently, cavitation process [20] has been attracting attention among the Advanced Oxidation Processes (AOPs), due to its elevated oxidative capability, linked to its ability of generating highly reactive free radicals [21]. There are four types of cavitation depending on the mode of its generation: acoustic, hydrodynamic, optic and particle cavitation. Among the cavitation techniques mentioned, acoustic [22] and hydrodynamic cavitation [23,24] have been the most studied and applied to dyes treatments, mainly due to the ease of operation, flexibility and capability to vary the required intensities of cavitation conditions. In particular, hydrodynamic cavitation (HC) requires less energy than the acoustic one [25,26]. For this reason, there is a great interest in developing innovative HC devices in order to optimize the wastewaters treatments as well as reduce the energy requirements. Recently, HC has been successfully used for remediation of polluted aqueous solutions containing persistent pollutant as pesticides [27], pharmaceutical drugs [28,29] and dyes [30–35].

Cavitation process involves the dissociation of vapours trapped in the cavitating bubbles, resulting in the generation of free radicals, such as $\bullet H$ and $\bullet OH$, which are very strong and not specific oxidizing species,

efficiently decomposing and destroying both organic and inorganic compounds. This effect works on water clusters, agglomerations of fibres and molecules. Given that $\bullet\text{OH}$ radical is the most oxidising free radical, the production rate of $\bullet\text{OH}$ radicals strongly influence the oxidation efficiency of contaminants. Among dyes, a great interest has grown on decolourization of RhB by using acoustic cavitation [22,32,33] and hydrodynamic cavitation [23–25,36,37], where the controlling mechanism of RhB degradation is the free radical attack [22,37].

As reviewed by Gogate et al. [38], several design configurations of the HC reactor had been proposed in order to optimize dyes degradation; all of them based on a closed loop circuit. A commonly used device for RhB removal is the HC unit based on orifice plate [25]. Sivakumar and Pandit [25], studying six types of plates with different diameter and number of holes, evaluated the effect of the geometry of the orifice plates on the RhB degradation. Mishra and Gogate [24], investigated the effect of inlet pressure (over a range 2.9 - 5.8 atm), operating temperature (30 and 40°C) and pH (over a range 2.5 - 11) on the RhB degradation by using two different cavitating devices viz. orifice plate and Venturi. Gore et al. [35] studied the degradation of orange 4 dye by using a circular Venturi as cavitating device. Wang et al. [23] discussed the effect of operating conditions on RhB degradation by using a swirling jet-induced cavitation system. A liquid whistle reactor, comprising of an orifice and a blade, has been used to treat chemical manufacturing wastewaters by HC [39]. A low pressure pilot scale HC reactor using fixed scrap iron sheets as heterogeneous catalyst has been used for decolorization of RhB [36]. A HC device comprising of a stator and rotor assembly has been used by Badve et al. [40] and Petkovšek et al. [41] to study the treatment of a wastewater from wood finishing industry and pharmaceutical industry, respectively.

Further, several researchers have investigated the intensification of degradation of RhB using HC in the presence of additives. Hydrogen peroxide (H_2O_2), Fenton chemistry ($\text{FeSO}_4:\text{H}_2\text{O}_2$ in the ratio of 1:5) and Chloroalkanes (CCl_4) had been investigated as useful additives in improving the efficacy of HC reactor by Mishra and Gogate [24]. The only use of H_2O_2 combined with HC had been studied by Wang et al [37]. Ozone had been used combined with HC to degrade orange 4 dye [35]. Sodium hypochlorite (NaOCl) have been used to promote degradation of Rhodamine B using sonochemical cavitation [42] and the degradation of orange acid II and brilliant green dye using HC [26].

To date, it appears that the processes based on HC has to be improved for dyeing industrial application. A good design and fabrication of a hydrodynamic set-up differing in flow field, turbulence characteristics and geometry are needed to enhance the use of this process as a sustainable supplement process for wastewaters treatment.

The present work has been dedicated to study and compare the effectiveness of two modes of industrial HC device viz. an orifice plate and a modified swirling jet-induced reactor, named Ecowirl reactor [43]. Due to its presence in water distribution systems as residual chlorine, the use of NaOCl as additive to intensify the extent of degradation of RhB has been investigated. Further, the study has been devoted to maximize the hybrid treatment scheme based on HC and NaOCl , concentrating on the optimization of operating parameter of the hybrid system (inlet pressure, pH, concentration of RhB and NaOCl) and the geometry of the constriction

chamber (using both orifice plate and Ecowirl reactor). The energetic consumptions of the cavitation devices have been evaluated.

2. Material and methods

2.1 Reagents

RhB was obtained from Sigma-Aldrich Co. LLC, and was 95% pure. A stock solution 10.0 g L^{-1} of RhB was prepared by dissolving the dye in distilled water. Afterwards, it was diluted obtaining a working standard solution in the range of $2.0 - 5.0 \text{ mg L}^{-1}$. Both distilled water and tap water were used. Tap water contained a residual chlorine in the range of $0.1 - 0.2 \text{ mgCl}_2 \text{ L}^{-1}$. NaOCl solutions were prepared by dilution of the commercial product (13% w/v, Acros Organics); concentrations are reported as mgNaOCl L^{-1} . Sulphuric acid H_2SO_4 (0.1 mol L^{-1}) and sodium hydroxide NaOH (0.1 mol L^{-1}) were used to adjust the pH of the dye solution. All chemicals used were of analytical grade (Sigma).

2.2 Hydrodynamic cavitation system

Fig. 1 shows a schematic representation of the experimental configuration used for HC. It was a closed loop circuit designed to draw a RhB dye solution from a feed tank of 50 L volume, then taking it into a flow channel internally accommodating the cavitating device and then discharging the treated solution back to the tank with a pump. The solution to treat was recirculated and entered again into the feed tank. The suction side of the pump was connected to the bottom of the tank. The flow channel terminated well inside the feed tank, below the liquid level in order to avoid any introduction of air into the system.

Details are as follows: (1) a feed tank; (2) a mono screw pump (3.0 kW, Netzsch Pumps & Systems GmbH Germany); (3) an inverter (Bonfiglioli Vectron - Active) used to control the pump flow rate (in the range of $0.5 - 6 \text{ m}^3 \text{ h}^{-1}$) and the inlet pressure (about 0.5 - 12 bar) of the liquid by adjusting the frequency, (4) a cavitating device; (5) a sampling port; a system of control valves at appropriate places (V1, V2, V3, V4); a pressure gauge to measure the inlet pressure (P1); a vacuum gauge to measure the vacuum after the cavitating device (P2). During each experimentation, valves V1 and V2 were always kept fully open, while valves V3 and V4 were used at the beginning and at the end of each experiment, in order to feel and draw the feed tank, respectively.

Two different cavitation devices were used viz. an orifice plate and a modified swirling jet-induced reactor. The orifice plate used in this study was circular with a diameter of 40 mm and 33 holes of 2 mm diameter each (Fig. 2a). Four orifice plates, with different thickness (1, 2, 3 and 4 mm) have been considered. The plates were made of stainless steel (AISI 316).

A modified swirling jet-induced reactor device, named Ecowirl [43], patented by Econovation GmbH, Germany and commercialized and optimized by Officine Parisi S.R.L., Italy, had been used as innovative HC device (Fig. 2b). Ecowirl is a full scale HC reactor, made of stainless steel (AISI 316) and based on a particular geometry of constrictions which create multi-dimensional vortices of liquid that never hint the walls of the reactor, avoiding problems of erosion, allowing to harness the impressive effects of HC for chemical-physical

transformations. Fig 3. shows as this device operates like a swirling jet-induced reactor, in which cavitation is generated by using a multi-dimensional vortices generator, consisting of (i) a frustum-conical pre-swirling chamber with six injection slots at the vertex through which the flow enters and (ii) a double cone chamber where cavitation mainly occurs, resulting in an increase in the extent of cavitation. Injection slots (upstream diameter 10 mm - downstream diameter 8 mm) divide the radial vortex in six single vortices generating a braided stream along the jet axis with a helical shape. Due to centrifugal forces, the pressure in the core of the braided stream is lower than the vapour pressure of water, and cavitation bubbles are expected to generate. The frustum-conical pre-swirling chamber both accelerates the braided stream and shakes the solution to treat. Then, the braided stream is ejected from the conical pre-swirling chamber to the double-cone chamber and impacts to a perpendicular insert to the braided stream where the pressure is risen rapidly and the cavitation bubbles collapse. The field of helical vortex produces more than 1000 pulses per second.

2.3 Procedures

In a typical experiment, 50 L aqueous solutions of RhB were subjected to cavitation. The degradation of the contaminants by using HC is carried out for successive cycles. For this reason, each experiment included the recirculation of RhB dye solution. Initially, the degradation of RhB by using HC alone had been investigated. For this purpose, two different cavitating devices, orifice plate and modified swirling jet-induced reactor (Ecowirl reactor with standard double cone chamber), were used separately to treat the contaminated dye solution.

Afterwards, the effect of NaOCl as additive to intensify the degradation of RhB using HC has been studied. Treating an aqueous solution with an initial content of 3.0 mg RhB L⁻¹, the effects of sodium hypochlorite at 0.5 and 4.0 mg L⁻¹ in a mixing system and in the hybrid scheme have been investigated. Hence, the investigation of a progressive increase in the concentration of NaOCl (0.5, 1.0, 2.0, 3.0, 4.0 mg L⁻¹) was carried out using the Ecowirl reactor (standard type). Tap water containing a residual chloride in the range of 0.1 - 0.2 mg L⁻¹ and RhB was also tested.

Using the Ecowirl reactor, the effects of inlet operating pressure (2.0, 3.0, 4.0 bars) and geometry of the double-cone chamber (Type standard, type A, B and C) on the degradation rate of RhB were studied in the hybrid scheme based on HC and NaOCl chemistry. At the same time, using the orifice plate, the effects of operating conditions such as inlet operating pressure (2.0, 3.0, 4.0 bar), thickness of the plate (1, 2, 3, 4 mm), initial concentration of RhB (2.0, 3.0, 4.0 mg L⁻¹) and pH of solution (2.0, 3.0, 4.0, 5.5, 7.0, 8.0, 9.0, 10.0, 11.5) were studied in the hybrid scheme.

Table 1 shows parameters and operating conditions that have been varied during the experiments. The geometry of the double cone chambers differed for the length of the cylinder in the middle of the double cone. Type C is illustrated in Fig. 4.

The resultant flow rate through the system, and thus the applied frequency of the inverter, the absorbed power and the treatment time changed as a function of the installed cavitating device and the inlet operating pressure

are reported in Table 2. The desired inlet pressure value was fixed by setting the number of revolutions of the pump through the inverter.

A base for comparison was taken to be the 260th cycle, even though the complete degradation was not obtained during the corresponding treatment time. Through a sampling valve on the bottom of the feed tank, samples were taken out at an interval of 20 cycles for an analysis of the progress of degradation. The collected samples were analysed at the maximum absorption wavelengths of RhB (553 nm) by using a DR/2010 spectrometer (Hach Lange). RhB concentration was determined from the measured absorbance, using a pre-calibrated chart. Concentrated H₂SO₄ and NaOH were used for the pH adjustments. The temperature at the beginning of each run was fixed around at 20°C, while it was allowed to vary during the experiment. Throughout each run, temperature and pH had been monitored. All experiments were repeated at least two times and the reported values are an average of the different experimental runs. The experimental errors were within 2-3% of the reported value of the extent of degradation.

2.4 Calculations

There are several parameters able to quantize the degree of the gradual degradation of RhB by using an HC process. In order to estimate the extent of degradation (ED) of RhB, a percentage of removal was considered. The ED was calculated using the following equation:

$$ED(\%) = (C_0 - C)/C_0 \cdot 100 \quad (1)$$

The initial value of RhB concentration is denoted as C₀ [mg L⁻¹], the residual RhB concentration at the generic instant is written as C [mg L⁻¹].

Another parameter used for the characterization of the cavitation systems is the cavitation yield (C.Y.), defined as the ratio of the observed cavitation effect, in terms of RhB degradation, to the total energy supplied to the system. C.Y has been calculated from the equation (2) [44].

$$C.Y. = \text{RhB degraded}/\text{Power density} \quad (2)$$

where RhB degraded is the amount of dye in mg L⁻¹ removed in the experiment, while power density, in J L⁻¹, is represented by the following equation:

$$\text{Power density} = (P_{\text{abs}} \cdot t)/V \quad (3)$$

where V is the volume of liquid [L], P_{abs} the pump absorbed power [W] and t the time of treatment [sec]. Finally, the pressure difference (ΔP_{HC}), between the inlet operative pressure upstream of the constriction (P_{inlet}) and the operative pressure downstream of the constriction (P_{outlet}, where the vacuum is achieved), has been calculated for each test.

3. Results and discussion

3.1 Degradation using hydrodynamic cavitation alone

Degradation of RhB was investigated using two different cavitating devices viz. orifice plate and modified swirling jet-induced reactor. Experiments were performed using 3.0 mg RhB L⁻¹ aqueous solutions obtained

using distilled water and two approaches were put forward: (1) using orifice plate (33 holes x F = 2 mm, plate thickness= 2 mm); (2) using swirling jet-induced cavitation device (Ecowirl reactor - standard type, L=0cm). The frequency of the inverter was adjusted to provide an inlet pressure of 2.0 bar, corresponding to a flow rate of 6.0 m³ h⁻¹ and 4.6 m³ h⁻¹ for the orifice plate and Ecowirl reactor, respectively. Each test lasted 260 passes through the cavitation system, which corresponded to 130 minutes and 169 minutes using orifice plate and Ecowirl reactor, respectively. Other experimental conditions involved the solution temperature 20.0±1.0°C and pH 4.0.

The results are showed in Fig. 5. Comparing the two cavitating devices used in the present work, it can be seen from the Fig. 5 that, at similar operative conditions, higher extents of degradation were obtained using Ecowirl reactor rather than orifice plate. ED of 15% and 9% had been achieved using Ecowirl reactor and orifice plate, respectively. Up to date, other studies have been demonstrated the low efficiency of orifice plate as compared with other HC device. Mishra and Gogate [24] found a higher extents of RhB degradation using Venturi rather than orifice plate. In their study, the author attributed the greater efficiency of Venturi to the higher velocities in the reactor and hence to the higher number of passes through the cavitating zone for the same time of operation, resulting into higher degradation rates. In our study, for the same number of passes we achieved a higher ED using the Ecowirl reactor as compared to the orifice place. The obtained results can be attributed to the fact that the operating pressure downstream the Ecowirl reactor was lower (-0.85 bar) as compared to the value downstream of the orifice plate (0.30 bar) at similar inlet operating pressure (2.0 bar), resulting in a higher pressure drop. ΔP_{HC} values of 2.85 and 1.7 bar had been measured for the Ecowirl reactor and the orifice plate respectively (Table 3).

The efficiency can be also compared on the basis of cavitation yield (C.Y.). It can be noted that the Ecowirl reactor gives 1.3 times more cavitation yield as compared to the orifice plate, when operated individually under the same operative conditions (Table 3). Thus, even if the treated flow rate was lower using Ecowirl reactor, the corresponding C.Y. was greater mainly due to the higher extent of degradation, showing that Ecowirl reactor was the most performing cavitation device.

Finally, it was found that the concentration of RhB in aqueous solutions by using orifice plate and Ecowirl reactor decreased exponentially with reaction time, following a pseudo first order kinetic reaction. The degradation rate can be expressed by the following equation:

$$C = C_0 \exp(-kt) \text{ or } \ln(C/C_0) = -kt \quad (4)$$

where C is the concentration of RhB at time t and C₀ is initial concentration, k is degradation rate constant, and t is degradation time. The degradation rate constants (k) were 0.7·10⁻³ (R²=0.8449) and 1.0·10⁻³ (R²=0.9947) min⁻¹ for orifice plate and Ecowirl reactor, respectively.

3.2 Synergetic effect between hydrodynamic cavitation and NaOCl

Sodium hypochlorite (NaOCl), known as bleaching agent, is commonly used as a disinfectant for treating wastewaters. If used individually, the efficiency of NaOCl in oxidizing the RhB is high but extremely slow because sodium hypochlorite decomposition is usually a very slow process under room temperature conditions.

Nevertheless, the efficiency of NaOCl in degrading RhB can be enhanced significantly if used in combination with HC.

In this study, degradation of RhB was investigated using Ecowirl reactor (standard type) in combination with NaOCl, at concentration of 0.5 mg L⁻¹ and 4.0 mg L⁻¹. Experiments were conducted using 3.0 mg RhB L⁻¹ aqueous solutions, at 20.0 ± 1.0 °C, pH 4.0 and inlet pressure of 2.0 bar. Control experiments in the absence of HC were performed with NaOCl, at concentration of 0.5 mg L⁻¹ and 4.0 mg L⁻¹, only mixing.

It can be seen from Fig. 6 that there is an obvious synergetic effect between HC and NaOCl for the degradation of RhB. The combined process HC and NaOCl at 0.5 mg L⁻¹ increased the efficiency of RhB degradation of about 45-50% in 260 number of passes (169 min of operation time) as compared to the HC alone. Similar results were achieved using the orifice plate as cavitating device (data not showed).

Furthermore, the acceleration of the kinetic of RhB degradation promoted by the HC is clear. In absence of HC, 75% of the RhB content is lost in ca. 52 min, whereas only 26 min (40 number of passes through the Ecowirl reactor) are needed when using the hybrid treatment based on HC + NaOCl (4.0 mg L⁻¹).

As known, HC in water causes the formation of •OH radicals which are very strong and non-specific oxidizing species. Since •OH radicals are major free radical and important precursors for many products formed in degradation process, the production rate of •OH radicals strongly influence the oxidation efficiency of pollutants. On the other hand, hypochlorite bleaches via the oxidising OCl⁻ ion, which in aqueous solution is in equilibrium with the strongly oxidising hypochlorous acid HOCl, so that the reactions are pH dependent. When the pH is between 2–7, the equilibrium favors HOCl. As the pH falls below 2, the main form is Cl₂. At a pH of 7.4, HOCl and OCl⁻ are about equal, and as the pH goes above 7.4, increasing proportions of OCl⁻ are present. Thus, at pH of 4.0, the strongly oxidising HClO is the dominant form. Tiong and Price, [42], suggested that undissociated hypochlorous acid could also evaporate into a cavitation bubble and undergo sonolysis, also producing •OH radicals, resulting in higher concentrations of these highly oxidising species, contributing to the acceleration of the degradation process. Zeng et al. [45], also hypothesized that the presence of HOCl could result in the production of more hydroxyl radicals to accelerate the degradation of aqueous dyestuffs. This suggests that the synergetic effect between HC and NaOCl for the degradation of RhB could be mainly due to the contribution of additional •OH radicals production.

3.3 Effect of NaOCl concentration

The effect of the NaOCl concentration ranging from 0.5 to 4.0 mg L⁻¹, corresponding to 0.3 - 3.7 mgOCl⁻ L⁻¹, on the degradation of RhB was investigated using a 3.0 mg L⁻¹ RhB aqueous solution at 20 °C, pH 4.0, inlet pressure of 2.0 bar and Ecowirl reactor (standard type) as cavitation device. Fig. 7 shows that an increase in NaOCl concentration involved an intensification of the extent of degradation of RhB. As mentioned above, the enhancement of ED could be mainly due to the formation of hypochlorous acid (HOCl) and to the production of additional •OH radicals. Quantitatively speaking, about 94% RhB degradation was obtained at the maximum oxidant loading of 4.0 mg NaOCl L⁻¹ within 169 min of treatment time. At the minimum loading

(0.5 mgNaOCl L⁻¹), the extent of decolourization was about 31% at the end of 169 min, which is higher as compared to HC alone.

When tap water solution characterized by a residual chloride content of 0.1 - 0.2 mg L⁻¹ was used, an ED of 29% was achieved, showing the possibility to use the residual chlorine in waters as a possible way to spare the chemical consumption. In order to meet residual chloride discharge limits of 0.2 mg L⁻¹, and simultaneously benefit of the synergic effect of the hybrid treatment scheme based on HC and NaOCl, a value of 0.5 mg NaOCl L⁻¹ was selected as the sustainable NaOCl addition dose in the present research.

3.4 Effect of the pressure

The effect of fluid pressure on the degradation ratio of RhB were also investigated in the hybrid treatment scheme based on HC and NaOCl (0.5 mg L⁻¹), using the two different cavitating devices viz. orifice plate (plate thickness: 2 mm) and Ecowirl reactor (standard type). The experiments were carried out at three different inlet pressure, 2.0, 3.0 and 4.0 bar. The experiments were conducted in aqueous solution at 3.0 mg L⁻¹ RhB, an initial temperature of 19.0 ± 0.5 °C and pH 4.0. The obtained results have been depicted in Fig. 8 (a) for orifice plate as the cavitating device and in Fig. 8 (b) for Ecowirl reactor.

Using the orifice plate, the degradation rates increased with an enhance in the inlet pressure until an optimum value of 3.0 bar, where an ED of 24.3% had been reached. At 4.0 bar pressure, the extent of degradation has been observed to drop marginally.

Mishra and Gogate [24] both using Venturi and orifice plate as cavitating devices, treating a 10 mg RhB L⁻¹ solution at 30-40°C, obtained a decrease in ED at a high inlet pressure of 5.9 atm. In their study the Authors attributed this phenomenon to the onset of super cavitation i.e. indiscriminate growth of the bubbles downstream of the constriction resulting in splashing and vaporization of the flow and enhancing phenomena of coalescence that produce less effective bubbles in terms of degradation. In our study, the inlet pressure are lower, however the ΔP_{HC} values measured using the orifice plate were 1.70, 2.65 and 3.60 bar, at 2.0, 3.0, and 4.0 bar, respectively (Table 3). Thus, a pressure drop of 3.6 bar was the ΔP_{HC} value for which the super cavitation may occur using the specific orifice place and the RhB solution.

Using Ecowirl reactor, instead, it was found a continuous decrease in the extent of degradation with the increase in the operating inlet pressure from 2.0 to 4.0 bar. In the case of Ecowirl reactor, a ΔP_{HC} of 2.85 bar was measured at 2.0 bar. Increasing the inlet operative pressure the ΔP_{HC} increased up to 3.90 and 4.95 bar at 3.0 and 4.0 bar, respectively. Similarly to the results of the orifice plate experiments, a pressure drop of 3.90 bar was the ΔP_{HC} value for which the super cavitation may occur using the specific swirling jet reactor and the RhB solution.

Different results were achieved by using a swirling jet-induced cavitation device, where increase of degradation rates of RhB were observed with the increase of the inlet pressure, from 2.0 to 6.0 bar [23,37]. However, different operative conditions were used in terms of temperature and concentration of RhB. In a swirling jet-induced cavitation device, treating a 5.0 mg RhB L⁻¹ solution at 6.0 bar and 40°C, a maximum ED of 60% was achieved [23]. Using H₂O₂ as additive, in a swirling jet-induced cavitation, treating a 10.0 mg RhB

L⁻¹ solution at 6.0 bar and 50°C, a maximum ED of 95% was achieved [37]. Finally, in a swirling jet-induced cavitation, treating reactive brilliant red K-2BP solution (20 mg L⁻¹) at 6.0 bar and 50°C, where a maximum ED of 75% was achieved, a ΔP_{HC} of about 5.9 bar can be calculated [46], that is comparable with the pressure drop that we measured in our experiments.

However, as recently reviewed by Bagal and Gogate [47], the effect of operating pressure is strongly dependent on the geometry of the cavitation chamber as well as on the pollutant nature and fluid dynamic characteristics of the solution to treat. Hence, the optimization of the inlet pressure is indispensable to obtain maximum cavitation effects.

Table 3 shows the operating parameters and the extent of degradation of RhB, in terms of ED and C.Y., by using orifice plate and Ecowirl reactor and by varying the inlet pressure on cavitating system. In the case of orifice plate, the C.Y. is almost the same value at 2.0 and 3.0 bars, then decreases at 4.0 bars. This is due mainly to the fact that up to 3.0 bars both the flow rate and ED increased, thus increasing the amount of RhB degraded. After 3.0 bar, even if the flow rate increased with the increasing of the inlet operative pressure, ED decreased causing a lower amount of degraded dye molecules. Further, increasing the inlet operating pressure, the power density increased as well, thus resulting in a decrease in mg of pollutant degraded to the total energy input to the system. Concerning Ecowirl reactor, as the operative pressure increased, even if the flow rate increased, the ED decreased, resulting in a decreasing amount of RhB. On the other hand, even if the treatment time decreased, the adsorbed power increased causing an increasing power density. The resulting C.Y. decreased with the increase of inlet operating pressure.

3.5. Effect of geometry

Based on the geometrical configuration of the cavitating system, it is possible to achieve different values of the extent of degradation of RhB. Concerning orifice plate, while many studies have been carried out on holes number and diameter, and consequently, on cross-sectional area and perimeter [25], only few studies have been performed on the thickness of orifice plates. Furthermore, no studies are present on the geometry of Ecowirl reactor. The effect of the geometry has been investigated in the hybrid treatment scheme based on HC and NaOCl (0.5 mg L⁻¹).

3.5.1 Effect of the orifice plate thickness

In the present study, the influence of thickness of the orifice plate (the orifice length or holes depth) on the RhB degradation was analysed. The tests were carried out at a thickness of 1, 2, 3 and 4 mm, using an aqueous solution at initial dye concentration of 3.0 mg L⁻¹, pH 4.0, an inlet pressure of 2.0 bar, a temperature of 19.0 ± 1.0 °C and 0.5 mg NaOCl L⁻¹.

Even if no significant difference in ED was found for the different orifice plates investigated, the highest ED was achieved for the plate characterized by the lowest thickness (1 mm), and thus the lowest unit length to diameter ratio, for which an ED of 24.3% had been reached (Table 3). The experiments of the present study confirmed the results observed by Parsa and Zonouzian [36], who used two different types of orifice plates (type A: 1 mm of thickness, ED = 71.0%; type B: 2 mm of thickness, ED = 64.8%). The Authors suggested

that the thicker plate (plate type B) had a higher inlet pressure and a lower flow rate, and consequently, fewer intense collapses and lower ED [48]. Unlike Parsa and Zonouzian, we worked at constant inlet operating pressure and constant flow rate. In the present study, the pressures downstream of the orifice plate increased from 0.28, 0.30, 0.32 to 0.35 bar using the 1, 2, 3 and 4 mm thickness orifice plates, respectively. From those results, it seems that the higher efficiency could be linked to the lowest outlet pressure measured downstream of the orifice plate, and thus at the highest ΔP_{HC} , equal to 1.72 bar. Thus, working at the same inlet operative pressure, it means that a higher HC effect can be obtained using the 1 mm thickness orifice plate.

3.5.2 Effect of the double cone

In the Ecowirl reactor, the geometry of double cone chamber was investigated. The interest in studying this zone of the reactor was due to the cavitation phenomenon that occurs in this region of space. The tests were conducted considering four different types of cavitation chambers, type standard, type A, B and C, different for the length of the cylinder in the middle of the double cone, using an aqueous solution at initial dye concentration of 3.0 mg L^{-1} , pH 4.0; 2.0 bar, $19.0 \pm 2.5 \text{ }^\circ\text{C}$ and $0.5 \text{ mgNaOCl L}^{-1}$.

The results, shown in Fig. 9, confirmed that choosing different geometric configurations of the double cone chamber it is possible to obtain different extent values of the extent of degradation of RhB. For all new types considered, the extent of degradation on RhB was lower than the values measured using the standard double cone chamber (Table 3). The ED decreased with the increasing of the length of the cylinder. The lower efficiency associated to the configuration A, B and C could be related both to the high measured ΔP_{HC} value of 2.95 bar as compared to the standard type (2.85 bar), which could increase the phenomena of coalescence, and lead to a less violent implosion of the bubbles, due to the fact that they are subjected to a slower pressure increase in the longer double cones as compared to the standard double cone, where a very rapid pressure increase occurred. Hence, the need for further studies on the definition of new geometries of the Ecowirl reactor, able to induce an appropriate ΔP_{HC} value and a rapid pressure increase, that may increase the intensity of cavitation and thus ensure greater degradation of the dye.

3.6. Effect of operating pH

In cavitation process, the pH of the medium is an important parameter on the degradation of chemical pollutants. Indeed, it can heavily influence the chemical state of the compound to remove. Further, using NaOCl, the pH influences the distribution of free chlorine species in aqueous solutions.

In this study, the effect of pH in a range between 2.0 and 11.5 was investigated on a 3.0 mg L^{-1} RhB solution by using the hybrid system based on HC and $0.5 \text{ mg NaOCl L}^{-1}$. Orifice plate (plate thickness: 2 mm) had been used as cavitating device. Other experimental conditions involved the solution temperature $18.2 \pm 2.6^\circ\text{C}$ and the inlet fluid pressure 2.0 bar. The ΔP_{HC} value was the same for the all the performed tests and equal to 1.7 bar. The obtained results have been depicted in Fig. 10.

According to results from other studies [22–24], our results confirmed the degradation of RhB was strongly dependent on the pH solution. It can be seen from the Fig. 10a that the highest ED of RhB was reached for strongly acid pH (2.0 - 4.0). The maximum degradation of 65.0% was observed at pH value of 2.0, while it

drop significantly and remained constant at neutral pH (5.0 - 8.0). The lowest ED was observed at pH 9.0, while it slightly increased again for very basic pH (11.5), reaching a degradation of 7.4% at pH of 11.5.

The same degradation trend at acid pH was observed by Mishra and Gogate [24], using a Venturi device to treat a solution with an initial RhB concentration of 10.0 mg L⁻¹, at 30 - 40°C and 4.9 bar and by Wang et al. [23], using a swirling jet-induced cavitation system to treat a solution with an initial RhB concentration of 5.0 mg L⁻¹ at 40 °C and 6.0 bar. Further, this result is correspondent closely with that reported for the degradation of RhB by ultrasonic cavitation [49].

The different value of the extent of degradation of RhB by varying the pH of the contaminated solution is due to the possibility for the dye to assume two different forms that can react differently in contact with •OH free hydroxyl radicals made by cavitation process. At low pH prevails the cationic form of RhB while at high values prevails the zwitterionic form, [22]. It has been reported that the cationic form is easier to the degradation [23], and thus at low values of pH the oxidation of RhB is higher. The acidity of the medium, which results in modification of the physical properties of molecules, plays an important role in the degradation of chemical pollutants. Similar results were also obtained for other dyes. Further, as suggested by Wang et al. [23], the increasing of the oxidation potential of OH• in the acidic solution might be another reason for the degradation rate increase. Using NaOCl as additive, at acid pH prevails the undissociated hypochlorous acid, HOCl. It is both a strong oxidants and it could evaporate into a cavitation bubble and undergo HC, also producing •OH radicals, resulting in an acceleration of the RhB degradation process [42]. Furthermore, in the present study, the slight increase in ED observed at basic pH could be justified by the prevalence at pH > 9.0 of the oxidising OCl⁻ ion. Fig. 10b clearly shows how the kinetics of degradation are higher for lower pH compared to higher ones.

3.7. Effect of initial dye concentration

Degradation of RhB was investigated at different initial concentration of RhB values (2.0, 3.0, 4.0 mg L⁻¹) using the hybrid system based on HC and NaOCl at 0.5 mg L⁻¹ at 18.1 ± 1.3 °C. Orifice plates (plate thickness: 2 mm) had been used as cavitating system under optimum conditions for pH (pH = 2.0), while the inlet pressure was fixed at 2.0 bar. The obtained results have been shown in Fig. 11. It can be seen from the figure that, according to Parsa and Zonouzian [36], the efficiency of process was inversely proportional to the initial dye concentration. As the initial concentration increased from 2.0 to 4.0 mg L⁻¹, the ED decreased from 76% to 61%. An increase in concentration of the contaminant in solution involves a greater amount of dye molecules, but the amount of free hydroxyl radicals remains constant.

With increasing the initial concentration from 2.0 mg L⁻¹ to 4.0 mg L⁻¹, the degradation rate constants (k) decreased from 13.3·10⁻³ min⁻¹ or 20·10⁻⁵ s⁻¹ (R² = 0.9944) to 7.8·10⁻³ min⁻¹ or 13·10⁻⁵ s⁻¹ (R² = 0.9953), respectively. This result is very similar with that reported for sonochemical degradation of RhB [22] and others HC systems. Sivakumar and Pandit [25] measured degradation rate constants of RhB using multiple hole orifice plates at 35.0 - 40.0 °C in the range of 2.67 – 5.33·10⁻⁵·s⁻¹. In a swirling jet-induced cavitation device, Wang et al [23] reported a degradation rate constant k of 5.13·10⁻³ min⁻¹ or 8.55·10⁻⁵ s⁻¹ with regression

coefficient $R^2 = 0.9972$ for 5.0 mg L^{-1} RhB in aqueous solution at temperature $40.0 \text{ }^\circ\text{C}$ and pH 5.4. Parsa and Zonouzian [36], using orifice plates in a submerged mode at temperature $40 \text{ }^\circ\text{C}$, 5.8 bar and pH 5.4, showed that while the initial concentrations were increased from 2.0 mg L^{-1} to 5.0 mg L^{-1} , the degradation rate constants decreased from $9.0 \cdot 10^{-3} \text{ min}^{-1}$ to $5.7 \cdot 10^{-3} \text{ min}^{-1}$.

However, from the results reported in Table 3, it can be observed that even if the ED decreased by increasing the initial dye concentration up to 4.0 mg L^{-1} , the amount of degraded RhB increased as effect of the higher concentration of RhB, resulting in an increase of the C.Y. as well. The same result was achieved by Parsa and Zonouzian [36]. Using a heterogeneous catalytic hydrodynamic cavitation reactor combined with H_2O_2 , the Authors observed that the C.Y. increased by increasing the initial dye concentration up to 10.0 mg L^{-1} , while decreased after this point, probably due to the limited amount of generated H_2O_2 and shortage of hydroxyl radicals.

3.8. Energy consumption analysis

Since the aim of the work is to evaluate the industrial sustainability of the cavitation processes studied for the treatment of wastewaters containing RhB, the energy consumption of different processes in degrading RhB has been evaluated and compared. The parameter used for the comparison is the C.Y., which indicates the ability of the equipment in producing the desired change based on the electric energy actually used for generating cavitation. Considering HC systems, the main energy-consuming component is the pump that is used for recirculation of the aqueous solution of the pollutant through the cavitation chamber. Table 3 shows such comparison. Concerning the HC devices alone, the energy consumption calculations shows the superiority of Ecowirl reactor compared to the orifice plate, as Ecowirl reactor enhances the extent of degradation of RhB. Moving from orifice plate to Ecowirl reactor an increase in C.Y. value from $2.07 \cdot 10^{-6}$ to $2.72 \cdot 10^{-6} \text{ mg J}^{-1}$ has been calculated. Further, it should be highlighted that over the experiments performed in this study, a slight higher increase in temperature of the liquid was measured using Ecowirl reactor rather than orifice plate, thus further improving the cavitation effects on RhB degradation [23]. Then, the hybrid scheme (HC + NaOCl) has been analysed.

The use of NaOCl alone in a mixing process to treat dye wastewater could require lower energy as compared with the HC but it is definitely not sustainable to scale up the system [26]. However, benefits of lower energy requirements and lower chemical use can be achieved combining HC with chemical oxidation using NaOCl. At the minimum NaOCl dose tested (0.5 mg L^{-1}) and pH 4.0, the C.Y. increased of about 50% as compared to the HC alone. Using orifice plate the C.Y. increased from $2.07 \cdot 10^{-6}$ to $4.52 \cdot 10^{-6} \text{ mg J}^{-1}$, while using Ecowirl reactor C.Y. raised from $2.72 \cdot 10^{-6}$ to $4.60 \cdot 10^{-6} \text{ mg J}^{-1}$. The C.Y. can further be increased working at acid pH values or higher NaOCl concentrations. Indeed, by using Ecowirl reactor and working at pH 2.0 and $4.0 \text{ mg NaOCl L}^{-1}$, the C.Y. value increased up to $4.35 \cdot 10^{-5} \text{ mg J}^{-1}$. The C.Y. values of the Ecowirl reactor and the hybrid system studied were compared with those of other cavitation device reported in literature (Table 4). Generally, by comparing the C.Y., Table 4 shows that HC reactors are more energy efficient as compared to

the acoustic counterparts, giving higher cavitation yields. Further, Ecowirl reactor is more energy efficient as compared to the other cavitating devices and the scale up of this reactor is easier. The efficient design of the Ecowirl reactor helps in reducing the treatment cost of wastewaters containing RhB. In the case of the hybrid treatment scheme based on HC and NaOCl, the optimization of operating parameters such as inlet pressures/flow rates, pH and loadings of NaOCl helps in reducing the overall treatment cost as it reduces the electrical cost and cost of chemicals. Overall, the use of Ecowirl in the hybrid treatment based on HC and NaOCl as additives at optimum loadings looks promising and economical as compared to other hydrodynamic and acoustic cavitation based process.

4. Conclusions

The present work has allowed studying a hydrodynamic cavitation reactor (Ecowirl), based on swirling jet induced cavitation, able to remove RhB dye from wastewater. Experimental evidences proved that Ecowirl reactor resulted in more intense cavitation as compared to multiple hole orifice plates giving better efficacy on degradation of RhB. Using only cavitation in absence of additives, the higher ED obtained can be attributed to the operating pressure measured in downstream cavitation zone of Ecowirl reactor with a value of -0.85 bar that resulted to be lower than the value downstream of the orifice plate (0.30 bar) at similar inlet operating pressure (2.0 bar), resulting in pressure drop values, ΔP_{HC} , of 2.85 and 1.7 bar, respectively. Furthermore, higher values (1.3 times more) of C.Y. in Ecowirl reactor than in hole orifice plates were observed, which means that for similar values of energy supplied to the cavitation system, a greater amount of RhB was degraded using Ecowirl reactor. A study of different geometric configurations of the cavitating device was carried out inspired by these considerations. The geometry and the fluid dynamic characteristic of the solution to treat affect the pressure distribution and the pressure recovery profile downstream of the constriction and hence the active cavitation volume, which is very important considering global effects of the HC reactor.

The hybrid scheme treatment based on HC by using Ecowirl reactor (20 °C, 2.0 bar, pH 2.0 or 4.0) and NaOCl (minimal dose 0.5 mg L⁻¹) was found to be the most energy efficient and environmental friendly method to treat wastewater containing RhB. The combined process HC and NaOCl increased the efficiency of RhB degradation as compared to the HC alone or to the NaOCl oxidation process implying an acceleration of the kinetic of RhB degradation and resulting in a decrease of treatment time and hence of treatment costs. Swirling jet-induced cavitation by using Ecowirl combined with NaOCl was more energy efficient if compared to other hydrodynamic and acoustic cavitation based processes.

The aim of the designers should be to maximize further the energy efficiency. This can be done based on manipulation of the operating conditions and geometric parameters of the reactor, resulting in optimal ΔP_{HC} and rapid pressure increase, to give the desired effect in terms of the observed chemical change. Finally, further studies, in particular modelling studies, are needed to better understand the fluid dynamic of swirling jet induced cavitation devices.

Appendix A or supporting material

Cavitation yield for hydrodynamic cavitation (Ecowirl) at optimum pressure (2.0 bar) and pH (pH = 4.0) alone and combined with NaOCl

Following conditions have been used for the operation of hydrodynamic cavitation alone:

Reaction volume – 50 L

Initial dye concentration – 3.0 mg L⁻¹

Absorbed Power rating of pump – 0.8 kW (800 W)

Treatment time – 169 min

In hydrodynamic cavitation alone, 14.7% decolourization of RhB has been observed at operating conditions.

The cavitation yield for hydrodynamic cavitation reactors can be calculated as follows:

C. Y. = RhB degraded/Power density

$$\text{RhB degraded} = (14.7 \cdot 3 \text{ mg L}^{-1})/100 = 0.441 \text{ mg L}^{-1}$$

$$\text{Power density} = (P_{\text{abs}} \cdot t)/V = (800\text{W} \cdot 169\text{min} \cdot 60 \text{ sec min}^{-1})/50\text{L} = 162240 \text{ J L}^{-1}$$

$$\text{C. Y.} = 0.441 \text{ mg L}^{-1}/162240 \text{ J L}^{-1} = 2.72 \cdot 10^6 \text{ mg J}^{-1}$$

Following conditions have been used for the operation of hydrodynamic cavitation and NaOCl (0.5 mg L⁻¹):

Reaction volume – 50 L

Initial dye concentration – 3.0 mg L⁻¹

Absorbed Power rating of pump – 0.8 kW (800 W)

Treatment time – 169 min

In hydrodynamic cavitation combined with 0.5 mg NaOCl L⁻¹, 24.9% decolourization of RhB has been observed at operating conditions. The cavitation yield for hydrodynamic cavitation reactors can be calculated as follows:

C. Y. = RhB degraded/Power density

$$\text{RhB degraded} = (24.9 \cdot 3 \text{ mg L}^{-1})/100 = 0.747 \text{ mg L}^{-1}$$

$$\text{Power density} = (P_{\text{abs}} \cdot t)/V = (800\text{W} \cdot 169\text{min} \cdot 60 \text{ sec min}^{-1})/50\text{L} = 162240 \text{ J L}^{-1}$$

$$\text{C. Y.} = 0.747 \text{ mg L}^{-1}/162240 \text{ J L}^{-1} = 4.60 \cdot 10^6 \text{ mg J}^{-1}$$

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FIGURE CAPTIONS

Fig. 1 - Schematic representation of the experimental setup.

Fig. 2 - (a) Orifice plate; (b) Ecowirl reactor.

Fig. 3 - Schematic representation of the operation of Ecowirl reactor.

Fig. 4 - Geometry of double cone type C in the Ecowirl reactor.

Fig. 5 - **Comparison between different HC devices alone** (volume 50 L; initial RhB concentration 3.0 mg L⁻¹; pH 4.0; inlet pressure 2.0 bar; initial temperature 20.0 ± 1.0°C).

Fig. 6 - **Synergetic effect between hydrodynamic cavitation and NaOCl on degradation of RhB** (volume 50 L; initial RhB concentration 3.0 mg L⁻¹; pH 4.0; inlet pressure 2.0 bar; initial temperature 20.0 ± 1.0°C).

Fig. 7 - **Effect of hydrodynamic cavitation using Ecowirl in presence of NaOCl on degradation of RhB** (volume 50 L; initial RhB concentration 3.0 mg L⁻¹; pH 4.0; inlet pressure 2.0 bar; initial temperature 19.0 ± 1.0 °C; mg NaOCl L⁻¹).

Fig. 8 - **Effect of inlet pressure on degradation of RhB by using (a) orifice plate and (b) Ecowirl reactor** (volume 50 L; initial dye concentration 3.0 mg L⁻¹; pH 4.0; initial temperature 19.0 ± 0.5°C; 0.5 mg NaOCl L⁻¹; inlet pressure).

Fig. 9 - **Effect of the geometry of the double cone chamber of Ecowirl reactor on degradation of RhB** (volume 50 L; initial RhB concentration 3.0 mg L⁻¹; pH 4.0; inlet pressure 2.0 bar; initial temperature 19.0 ± 2.5 °C; 0.5 mg NaOCl L⁻¹; double cone).

Fig. 10 - (a) **Effect of pH on degradation of RhB by using orifice plate, (b) Degradation kinetics** (volume 50 L; initial RhB concentration 3.0 mg L⁻¹; initial temperature 18.2 ± 2.6 °C; inlet pressure 2.0 bar; 0.5 mg NaOCl L⁻¹; pH).

Fig. 11 - **Effect of initial dye concentration on RhB degradation by using orifice plate** (volume 50 L; pH 2.0; initial temperature 18.1 ± 1.3 °C; pH 2.0; inlet pressure 2.0 bar; 0.5 mg NaOCl L⁻¹; mg RhB L⁻¹).

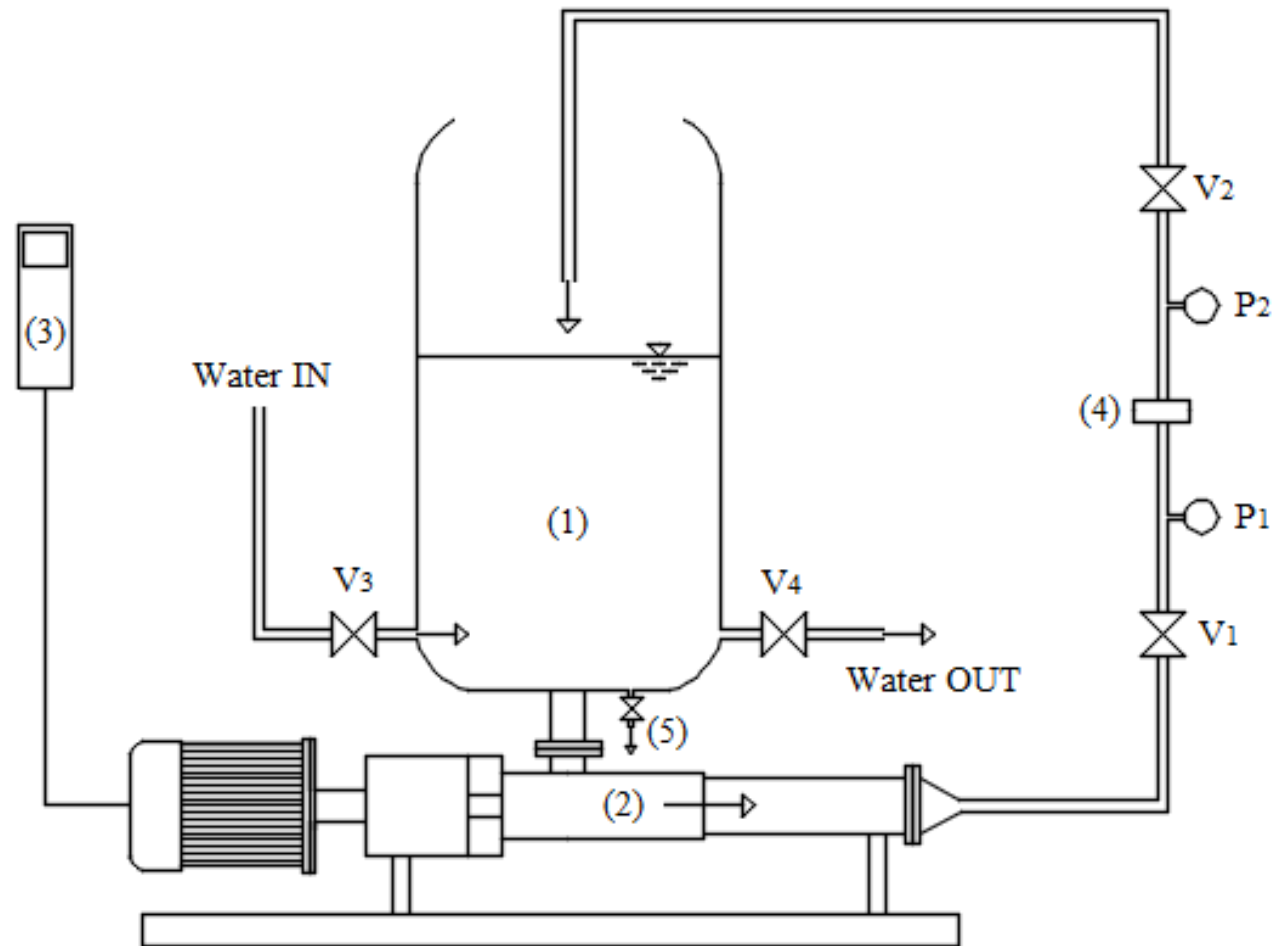
TABLE CAPTIONS

Table 1 - Parameters and operating conditions for the two different cavitating devices used.

Table 2 - Flow characteristics for the two different cavitating devices used.

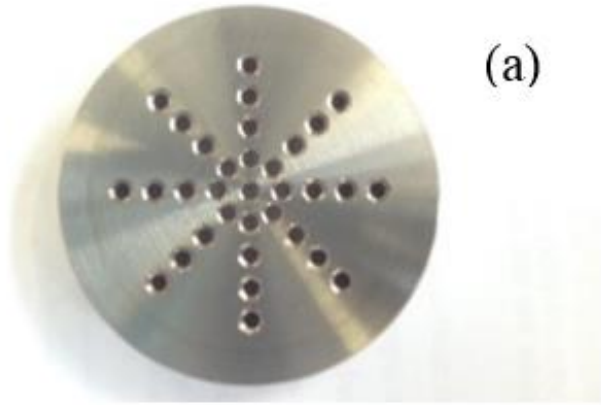
Table 3 - Operative parameters and efficiency measured at the end of each test.

Table 4 - Variation of cavitation yield (C.Y.) for different cavitation equipments.

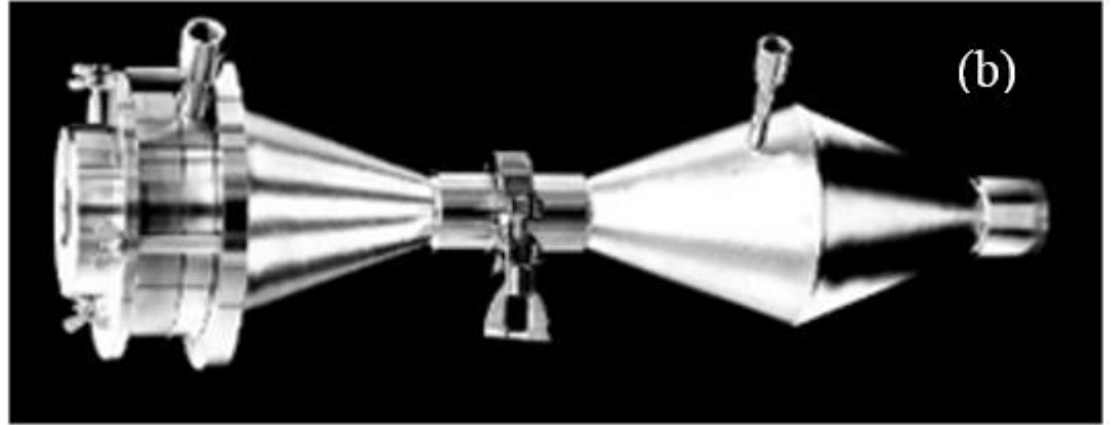


1. Feed tank
2. Screw pump
3. Inverter
4. Cavitating device
5. Sampling port

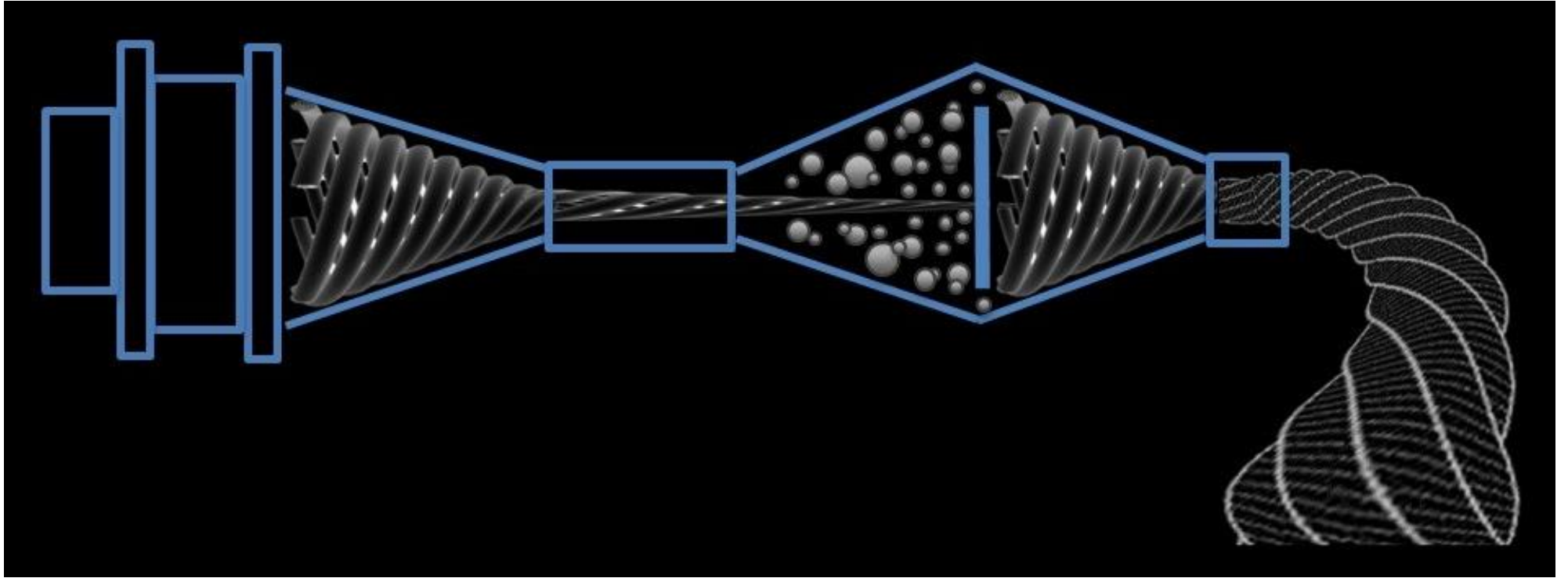
V₁, V₂, V₃, V₄ Control valves
 P₁ Pressure gauge
 P₂ Vacuum gauge

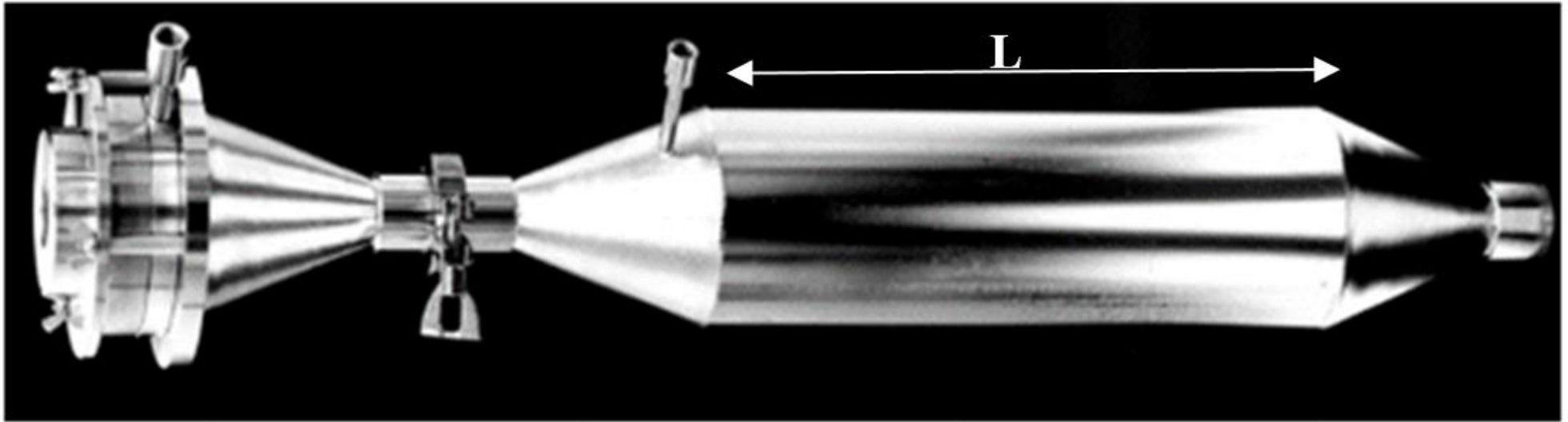


(a)

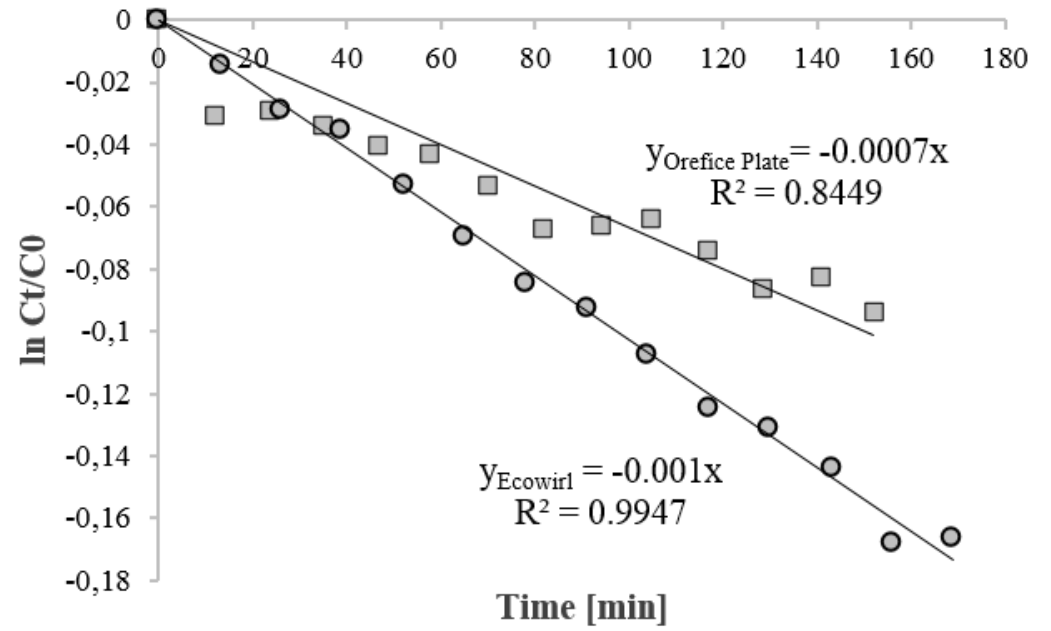
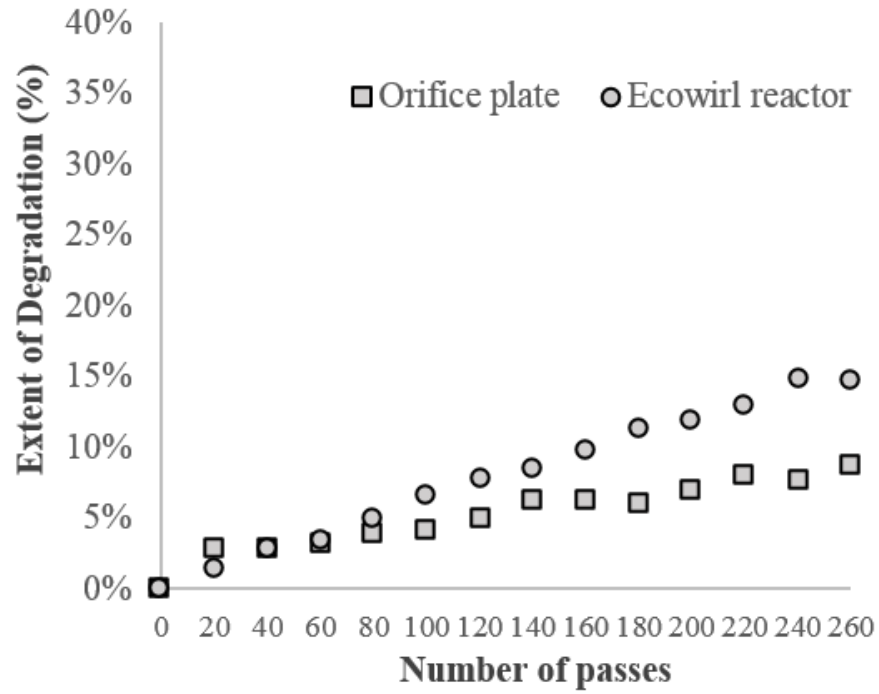


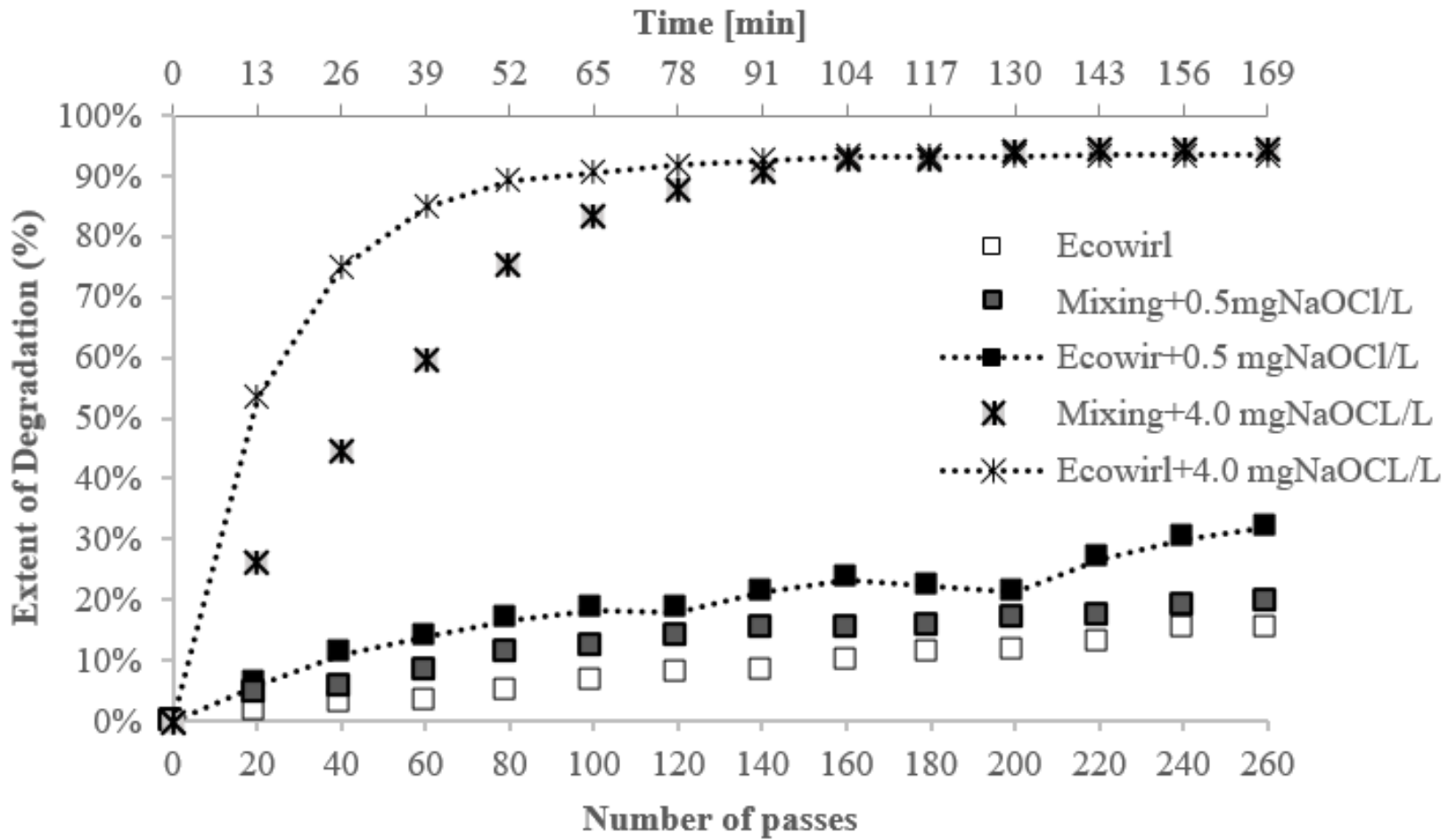
(b)

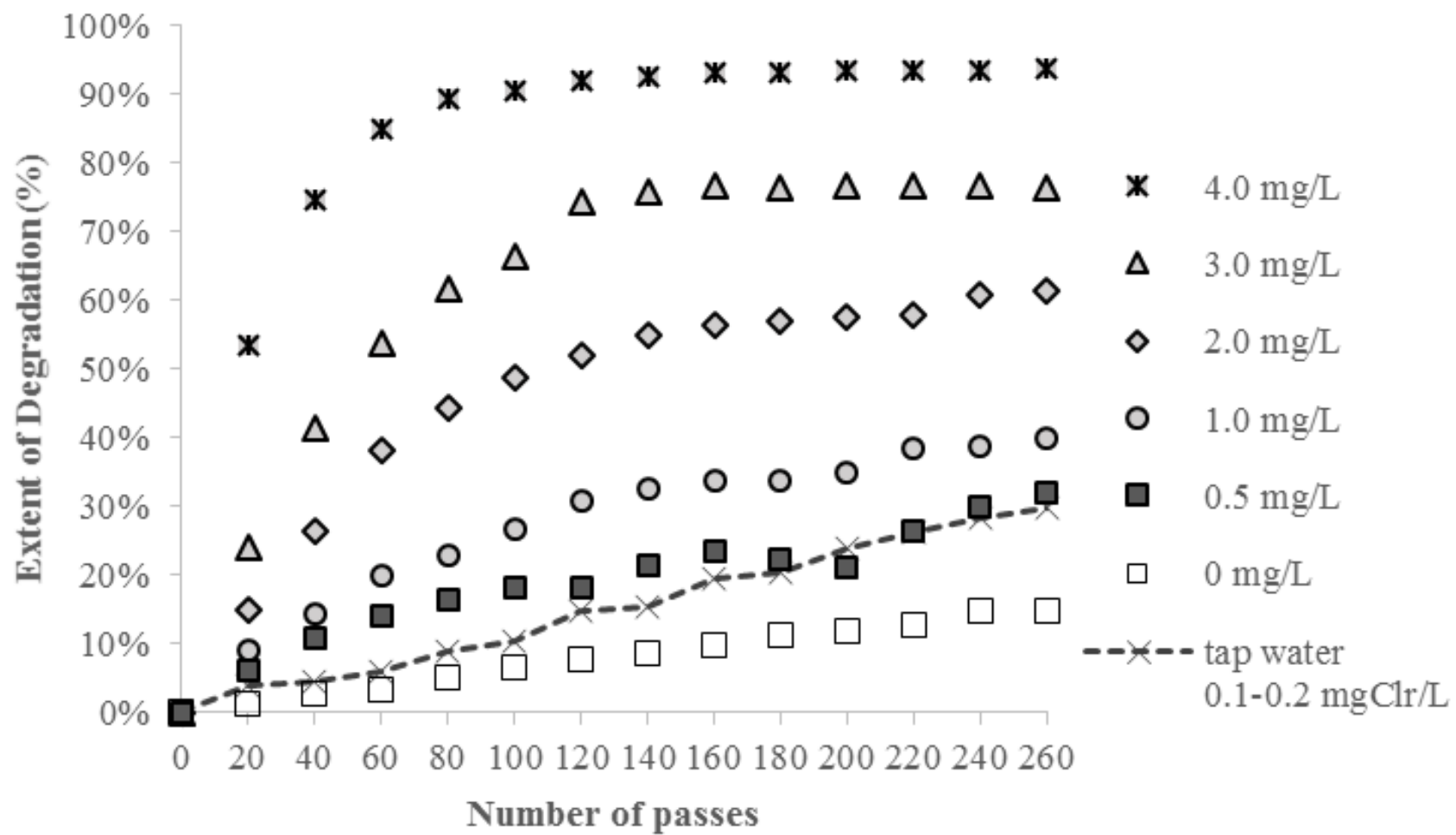


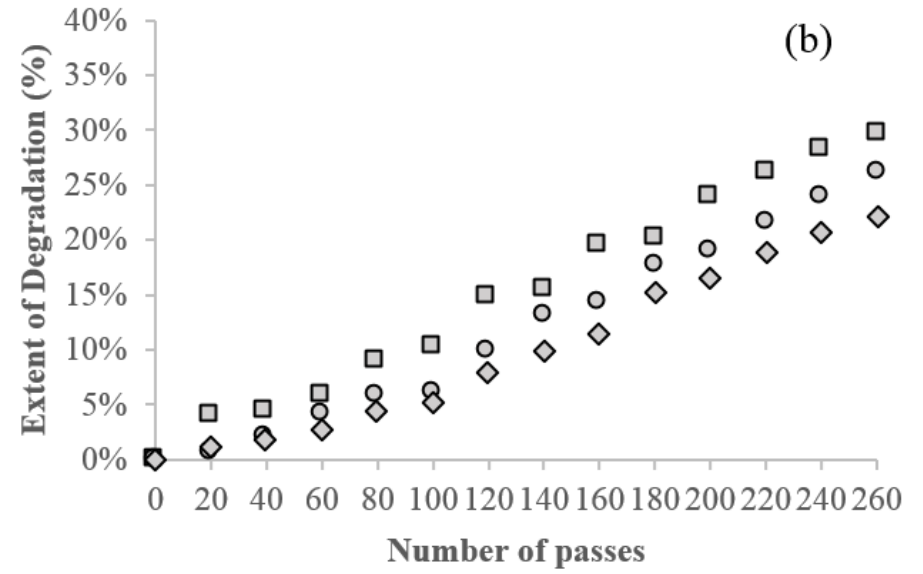
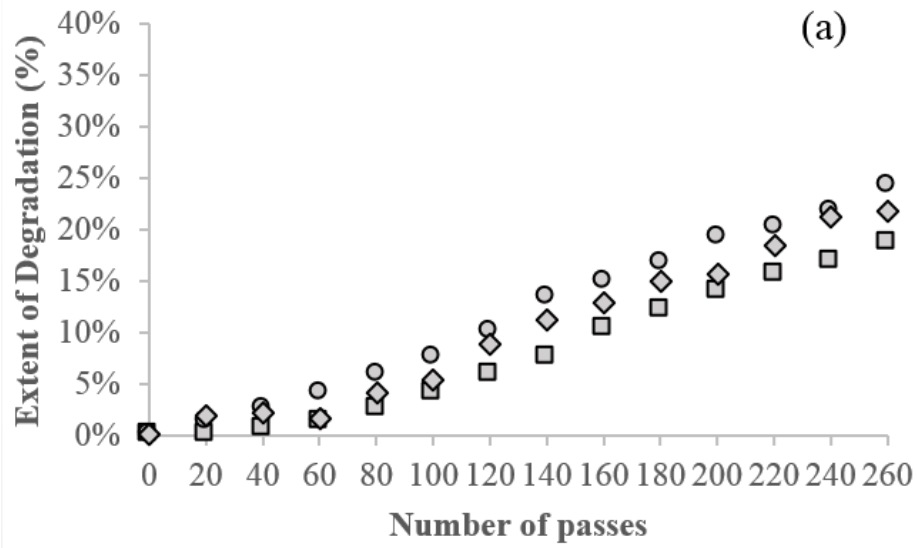


Type Std \rightarrow $L = 0$ cm; Type A \rightarrow $L = 20$ cm; Type B \rightarrow $L = 40$ cm; Type C \rightarrow $L = 60$ cm

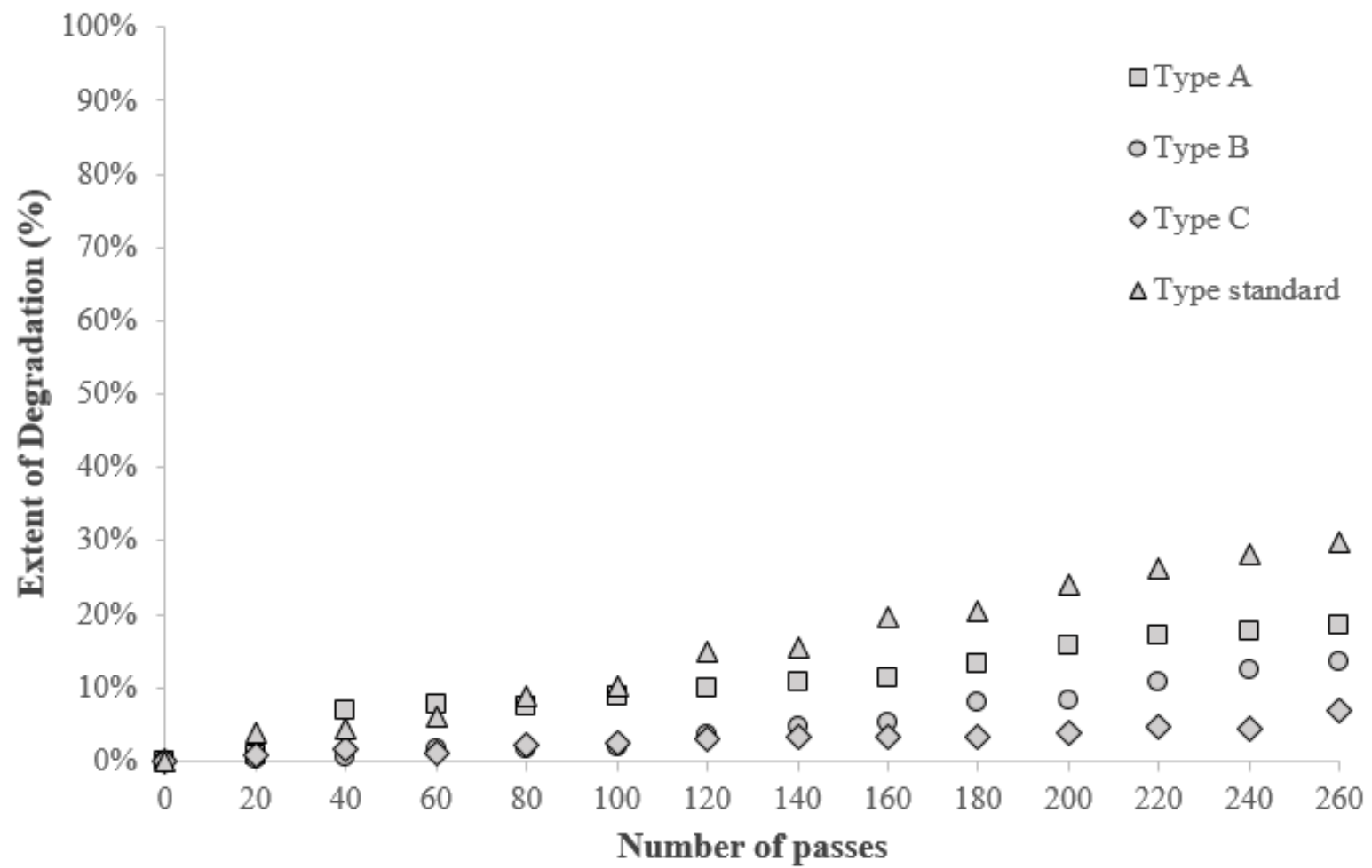


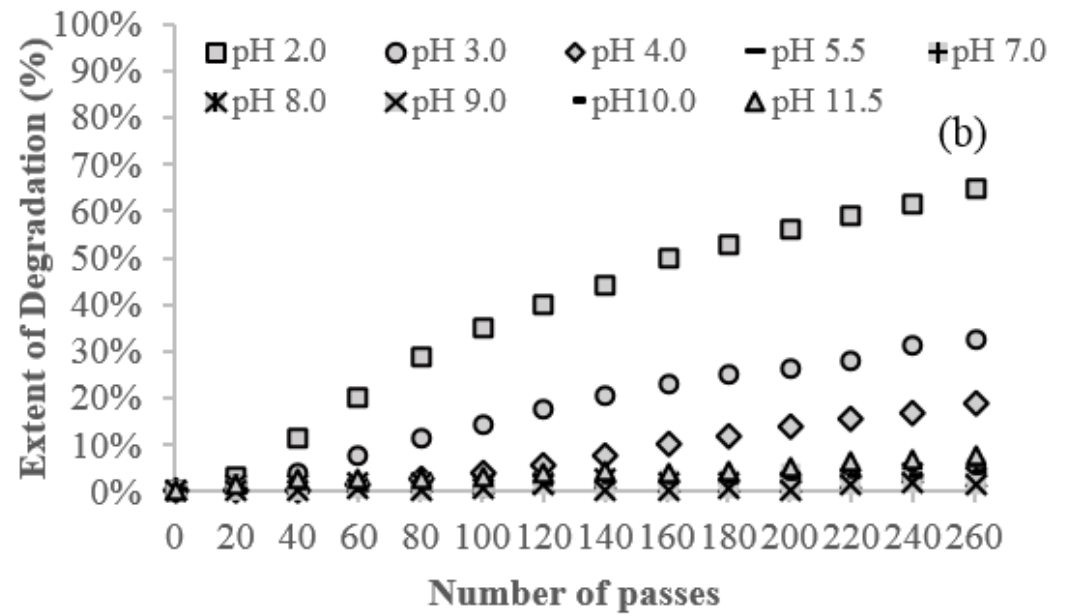
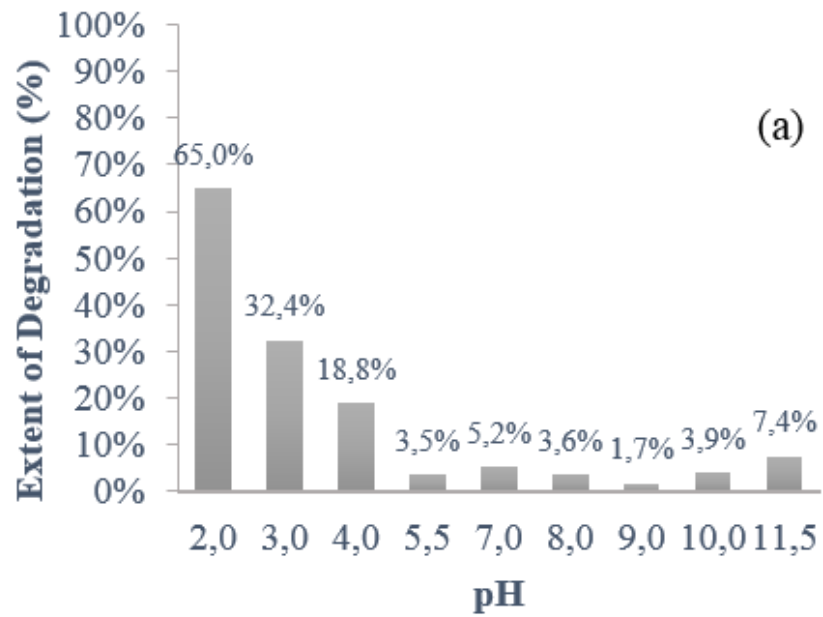


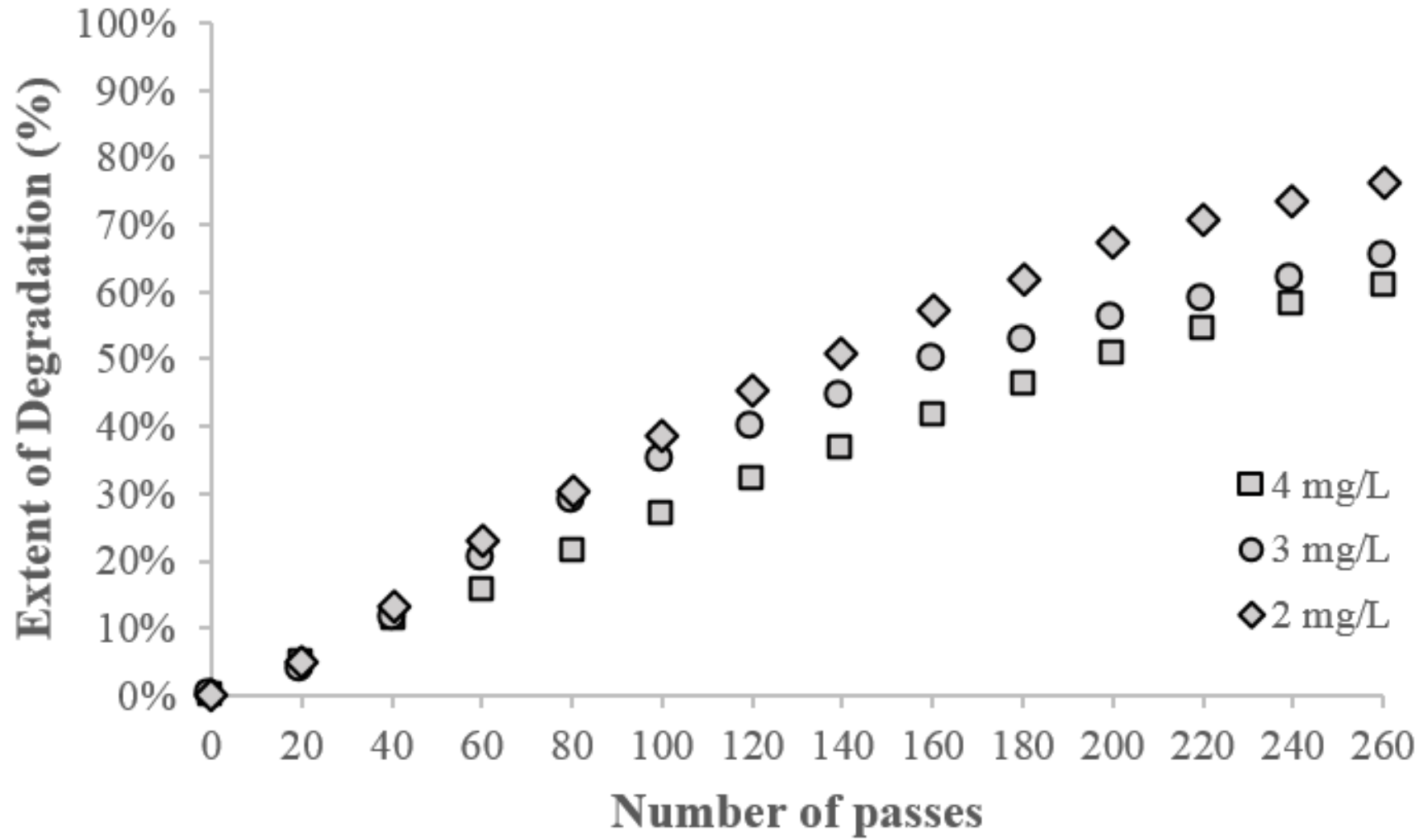




■ 2 bar ● 3 bar ◆ 4 bar







Orifice plate					Ecowirl reactor				
Pressure (atm)	pH	Thickness (mm)	[RhB] (mg L ⁻¹)	[NaOCl] (mg L ⁻¹)	Pressure (atm)	pH	Double-cone (Type)	[RhB] (mg L ⁻¹)	[NaOCl] (mg L ⁻¹)
2	4.0	2	3.0	0.0 → 4.0	2	4.0	Std	3.0	0.0 → 4.0
2 - 3 - 4	4.0	2	3.0	0.5	2 - 3 - 4	4.0	Std	3.0	0.5
2	4.0	1 - 2 - 3 - 4	3.0	0.5	2	4.0	A, B, C, Std	3.0	0.5
2	2.0 → 11.5	2	3.0	0.5					
2	2.0	2	2.0 - 3.0 - 4.0	0.5					

Orifice plate					Ecowirl reactor				
Pressure (atm)	Frequency (Hz)	Flow rate (m ³ h ⁻¹)	Corresp. time to 260 cycles (min)	Absorbed power (kW)	Pressure (atm)	Frequency (Hz)	Flow rate (m ³ h ⁻¹)	Corresp. time to 260 cycles (min)	Absorbed power (kW)
2	59.0	6.0	130	0.8	2	47.0	4.6	169	0.8
3	72.0	7.2	110	1.3	3	59.0	5.7	137	1.1
4	83.0	8.4	92	1.8	4	69.0	6.6	118	1.4

Orifice plate

P inlet (bar)	pH	Thickness (mm)	[RhB] (mg L ⁻¹)	NaOCl (mg L ⁻¹)	ED after 260 cycles (%)	P outlet (bar)	ΔP_{HC} (bar)	RhB degraded (mg L ⁻¹)	Power density (kJ L ⁻¹)	C.Y. (mg J ⁻¹)
2.0	4.0	2	3.0	0	8.6	0.30	1.70	0.258	124.80	$2.07 \cdot 10^{-6}$
2.0	4.0	2	3.0	0.5	18.8	0.30	1.70	0.564	124.80	$4.52 \cdot 10^{-6}$
3.0	4.0	2	3.0	0.5	24.3	0.35	2.65	0.729	171.60	$4.25 \cdot 10^{-6}$
4.0	4.0	2	3.0	0.5	21.7	0.40	3.60	0.651	198.72	$3.28 \cdot 10^{-6}$
2.0	4.0	1	3.0	0.5	24.3	0.28	1.72	0.729	145.92	$5.00 \cdot 10^{-6}$
2.0	4.0	2	3.0	0.5	18.8	0.30	1.70	0.564	124.80	$4.52 \cdot 10^{-6}$
2.0	4.0	3	3.0	0.5	20.0	0.32	1.68	0.66	131.76	$5.00 \cdot 10^{-6}$
2.0	4.0	4	3.0	0.5	22.9	0.35	1.65	0.687	138.00	$4.98 \cdot 10^{-6}$
2.0	2.0	2	3.0	0.5	65.0	0.30	1.70	1.950	124.80	$15.63 \cdot 10^{-6}$
2.0	3.0	2	3.0	0.5	32.4	0.30	1.70	0.972	124.80	$7.79 \cdot 10^{-6}$
2.0	4.0	2	3.0	0.5	18.8	0.30	1.70	0.564	124.80	$4.52 \cdot 10^{-6}$
2.0	5.5	2	3.0	0.5	3.5	0.30	1.70	0.105	124.80	$0.84 \cdot 10^{-6}$
2.0	7.0	2	3.0	0.5	5.2	0.30	1.70	0.156	124.80	$1.25 \cdot 10^{-6}$
2.0	8.0	2	3.0	0.5	3.6	0.30	1.70	0.108	124.80	$0.87 \cdot 10^{-6}$
2.0	9.0	2	3.0	0.5	1.7	0.30	1.70	0.051	124.80	$0.41 \cdot 10^{-6}$
2.0	10.0	2	3.0	0.5	3.9	0.30	1.70	0.117	124.80	$0.94 \cdot 10^{-6}$
2.0	11.5	2	3.0	0.5	7.4	0.30	1.70	0.222	124.80	$1.78 \cdot 10^{-6}$
2.0	2.0	2	2.0	0.5	76.1	0.30	1.70	1.52	124.80	$12.20 \cdot 10^{-6}$
2.0	2.0	2	3.0	0.5	65.0	0.30	1.70	1.95	124.80	$15.63 \cdot 10^{-6}$
2.0	2.0	2	4.0	0.5	61.3	0.30	1.70	2.45	124.80	$19.65 \cdot 10^{-6}$

Ecowirl reactor

P inlet (bar)	pH	Double cone (Type)	[RhB] (mg L ⁻¹)	NaOCl (mg L ⁻¹)	ED after 260 cycles (%)	P outlet (bar)	ΔP_{HC} (bar)	RhB degraded (mg/L)	Power density (kJ L ⁻¹)	C.Y. (mg J ⁻¹)
2.0	4.0	Std	3.0	0	14.7	-0.85	2.85	0.441	162.24	$2.72 \cdot 10^{-6}$
2.0	4.0	Std	3.0	0.5	24.9	-0.90	2.90	0.747	162.24	$4.60 \cdot 10^{-6}$
2.0	4.0	Std	3.0	1.0	39.8	-0.90	2.90	1.194	162.24	$7.36 \cdot 10^{-6}$
2.0	4.0	Std	3.0	2.0	61.5	-0.90	2.90	1.845	162.24	$11.37 \cdot 10^{-6}$
2.0	4.0	Std	3.0	3.0	76.5	-0.90	2.90	2.295	162.24	$14.15 \cdot 10^{-6}$
2.0	4.0	Std	3.0	4.0	93.6	-0.90	2.90	2.808	162.24	$17.31 \cdot 10^{-6}$
2.0	4.0	Std	3.0	0.5	29.8	-0.85	2.85	0.894	162.24	$5.51 \cdot 10^{-6}$
3.0	4.0	Std	3.0	0.5	26.0	-0.90	3.90	0.754	180.84	$4.17 \cdot 10^{-6}$
4.0	4.0	Std	3.0	0.5	22.1	-0.95	4.95	0.663	198.24	$3.34 \cdot 10^{-6}$
2.0	4.0	Std	3.0	0.5	29.8	-0.85	2.85	0.894	162.24	$5.51 \cdot 10^{-6}$
2.0	4.0	A	3.0	0.5	18.5	-0.95	2.95	0.555	162.24	$3.42 \cdot 10^{-6}$
2.0	4.0	B	3.0	0.5	13.4	-0.95	2.95	0.402	162.24	$2.48 \cdot 10^{-6}$
2.0	4.0	C	3.0	0.5	9.0	-0.80	2.80	0.270	162.24	$1.66 \cdot 10^{-6}$

C.Y. has been calculated after 260 number of passes

Technology	Cavitation reactor	Chemicals	T (°C)	pH	P (bar)	V (L)	Flow rate (m ³ h ⁻¹)	Time (min)	[RhB] (mg L ⁻¹)	P Nominal (W)	P Absorbed (W)	ED (%)	[RhB] degraded (mg L ⁻¹)	Power density (kJ L ⁻¹)	C. Y. (mg J ⁻¹)	Reference
HC	Swirling jet-induced cavitation	H ₂ O ₂ (100.0 mg L ⁻¹)	50.0	3.0	6.0	25.00	3.6	180	10.0	2500.0	-	99.0	9.900	1080.0	9.17E-06	(Wang et al 2009) [37]
HC	Swirling jet-induced cavitation	No	50.0	3.0	6.0	25.00	3.6	180	10.0	2500.0	-	55.0	5.500	1080.0	5.09E-06	(Wang et al 2009) [37]
HC	Swirling jet-induced cavitation	No	40.0	5.4	6.0	40.00	-	180	5.0	3500.0	-	46.8	2.340	945.0	2.48E-06	(Wang et al 2009) [37]
HC	Heterogeneous catalytic hydrodynamic cavitation reactor	Catalyst: Scrap iron sheets	25.0	3.0	5.8	30.00	2.4	240	2.0	5500.0	-	87.0	1.740	2640.0	6.59E-07	(Parsa e Zonouzian 2013) [36]
HC	Orifice Plate	No	40.0	5.0	2.0	50.00	2.4	76	5.0	5500.0	-	15.0	0.750	500.0	1.50E-06	(Sivakumar and Pandit 2002) [25]
HC	Venturi	No	30.0	2.5	4.8	4.00	0.4	120	5.0	1100.0	-	60.0	3.000	1980.0	1.52E-06	(Mishra and Gogate 2010) [24]
HC	Venturi	No	30.0	4.7	4.8	4.00	0.4	120	5.0	1100.0	-	25.0	1.250	1980.0	6.31E-07	(Mishra and Gogate 2010) [24]
HC	Orifice Plate	No	30.0	4.7	4.8	4.00	0.4	120	5.0	1100.0	-	20.0	1.000	1980.0	5.05E-07	(Mishra and Gogate 2010) [24]
HC	Orifice plates	No	20.0	4.0	2.0	50.00	6.0	130	3.0	3000.0	800	8.6	0.258	124.8	2.07E-06	This study
HC	Orifice plates	NaOCl (0.5 mg L ⁻¹)	20.0	4.0	2.0	50.00	6.0	130	3.0	3000.0	800	18.8	0.564	124.8	4.52E-06	This study
HC	Orifice plates	NaOCl (0.5 mg L ⁻¹)	20.0	2.0	2.0	50.00	6.0	130	3.0	3000.0	800	65.0	1.950	124.8	1.56E-05	This study
HC	Ecowirl reactor	No	20.0	4.0	2.0	50.00	4.6	169	3.0	3000.0	800	14.7	0.441	162.2	2.72E-06	This study
HC	Ecowirl reactor	NaOCl (0.5 mg L ⁻¹)	20.0	4.0	2.0	50.00	4.6	169	3.0	3000.0	800	24.9	0.747	162.2	4.60E-06	This study
HC	Ecowirl reactor	NaOCl (4.0 mg L ⁻¹)	20.0	2.0	2.0	50.00	4.6	65	3.0	3000.0	800	90.5	2.715	62.4	4.35E-05	This study
AC	Acoustic Cavitation	No	25.0	5.3	-	0.30	-	120	5.0	60.0	-	45.0	2.250	1440.0	1.56E-06	(Merouani 2010) [22]
AC	Acoustic Cavitation	No	25.0	-	-	0.01	-	30	10.0	16.5	-	88.0	8.800	2970.0	2.96E-06	(Sivakumar and Pandit 2001) [50]

AC =Acoustic Cavitation

HC = Hydrodynamic Cavitation