Separation and Purification Technology 151 (2015) 31–38

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Microbial disinfection of seawater using hydrodynamic cavitation

Mandar P. Badve, Mihir N. Bhagat, Aniruddha B. Pandit *

Department of Chemical Engineering, Institute of Chemical Technology, Mumbai 400 019, India

ARTICLE INFO

Article history:
Received 15 April 2015
Received in revised form 10 July 2015
Accepted 12 July 2015
Available online 13 July 2015

Keywords:
Hydrodynamic cavitation
Ballast water
Water disinfection
Seawater
Chlorination

ABSTRACT

Hydrodynamic cavitation has been effectively proven to be an efficient advanced oxidation process on an industrial scale. The utility of hydrodynamic cavitation for microbial disinfection of seawater has been reported in this work. Seawater is used as cooling water in refineries and nuclear power plants or as ballast water in the shipping industry. Various norms and regulations of the International Maritime Organization (IMO) make it compulsory for ship owners to treat the ballasting seawater before discharging it into the sea. Also, if the seawater is not properly treated, it causes biofouling which affects the performance of cooling tower and other heat transfer equipments. It has been observed through our study that, hydrodynamic cavitation can be effectively used for microbial disinfection of seawater. Effectiveness of different types of cavitating devices for the extent of disinfection was studied. It was conclusively proved that, slit type of geometry consumes 40% less energy compared to cylindrical geometry for similar extent of seawater disinfection. A combination of the conventional treatments of water disinfection such as chlorination and thermal treatment with hydrodynamic cavitation was found to increase the overall rate of disinfection significantly. Rate of reaction almost doubles when 5 ppm hypochlorite was used as disinfectant with the combination of cavitation compared to when only 5 ppm of hypochlorite was used. Similarly the rate of disinfection increases 2.5 times at 50 °C in combination with cavitation compared to when, only 50 °C was maintained and disinfection was carried out.

1. Introduction

For the past 30 years there has been a remarkable growth in the reported work on an efficient treatment and water purification technique by all categories of users. The categories include municipal, industrial, institutional, medical, commercial and residential. The increasingly broad range of the reported techniques for improving water quality has motivated the water treatment industry to refine existing techniques, combine different methods and explore new emerging water purification technologies. Similarly, seawater disinfection is equally important due to its applications in shipping industry and refineries.

Ships use ballast water to provide stability and maneuverability during a voyage. Water is taken on at one port when the cargo is unloaded and usually discharged at another port when the ship receives a cargo. The local microorganisms, ranging in size (from viruses to large fish) living in the surrounding water or sediments, are taken on board with ballast water. There is a potential danger for the introduction of non-native organisms – called *bioinvaders*, alien species, nonindigenous species or exotic species – into the port of discharge. In order to avoid this problem; IMO has made it compulsory to all shipping companies to treat the water before discharging it into the sea again [1]. Unfortunately no single ballast water management technique has been able to remove all types of organisms from ballast tanks. A combination of different methods may prove to be more effective than one method alone, however little research has been conducted into this possibility. It is difficult to implement treatments because the ship owners are understandably reluctant to install technology that is expensive, unreliable or time consuming. When evaluating ballast water treatment options a number of general factors must be considered. The factors include cost, the effectiveness of the method, the footprint and the possible external risks, which the treatment may pose to human health and the environment during its enforcements. The monetary cost of a treatment method includes the cost of the equipment, the crew needed to operate the treatment equipment, the cost of the disinfectant chemicals and the time needed for the treatment. Many treatment methods require the ships be retrofitted with the necessary equipment or in new ships these equipments included as an integral part in their design. Both of these options may be quite expensive. The ship's crew members have many tasks to perform on a ship, thus, the crew that is needed to operate this additional treatment task may decrease the number

---

* Corresponding author.
E-mail address: ab.pandit@ictmumbai.edu.in (A.B. Pandit).

http://dx.doi.org/10.1016/j.seppur.2015.07.020
1383-5866/

Nomenclature

N	viable microbial count at time t (CFU/ml)	k	rate constant for disinfection (min^{-1})
N_0	viable microbial count at the beginning of the experiment (CFU/ml)	P_h	pump discharge pressure (Pa)
E	hydraulic energy input (J)	Q	volumetric flow rate (m^3/min)
E'	hydraulic energy input per unit volume (J/m^3)	t	time (min)
		V	volume of seawater (m^3)

of crew members that are available for other essential ship operations. If a treatment method slows down the journey of a vessel or causes excess fuel consumption the voyage will be more expensive and uneconomical. Any adapted treatment method should also provide easy means for port authorities to monitor its operations and effectiveness. As many treatment methods work on the basis of killing the organisms in ballast water, the method itself may pose a risk to human health or to the environment if the treatment is not properly carried out in the ballast tanks. These risks and costs need to be evaluated and compared to the risk of introducing alien species in a port.

Different methods, physical and/or chemical can be used for treating the ballast water. Each method has its advantages as well as disadvantages. The physical methods include methods such as, filtration and use of hydro-cyclone [2–4]. In filtration, screens or strainers are used as filter media. In hydro-cyclones, high velocity centrifugal rotation of water is used to separate the particles/organisms. Both these methods can filter larger organisms and sediments from the seawater very effectively, but cannot filter out smaller target microorganisms. Also, filter screens need periodic backwashing and also a larger surface area for the higher filtration rates. Hydro-cyclones are less effective than filters in terms of their removal efficiency. Filtration can be used in combination with the other disinfection technologies as they are very effective in removing the larger organisms. The chemical methods for disinfection includes, use of chlorination, electrochlorination, ozonation and hydrogen peroxide [5–8]. In chlorination, chlorine gas is dosed in water which destroy cell walls of the organisms which leads to their death. Chlorine gas is inexpensive, but is extremely corrosive, even at residual level. Instead of chlorine gas, sodium hypochlorite can be used as a source of chlorine and can be injected into ballast water stream. The problem with chlorination is the high doses of chlorine requirement when other organic contaminants are present. It is dangerous in terms of handling and safety precautions needs to be taken. Also, the organic matter in the seawater forms toxic halogenated organic compounds during chlorination, which needs to be separated and disposed off safely. In electro-chlorination, electrolytic decomposition of seawater to $^{-}$OCl and HOCl (hypo-chlorous acid) takes place and the acid acts as a disinfecting agent. The only advantage of this method is that, it does not require any additional chemical storage and use. But this method is ineffective against cysts and form harmful disinfection by-products (DBP's). Also, separate installation of electrochemical cells can increase the initial capital cost investment. In ozonation, ozone gas is passed through the stream of seawater. Ozone is very powerful but unstable oxidizing agent which can effectively kill microorganisms along with spores when used as a disinfecting agent. Ozone chemistry in seawater differs from that in fresh water because of the presence of bromide ions [1,9]. It has been reported that the bromine in seawater gets converted to hypobromide ion and hypobromous acid, which leads to the formation of bromoform, which is a toxic by-product and possible carcinogen produced by reaction with organic matter. This bromine ion hindrance leads to the requirement of higher concentration of ozone and longer contact times. Hydrogen peroxide (H_2O_2) can be also be used as a disinfectant for seawater. Hydrogen peroxide is an uncharged molecule that passes easily through cell membranes by diffusion. Inside the cells, reactive and destructive hydroxyl radicals are liberated by H_2O_2. The oxidizing properties, the rapid degradation, the environmentally friendly degradation products (water and oxygen), and the fact that it can be produced electrochemically make H_2O_2 a promising disinfectant for onboard treatment of ballast water.

Several authors have reported the use of advanced oxidation processes such as microwave irradiation, UV radiation, fenton oxidation for ballast water treatment [10–13]. Although these techniques are effective in removing the seawater microorganisms, the major problems are associated with the scale up and maintenance of such processes on board a ship. Installation and operating costs of such systems is another major issue which has not been addressed yet satisfactorily.

In this work we have tried to use the technique of hydrodynamic cavitation for microbial disinfection of seawater. Hydrodynamic cavitation has been effectively proved to be an efficient technique in terms of energy consumed and cost of operation for the disinfection of bore well water and industrial effluents [14,15]. Shivram et al. [16] have carried out the seawater disinfection using cavitation produced by vortex diode and have proved its effectiveness in killing of various types of zooplanktons present in the seawater.

The physical and chemical effect of hydrodynamic cavitation includes creation of high temperature and pressure shock waves and generation of highly reactive hydroxyl radicals [17]. Shock waves could also possibly cleavage the molecular bonds. The free radicals thus generated can oxidize organic pollutants, and extreme temperatures (hot spots) can also pyrolyse the molecules if they are in the vicinity of the collapsing cavity [18]. However these processes are most likely of less importance in the case of disinfection by hydrodynamic cavitation, because of the larger sizes of the microorganisms [19] which need to be targeted. In addition to the generation of strong oxidizing agents, cavitation bubble collapse also results in the generation of shock waves, high shear regions, high temperature and pressure pulses. Such adverse/extreme local environmental conditions may result in the mechanical rupture of the cell walls, loss of intracellular materials which eventually results in cell death. Which of these diverse mechanism is responsible for the actual disinfection and to what extent, is very difficult to predict. It has been assumed that the combination of all these collapse conditions contribute at least partially to the disinfection of microorganisms in the case of hydrodynamic cavitation. It is very difficult to predict the exact mechanism of disinfection in the case of cavitation based disinfection/disruption operations. Several authors have tried to predict the mechanism of disinfection/disruption using cavitation. Balasundaram and Harrison [20] have carried out the disruption of *Escherichia coli* using orifice plate for the purpose of preferentially releasing the intracellular proteins from organisms. They have proposed a stage wise disruption of cells for the protein release for multiple passes through orifice plate. In the first stage, the outer membrane is perforated allowing the loss of periplasmic proteins. In the second stage the cytoplasmic membrane gets exposed to the effects of cavitation. Continuous cavitation leads to complete breakdown of the outer membrane resulting in cell death. For cavitation based cell disruption method Save et al. [21] have proposed, that shock wave i.e. the pressure impulse produced from the collapsing cavities is the main cause of cell disruption. Kelemen and Sharpe [22] have found that during high-pressure homogenization, Gram-negative *E. coli* were disrupted at lower pressures (less cavitational intensity) than Gram-positive *Bacillus subtilis*. This was attributed to the composition of their cell walls. In absence of any concrete information about the mechanism of disinfection, Shivram et al. [16] have developed a mathematical correlation, in which they have correlated the net energy delivered by the collapsing cavity to the surrounding liquid and the cell wall strength of a particular type of cell with the extent of actual disinfection observed.

In this work we have studied the extent of microbial disinfection by hydrodynamic cavitation by using different types of cavitating devices such as slit venturi, circular venturi and orifice plate. The effect of the several other parameters such as temperature and pH along with the hydrodynamic cavitation on the extent of disinfection was also studied. Effect of sodium hypochlorite (with varying concentration) along with hydrodynamic cavitation for microbial disinfection was also studied. It has been found that the combination of hydrodynamic cavitation and hypochlorite is very effective in removing almost all the seawater microorganisms. Also, the quantity of hypochlorite required when it is used in combination with HC is very less compared to the quantity required for the conventional hypochlorite based disinfection. Overall, it has been found out that, hydrodynamic cavitation can be effectively utilized for commercial scale ballast water treatment systems as it is easy to scale up and install as well as it is energy wise cost effective.

2. Materials and methods

2.1. Materials

Seawater was collected from Shivaji Park chowpaty, Dadar, Mumbai, India. The water was then filtered with muslin cloth to remove debris and dirt and then stored in storage tanks for further use in the experimental study. All the chemicals used during the experiments, such as, sodium chloride, sodium hydroxide, sulfuric acid, sodium hypochlorite and Zobell Marine Broth for enumeration of seawater bacteria were purchased from High-Media Pvt. Ltd. India.

2.2. Experimental setup and cavitating devices

Schematic of the setup is as shown in Fig. 1. The setup includes a holding tank of 15 l volume, a positive displacement pump of power rating 1.1 kW, control valves and flanges to accommodate the cavitating device in the main line and a bypass line to control the flow through the main line. The suction side of the pump is connected to the bottom of the tank and the discharge from the pump branches into two lines; the main line and a bypass line. The main line flow rate was adjusted by changing the number of piston strokes per unit time of the pump using a variable frequency drive (VFD). Additionally, a valve is also provided in the bypass line to control the liquid flow through the main line. 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. Different types of cavitating devices such as orifice, cylindrical venturi and rectangular slit venturi were used in this study. Schematic of the cavitating devices as well as their geometric details are shown in Fig. 2 and Table 1.

2.3. Experimental work

Hydrodynamic cavitation based disinfection experiments were carried out under different operating conditions, using fixed seawater volume of 4 l and for different circulation time, depending upon the chosen experimental condition. Enumeration of viable bacteria present in sea water is done by plate count method. Single sample of 50 ml is drawn after the desired number of pass. These samples are serially diluted up to 10^4 fold, using filtered and autoclaved sea water. Out of all these diluted samples, a volume of 100 μl was spread plated on the Zobell Marine Agar (ZMA, 2216). The dilution and plating is done under the laminar flow hood to avoid error due to contamination. All the plates were inverted and incubated for a period of 48 h and then the colonies were counted. The results only for the plates showing 20–300 colonies

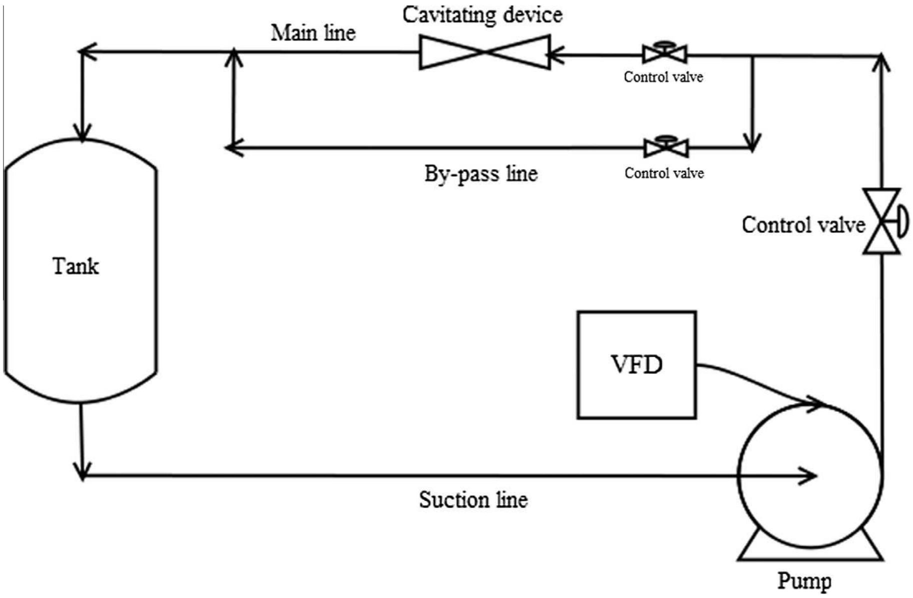

Fig. 1. Schematic of the hydrodynamic cavitation setup.

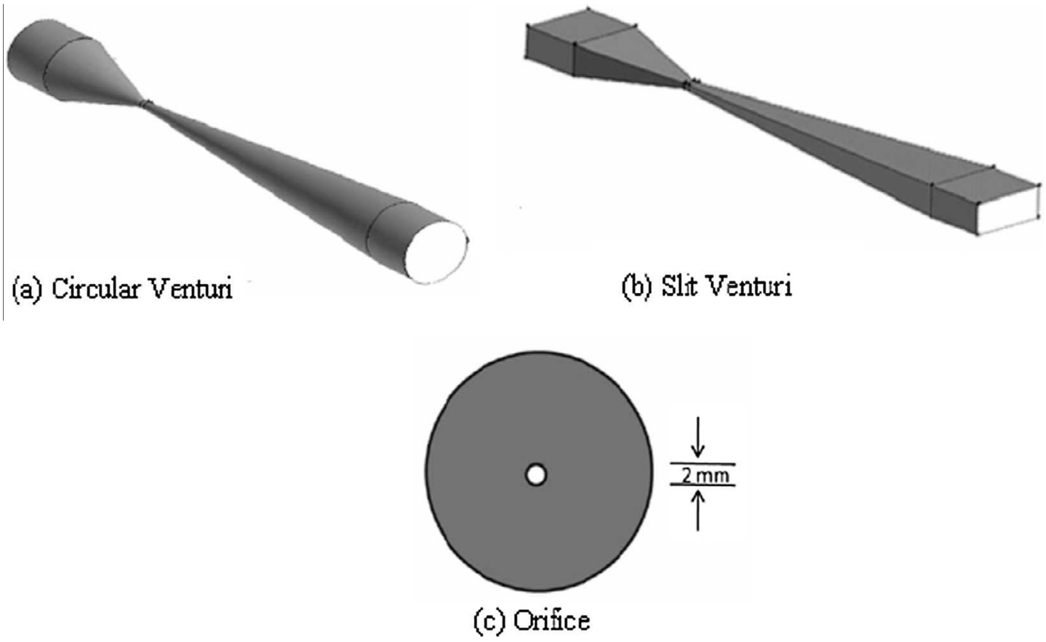

Fig. 2. Schematic of cavitating devices.

Table 1
Dimensions of circular and slit venturi.

Dimension	Circular venturi	Slit venturi
Dimension of throat	Circular hole of 2 mm diameter	$W = 3.7$ mm; $H = 0.92$ mm; $L = 0.92$ mm
Venturi length	106 mm	86 mm
Length of convergent section	18 mm	18 mm
Length of divergent section	67 mm	65 mm
Half angle of convergent section	22.6°	22.6°
Half angle of divergent section	6.5°	6.5°

were considered and averaged to give viable bacterial counts i.e. the Colony Forming Units (CFU) per ml of sea water.

3. Result and discussions

3.1. Effect of cavitating conditions on disinfection

Fig. 3 shows the effect of cavitating device geometry on the overall extent of disinfection. Initial CFU count in case of all the experiments is around 10^7 CFU/ml. Experiments were carried out at the different inlet pressure to the cavitating device developed by the pump. Seawater present in the tank was allowed to pass through the cavitating device for a certain fixed number of times through the cavitating device in each case. The time required for all the seawater in the tank to pass through the cavitating device is calculated based upon the overall pump generated flow rate of the seawater at the respective outlet discharge pressure of the pump/inlet pressure to the cavitating device. The time required for all the seawater to pass once through cavitating device is calculated using the following formula:

$$t(\text{min}) = \frac{\text{Total Volume of seawater (lit)}}{\text{Volumetric flow rate (LPM)}}$$

In all the experiments, a maximum of 50 passes of seawater through the respective cavitating device, were carried out. Samples were withdrawn at the regular interval of time and the rate of disinfection of seawater bacteria was also studied. It can be seen from Fig. 3 that as the inlet pressure to the cavitating device is increased; the overall disinfection obtained for the same number of passes also increases up to certain value of inlet pressure and then it decreases. This behavior of an increase in the cavitation disinfection efficiency of the process with an increase in the inlet pressure has been well studied and well explained phenomenon [23,24]. The extent of the cavitation occurring in any cavitating device is explained by the dimensionless number called as cavitation number [24]. According to the definition of the cavitation number, it is the ratio of, difference between the pressure head at the downstream of the cavitating device minus the vapor pressure of the cavitating medium to the velocity head at the

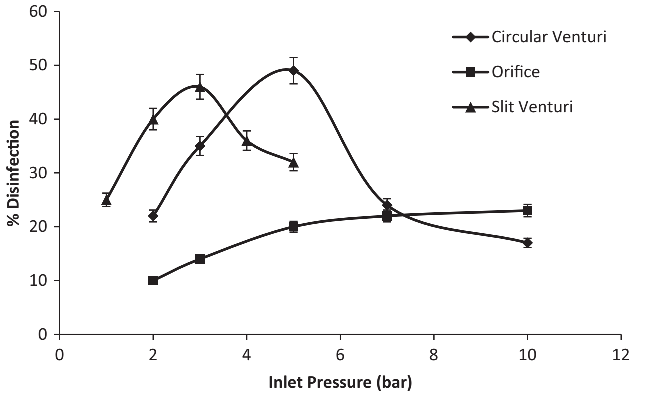

Fig. 3. Effect of different cavitating devices on disinfection, 50 passes.

constriction. In the absence of any cavitation in the system the sum of pressure and velocity head at the constriction should be equal to pressure head downstream of the cavitating device (neglecting the velocity head downstream, since it is negligible compared to the velocity head at the constriction). But when cavitation takes place, some of the energy is utilized in the generation of the secondary vapor phase and turbulence; thus the pressure head downstream of the cavitating device is less than the sum of pressure and velocity head at the constriction of the chosen cavitating device. Thus, for the constant downstream pressure, with an increase in the flow rate, i.e. increase in the velocity head at the constriction (because of the increase in inlet pressure), the energy taken up by the liquid for the generation of secondary vapor phase also increases, indicating an increase in the cavitational activity (generation of more number of vapor cavities). This explains the increase in the extent of disinfection of seawater with an increase in the inlet pressure to the cavitating device.

As far as the effect of geometry of the cavitational device is concerned, it can be seen that, for the same inlet pressure (let us assume 3 bar) the extent of disinfection obtained in orifice, circular venturi and slit venturi is different. Saharan et al. [25] have given the flow characteristics (velocity head and cavitation number vs inlet pressure) of these three geometries (orifice, circular and slit venturi) with respect to inlet pressure in their work. At 3 bar, Cavitation number obtained for orifice, circular and slit venturi is 0.62, 0.2 and 0.1 respectively. In the case of orifice plate, there is the sudden alteration in the flow geometry, because of which velocity head obtained at the constriction is very less. Low velocity head signifies, higher cavitation number, meaning very small number of cavitational events. Whereas, in the case of circular and slit venturi, flow alteration is gradual and therefore the velocity head obtained is quite large compared to orifice plate and hence lower cavitation number is obtained, i.e. more cavitational events occur in circular as well as slit venturi. Therefore, at the same inlet pressure to the cavitating device, the extent of disinfection obtained in orifice plate is considerably smaller than that of circular as well as slit venturi. It can also be seen from Fig. 3 that, there is a considerable difference between the extent of overall disinfection obtained in the case of circular and slit venturi for the same inlet pressure. This behavior of change in cavitational efficacy between circular and slit venturi is well explained numerically by Bashir et al. [26] and Dastane et al. [27]. Focus of their work was based on the hypothesis, that the cavitation is a function of perimeter/flow area (p/a) ratio of the constriction. They have simulated different circular and non-circular geometries and have proved that cavitation is a function of p/a ratio, the higher the ratio, higher will be the cavitational activity and higher cavitational efficiency. In the present work, p/a ratio for circular and slit venturi is 4 and 15.8 mm^{-1} respectively, which clearly indicates why maximum disinfection was achieved in the case of slit venturi compared to circular venturi for the same inlet pressure.

It can be also seen from Fig. 3 that the extent of disinfection decreases after certain value of inlet pressure in case of the circular and slit venturi. Several authors have reported this behavior of a decrease in the cavitational efficacy after certain value of the inlet pressure and has attributed it to choked cavitation. The choked flow is the condition which occurs in mostly in two phase flows with some sort of vapor locking. With an increase in the inlet pressure to the system, the flow rate increases up to a certain value of inlet pressure, after which no further increase in the flow rate is obtained. From the flow characteristic of the pump and cavitating device which was obtained for this setup, it was observed that the flow rate was increasing with an increase in the inlet pressure over the range at which the experiments were carried out. This indicates that, no choking condition is occurring under the covered experimental conditions. It can thus be said that the observed decrease in the rate of disinfection may not be because of the choked cavitation/flow as suggested by others. In order to analyze the cavitational behavior inside the cavitating device, Saharan et al. [24] have carried out a photographic study of a circular venturi. Photographs were taken at different inlet pressure of the venturi. It was observed that, as the inlet pressure to the cavitating device increase, the number density of cavities also goes on increasing. Cavities tend to behave as individual cavity at a relatively lower value of inlet pressure. With further increase in the inlet pressure a point is reached, where the number density of cavities becomes so high that entire downstream section gets filled with the cavities and the cavities start coalescing. A cavity cloud gets formed. In a collapsed cavity cloud, the energy released by a single cavity collapse gets dampened by the surrounding cavities and hence the overall effect of cavitation on the surrounding liquid goes down. Which explains the observed decrease in the overall disinfection of sea water after certain operating pressure, in the case of circular as well as slit venturi. Cavity cloud formation is the initial stage of choked cavitation. With further increase in the flow rate beyond the cavity cloud formation, number of cavities becomes so high that, interaction between the cavities leads to a formation of larger vaporous cavity cloud which leads to a condition of choked flow/-cavitation. It can be concluded that, this behavior of reduction in the cavitational efficacy is possibly due to cavity cloud formation and not because of the condition of choked cavitation.

3.2. Energy dissipation for different cavitating devices

In order to explain the effectiveness of the slit geometry of venturi over cylindrical venturi and orifice plate, the obtained cell count reduction was plotted against the hydraulic energy input (E) to the liquid for the respective geometry. The data selected for each geometry was the one for which maximum disinfection was obtained (slit: 3 bar, cylindrical: 5 bar, orifice: 5 bar). The hydraulic energy input to the liquid E is nothing but the product of the input hydraulic power (P_h) and disinfection time, t. For a volumetric flow rate, Q and a pump discharge pressure P_h, this can be calculated as:

$$E = P_h * Q * t \text{ J}$$

In order to generalize this, the input hydraulic energy per unit was calculated by dividing the energy by the treated liquid volume (V) (seawater in this case) used for the respective experiment.

$$E' = E/V = P_h * Q * t/V \text{ J/m}^3$$

The overall microbial count (N) was normalized with respect to the initial concentration (N_0), in order to compare the decrease in the microbial count in each experiment as each experiment had different initial CFU concentration.

It can be clearly seen from Fig. 4 that the energy input in the case of slit venturi is the least. It should also be noted that, the extent of disinfection obtained with slit venturi is at 3 bar inlet pressure while for cylindrical venturi, the optimum is at 5 bar. The maximum disinfection for the slit venturi with minimum energy input can be explained by the fact that the maximum flow rate has been observed in the case of slit venturi compared to cylindrical venturi and orifice plate, which leads to more cavitational events increasing the probability of cell wall disruption in the case of slit venturi compared to other geometries. Similar observation is reported by Loraine et al. [28]. The work is related to the disinfection of *E. coli* and *B. Subtilis* using different cavitating devices such as orifice plates and nozzles. They have reported that for the different geometries with the same flow area the change in disinfection rate was because of the hydrodynamic effects of the geometries and it is related to the liquid flow rate obtained for

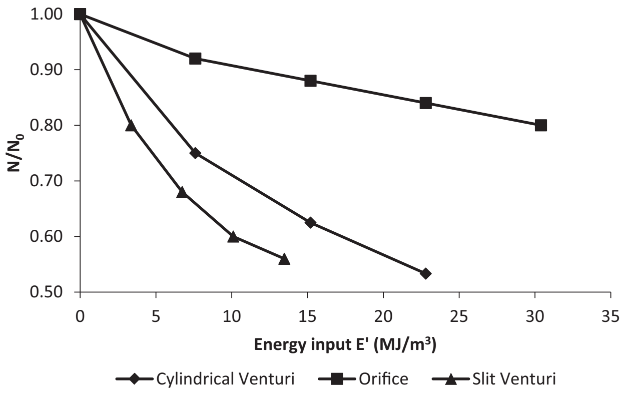

Fig. 4. Disinfection v/s energy input into the system.

the respective geometry. Arrojo et al. [19] also reported that the rate of *E. coli* disinfection using hydrodynamic cavitation was dependent on the cavitating device configuration. They have concluded that the venturi type devices outperformed the orifice geometry for desirable cavitational effects. Saharan et al. [25] have carried out the degradation of Orange G dye using hydrodynamic cavitation for different geometries such as slit, cylindrical and orifice. They have also concluded that the slit geometry is much better compared to cylindrical venturi and orifice plate in terms of energy dissipation and cavitational efficacy (termed as cavitational yield).

3.3. Effect of seawater pH on cavitation efficacy

Table 2 depicts the effect of seawater pH on disinfection efficacy of hydrodynamic cavitation. In order to get an overview of the effect of decrease in pH of seawater on the efficacy of disinfection using HC and also the survival rate of bacteria under such extreme conditions, experiments were carried out at the conditions of pH 3–10 [29]. Seawater pH was adjusted using with 0.1 M NaOH and 0.1 M H_2SO_4. All the experiments with hydrodynamic cavitation were carried out at 3 bar inlet pressure and with slit venturi. Experiments were carried out for a period of 15 min (≈60 passes). In order to quantify the effect of operating pH and hydrodynamic cavitation separately, control experiments were carried out where only pH was maintained at a particular value over an extended period of time. Its viable colony count was measured after the stipulated time. It can be clearly seen that the alkaline conditions favors the overall disinfection and also the obtained rate of disinfection is high in the case of alkaline conditions. It has also been reported by Carlucci and Pramer [30] that death of *E. coli* was more rapid in alkaline conditions than under acidic conditions. Starliper and Watten [31] have reported that, at higher pH, hydroxide ions may impart several lethal effects to bacterial cells, such as destruction of phospholipids (structural components of cell membranes), destruction of bonds of essential metabolic enzymes and loss of the tertiary structure and destruction of DNA. These observations are consistent with the current observations, where alkaline pH gave higher disinfection compared to that under acidic conditions. Although, considering the quantity of alkali required for increasing such high pH in the case of commercial scale ballast treatment, this appears to be a less viable option for ballast water treatment.

Table 2
Disinfection efficacy for various operating conditions.

	% disinfection in 15 min	Rate constant (min^{-1})	Disinfection per pass (CFU killed/pass)	% disinfection per pass
Effect of pH				
pH 4	8	–	–	–
pH 4 + HC	39	0.03	93,176	0.9%
pH 5	6	–	–	–
pH 5 + HC	37	0.03	84,706	0.8%
pH 8	3	–	–	–
pH 8 + HC	44	0.04	104,471	1.0%
pH 10	23	–	–	–
pH 10 + HC	56	0.06	169,412	1.5%
Effect of temperature				
30 °C	2	–	–	–
30 °C + HC	44	0.04	107,294	1.1%
40 °C	5	–	–	–
40 °C + HC	45	0.04	112,941	1.1%
50 °C	20	0.02	–	–
50 °C + HC	56	0.05	152,471	1.5%
60 °C	70	0.08	–	–
60 °C + HC	100	0.14	395,294	8.5%
Effect of addition of Sodium hypochlorite				
1 ppm	32	0.03	–	–
1 ppm + HC	75	0.09	260,894	2.6%
3 ppm	45	0.04	–	–
3 ppm + HC	82	0.11	321,882	3.2%
5 ppm	64	0.10	–	–
5 ppm + HC	100	0.20	564,706	13.0%

3.4. Effect of seawater temperature on cavitation efficacy

Thermal treatment of ballast water is a well-researched area among researchers, considering known susceptibility of microorganisms to higher temperatures [32,33]. Ample amount of waste heat available from the ship engines makes it even more interesting option to be studied and implement on board of ship. The major drawback however of the thermal treatment is different reported rate of bacterial disinfection for different types of microorganisms. Heat treatments that take hours to complete are not a practical option where vessel/ship operate on short journeys, where the time available for ballasting and deballasting is very short. In order to improve/increase the rate of disinfection, experiments were carried out by combining hydrodynamic cavitation with thermal treatment. Higher temperatures were expected to make the cell wall lucid. This will make easier to break the cell wall by hydrodynamic cavitation or vice a versa. This eventually leads to an increase in the total quantum of disinfection achieved as against when, where only the thermal or hydrodynamic cavitation are used in isolation. It can be seen from Table 2 that, when hydrodynamic cavitation was combined with thermal treatment, there is a 2.5 times increase in the rate of disinfection at 50 °C and 2 times increase in the rate at 60 °C. log 4 reduction in bacterial concentration was observed at 60 °C in combination with hydrodynamic cavitation in 15 min only (≈50 passes). Plot of viable microbial count v/s time, showed an exponential decrease. A Chick–Watson disinfection model was used to express the rate of disinfection as a function of microbial survival rate [34].

According to Chick–Watson model,

$$-\frac{dN}{dt} = k^{*}N^{1}$$

where k^{*} is a pseudo first-order reaction rate constant equal to k_1C. Chick's rate law states that the number of bacteria destroyed per unit time is proportional to the number remaining for a given concentration of disinfectant. Integration of Chick's law gives the pseudo first-order relationship

$$\ln\frac{N}{N_0} = -k^{*}T$$

where N is the concentration of bacteria at any time (CFU/ml), T is the time for disinfection (min) and N_0 is the initial concentration of bacteria (CFU/ml)

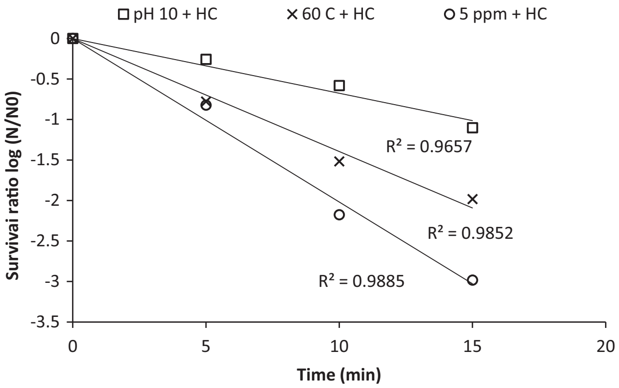

Fig. 5. Plot of $\log(N/N_0)$ v/s time for the determination of rate constant k (min^{-1}).

$$\log\frac{N}{N_0} = -kT$$

where $k = k^*/\ln(10)$

The rate constant was estimated by plotting survival rate of bacteria $\log N/N_0$ vs T. A straight line was obtained, the slope of which is the rate constant, k (min^{-1}). Fig. 5 shows the plot of log N/N_0 vs T for few cases.

3.5. Combination of hypochlorite and cavitation

Similar to temperature and cavitation combination study, chlorination study in combination with hydrodynamic cavitation was also carried out. Chlorination is one of the widely used technology for the disinfection of water in various industries. It was observed that by combining, chlorination with hydrodynamic cavitation, not only the rate of disinfection increases, but also the amount of chlorine/chlorinating agent required reduces. Sodium hypochlorite was used as a source of chlorine. The experiments were carried out with the 1 ppm, 3 ppm and 5 ppm concentration of sodium hypochlorite. Control experiments with only sodium hypochlorite were also carried out to quantify the effect of combination of chlorination and hydrodynamic cavitation over these individual treatments. It can be clearly seen from Table 2 that, rate of disinfection is increased by almost 2 times compared to that of only chlorination when it is combined with hydrodynamic cavitation. Less amount of sodium hypochlorite requirement will also result into less formation of disinfection by products which are harmful to the environment and which need to be disposed of safely [35,36] after the disinfection treatment. The per pass disinfection is also an important parameter as it tells us the number of passes through the cavitating device needed to achieve log 4 reduction.

4. Conclusions

1. Hydrodynamic cavitation can be effectively used for the microbial disinfection of seawater.
2. Slit type geometry performs better than cylindrical venturi and orifice plate in terms of disinfection efficacy as well as the amount of energy consumed.
3. Thermal treatment coupled with hydrodynamic cavitation increases the rate of disinfection 4 times at 60 °C, compared to that of conventional only thermal treatment at 60 °C.
4. The combination of chlorination along with the hydrodynamic cavitation also increases the rate of disinfection compared to that of conventional chlorination. Quantity of chlorine required also reduces when it is used in combination with hydrodynamic cavitation which can reduce the amount of disinfection byproducts formed during the conventional chlorination process.
5. Overall authors would like to conclude that; hydrodynamic cavitation can be easily scaled-up to commercial scale. In order to reduce the time for disinfection, hydrodynamic cavitation can be combined with other techniques such as thermal treatment and/or chlorination; cavitator can be designed in such a way that it can create more intense cavitating conditions which will reduce the disinfection time further.

Acknowledgments

Authors would like to acknowledge the University Grants Commission (UGC), New Delhi, India for financial support through SRF and NRC grants.

References

[1] E. Tsolaki, E. Diamadopoulos, Technologies for ballast water treatment: a review, J. Chem. Technol. Biotechnol. 85 (2010) 19–32, http://dx.doi.org/10.1002/jctb.2276.
[2] V. Karanikola, A.T. Ngo, J.R. Valdes, Plankton filtration with compressible crumb rubber packs, Chemosphere 82 (2011) 597–602, http://dx.doi.org/10.1016/j.chemosphere.2010.10.098.
[3] A.A. Cangelosi, N.L. Mays, M.D. Balcer, E.D. Reavie, D.M. Reid, R. Sturtevant, et al., The response of zooplankton and phytoplankton from the North American Great Lakes to filtration, Harmful Algae 6 (2007) 547–566, http://dx.doi.org/10.1016/j.hal.2006.11.005.
[4] Z. Tang, M.A. Butkus, Y.F. Xie, Crumb rubber filtration: a potential technology for ballast water treatment, Mar. Environ. Res. 61 (2006) 410–423, http://dx.doi.org/10.1016/j.marenvres.2005.06.003.
[5] M. Fabbricino, G.V. Korshin, Formation of disinfection by-products and applicability of differential absorbance spectroscopy to monitor halogenation in chlorinated coastal and deep ocean seawater, Desalination 176 (2005) 57–69, http://dx.doi.org/10.1016/j.desal.2004.10.026.
[6] D.A. Wright, R.W. Gensemer, C.L. Mitchelmore, W.A. Stubblefield, E. Van Genderen, R. Dawson, et al., Shipboard trials of an ozone-based ballast water treatment system, Mar. Pollut. Bull. 60 (2010) 1571–1583, http://dx.doi.org/10.1016/j.marpolbul.2010.04.010.
[7] J.C. Perrins, W.J. Cooper, J. Van Leeuwen, R.P. Herwig, Ozonation of seawater from different locations: formation and decay of total residual oxidant–implications for ballast water treatment, Mar. Pollut. Bull. 52 (2006) 1023–1033, http://dx.doi.org/10.1016/j.marpolbul.2006.01.007.
[8] K.G.N. Nanayakkara, Y.M. Zheng, A.K.M.K. Alam, S. Zou, J.P. Chen, Electrochemical disinfection for ballast water management: technology development and risk assessment, Mar. Pollut. Bull. 63 (2011) 119–123, http://dx.doi.org/10.1016/j.marpolbul.2011.03.003.
[9] R. Balaji, O. Yaakob, Emerging ballast water treatment technologies: a review, J. Sustain. Sci. 6 (2011) 126–138.
[10] D. Wu, H. You, R. Zhang, C. Chen, D.-J. Lee, Ballast waters treatment using UV/Ag–$TiO_2 + O_3$ advanced oxidation process with *Escherichia coli* and *Vibrio alginolyticus* as indicator microorganisms, Chem. Eng. J. 174 (2011) 714–718, http://dx.doi.org/10.1016/j.cej.2011.09.087.
[11] N. Zhang, K. Hu, B. Shan, Ballast water treatment using UV/TiO_2 advanced oxidation processes: an approach to invasive species prevention, Chem. Eng. J. 243 (2014) 7–13, http://dx.doi.org/10.1016/j.cej.2013.12.082.
[12] E.R. Holm, D.M. Stamper, R.A. Brizzolara, L. Barnes, N. Deamer, J.M. Burkholder, Sonication of bacteria, phytoplankton and zooplankton: application to treatment of ballast water, Mar. Pollut. Bull. 56 (2008) 1201–1208, http://dx.doi.org/10.1016/j.marpolbul.2008.02.007.
[13] L.F. Martínez, M.M. Mahamud, A.G. Lavín, J.L. Bueno, Evolution of phytoplankton cultures after ultraviolet light treatment, Mar. Pollut. Bull. 64 (2012) 556–562, http://dx.doi.org/10.1016/j.marpolbul.2011.12.021.
[14] K.K. Jyoti, A.B. Pandit, Ozone and cavitation for water disinfection, Biochem. Eng. J. 18 (2004) 9–19, http://dx.doi.org/10.1016/S1369-703X(03)00116-5.
[15] K.K. Jyoti, A.B. Pandit, Water disinfection by acoustic and hydrodynamic cavitation, Biochem. Eng. J. 7 (2001) 201–212.
[16] S. Shivram, A. Chandrashekar, V. Krishnamurthy, C. Gaonkar, Effect of hydrodynamic cavitation on zooplankton: a tool for disinfection, Biochem. Eng. J. 42 (2008) 320–328, http://dx.doi.org/10.1016/j.bej.2008.08.001.
[17] M. Badve, P. Gogate, A. Pandit, L. Csoka, Hydrodynamic cavitation as a novel approach for wastewater treatment in wood finishing industry, Sep. Purif. Technol. 106 (2013) 15–21, http://dx.doi.org/10.1016/j.seppur.2012.12.029.
[18] L.C. Mandar, P. Badve, Parag R. Gogate, Aniruddha B. Pandit, Hydrodynamic cavitation as a novel approach for delignification.pdf, Ultrason. Sonochem. 21 (2014) 162–168.
[19] S. Arrojo, Y. Benito, A. Martínez Tarifa, A parametrical study of disinfection with hydrodynamic cavitation, Ultrason. Sonochem. 15 (2008) 903–908.
[20] B. Balasundaram, S.T.L. Harrison, Study of physical and biological factors involved in the disruption of *E. coli* by hydrodynamic cavitation, Biotechnol. Prog. 22 (n.d.) 907–913, http://dx.doi.org/10.1021/bp0502173.

[21] S.S. Save, A.B. Pandit, J.B. Joshi, Microbial cell disruption: role of cavitation, Chem. Eng. J. Biochem. Eng. J. 55 (1994) B67–B72, http://dx.doi.org/10.1016/0923-0467(94)06062-2.

[22] M. Kelemen, J. Sharpe, Controlled cell disruption: a comparison of the forces required to disrupt different micro-organisms, J. Cell Sci. 35 (1979) 431–441.

[23] V.K. Saharan, A.B. Pandit, P.S. Satish Kumar, S. Anandan, Hydrodynamic cavitation as an advanced oxidation technique for the degradation of Acid Red 88 Dye, Ind. Eng. Chem. Res. 51 (2012) 1981–1989, http://dx.doi.org/10.1021/ie200249k.

[24] V.K. Saharan, M.P. Badve, A.B. Pandit, Degradation of Reactive Red 120 dye using hydrodynamic cavitation, Chem. Eng. J. 178 (2011) 100–107, http://dx.doi.org/10.1016/j.cej.2011.10.018.

[25] V.K. Saharan, M.A. Rizwani, A.A. Malani, A.B. Pandit, Effect of geometry of hydrodynamically cavitating device on degradation of orange-G, Ultrason. Sonochem. 20 (2013) 345–353, http://dx.doi.org/10.1016/j.ultsonch.2012.08.011.

[26] T.A. Bashir, A.G. Soni, A.V. Mahulkar, A.B. Pandit, The CFD driven optimisation of a modified venturi for cavitational activity, Can. J. Chem. Eng. 89 (2011) 1366–1375, http://dx.doi.org/10.1002/cjce.20500.

[27] G.G. Dastane, M.P. Badve, V.K. Saharan, A.B. Pandit, Numerical optimization and experimental validation of hydrodynamic cavitating device, in: 8th Int. Symp. Cavitation, 2012, pp. 978–981, http://dx.doi.org/10.3850/978-981-07-2826-7.

[28] G. Loraine, G. Chahine, C. Hsiao, J. Choi, P. Aley, Disinfection of gram-negative and gram-positive bacteria using DYNA J ETS hydrodynamic cavitating jets, Ultrason. Sonochem. 19 (2012) 710–717, http://dx.doi.org/10.1016/j.ultsonch.2011.10.011.

[29] I. Joint, S.C. Doney, D.M. Karl, Will ocean acidification affect marine microbes?, ISME J 5 (2011) 1–7, http://dx.doi.org/10.1038/ismej.2010.79.

[30] A.F. Carlucci, D. Pramer, An evaluation of factors affecting the survival of *Escherichia coli*, Appl. Environ. Microbiol. 8 (1960) 247.

[31] C.E. Starliper, B.J. Watten, Bactericidal efficacy of elevated pH on fish pathogenic and environmental bacteria, J. Adv. Res. 4 (2013) 345–353, http://dx.doi.org/10.1016/j.jare.2012.06.003.

[32] G. Quilez-Badia, T. McCollin, K.D. Josefsen, A. Vourdachas, M.E. Gill, E. Mesbahi, et al., On board short-time high temperature heat treatment of ballast water: a field trial under operational conditions, Mar. Pollut. Bull. 56 (2008) 127–135, http://dx.doi.org/10.1016/j.marpolbul.2007.09.036.

[33] E. Ortega-Gómez, P. Fernández-Ibáñez, M.M. Ballesteros Martín, M.I. Polo-López, B. Esteban García, J.A. Sánchez Pérez, Water disinfection using photo-Fenton: effect of temperature on *Enterococcus faecalis* survival, Water Res. 46 (2012) 6154–6162, http://dx.doi.org/10.1016/j.watres.2012.09.007.

[34] Lyndon L. Gyiirek, Gordon R. Finch, Modeling water treatment chemical disinfection kinetics, J. Environ. Eng. 124 (1998) 783–793.

[35] N. Zhang, B. Ma, J. Li, Z. Zhang, Factors affecting formation of chemical by-products during ballast water treatment based on an advanced oxidation process, Chem. Eng. J. 231 (2013) 427–433, http://dx.doi.org/10.1016/j.cej.2013.07.055.

[36] S. Banerji, B. Werschkun, T. Höfer, Assessing the risk of ballast water treatment to human health, Regul. Toxicol. Pharmacol. 62 (2012) 513–522, http://dx.doi.org/10.1016/j.yrtph.2011.11.002.